Aircraft Taxiing Route Planning Based on Multi-agent System

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***Abstract*—This paper proposes a route planning method based on multi-agent system for the NP-hard problem in aircraft taxiing route planning. Route planning is made according to the flight schedule in sequence for one aircraft each time. The post-planned route does not damage the existing one and route planning is made by utilizing the free time window of the taxiing road section. The artificial intelligence algorithm based on multi-agent system is designed to search the free time windows so as to find out the optimal taxiing routes for the aircrafts. The simulation results show that the average taxiing time of aircrafts is significantly reduced by comparing with the fixed pre-selected taxiing path algorithm, and the taxiing time may be saved up to 19.6% at maximum.**

Keywords—Aircraft; Taxiing route Planning; Multi-agent System; Free Time Window

I. INTRODUCTION

With high speed development of global air transport industry, airport becomes more and more busy and increasing which becomes a bottleneck restricting the development of civil aviation. A scientific and efficient route planning can reduce the taxiing time of aircraft, increase the aircraft traffic flow in the airport surface and improve the overall operating efficiency of the airport surface.

There have been many domestic and foreign scholars who have studied the problem of aircraft taxi routing on the airport surface and have achieved a series of research results. Reference [1] points out that the taxiing route planning of aircraft on the airport surface was a typical NP-hard problem. References [2-3] have studied the routing and sequencing strategies with complex network theory. References [4-7] model the surface taxiing zone as a 'node-edge' model by using the directed graph and model the taxiing process of aircraft on the airport surface by using the mixed integer linear program. References [8-9] propose Petri net is used for modeling surface operation process of aircraft. Reference [10] proposes that the route planning of aircraft on the airport surface is divided two stages on the basis of using Petri net for modeling surface operation process of aircraft, the shortest taxiing path set shall be firstly calculated and then the aircraft shall be dynamically allocated with taxiing time.

There are some problems existing in modeling of aircraft taxiing zone on the airport surface and planning method although some achievements have been made in the present researches. It is not adequate to describe the complexity of taxiing process of aircraft on the airport surface although it is simple to model the surface taxiing zone with a directed directed graph; it is structurally complex with a large number of calculations although the Petri net modeling method can fully characterize the taxiing process on the airport surface. It has a huge number of calculations although the mathematical programming method can give the optimal solution of routing problem; it will cause the unbalanced traffic distribution on the airport surface, resulting in severe jamming in partial taxing zones and losing the overall optimization of route planning although the taxiing route planning of aircraft is performed by 2 steps to achieve the optimal solutions spatially and temporally and thus reduce the difficulty of the problem.

Therefore, the overall optimal taxiing route can be planned for the aircrafts on the airport surface only when considerations are made both from the perspectives of time and space. In the taxiing route planning of aircraft, the conflict between the difficulty of problem solving and route planning optimization must be resolved to minimize the calculations and ensure the optimal routing results. How to ensure the optimal route planning and consider the feasibility of the algorithm at the time are the problems to be researched in this paper.

II. MODELING OF TAXIING ZONE ON AIRPORT SURFACE

Definition 1: taxiing resource graph $G_R = (R, E_R)$, $R = V \bigcup E$ represents all taxiing road section resource nodes, and E_R represents the connection relation between the resource nodes.

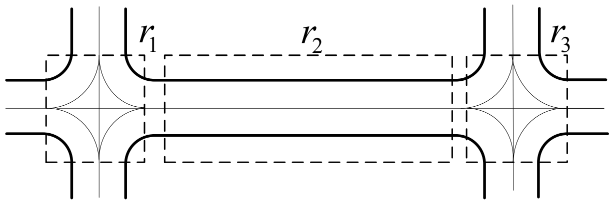

Fig. 1: Taxiing zone formed by 2 intersections and 1 taxiway

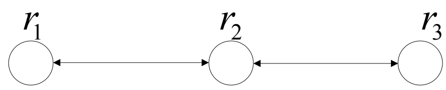

Fig. 2: Corresponding taxiing resource graph of Fig. 1

Fig. 1 represents the taxiing zone formed by 2 intersections r_1 , r_2 and 1 taxiway r_2 , which can be modeled using the taxiing resource graph model, as shown in Fig. 2. Here, $R = \{r_1, r_2, r_3\}$, $E_R = \{(r_1, r_2), (r_2, r_1), (r_2, r_3), (r_3, r_2)\}$, where , $(r_1, r_2) \in E_R$ represents that the aircraft can taxi directly from r_1 to r_2 . Any resource node r_i contains 2

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attributes: the shortest taxiing time $d(r_i)$ and capacity K. $d(r_i)$ represents the minimal taxiing time that the aircraft spends when passing through the resource node r_i. The resource node capacity is defined as unit capacity for convenient processing, namely, K=1, each resource node can maximally accommodate 1 aircraft simultaneously. A long taxiing road section can be divided into a number of resource nodes indicatively based on the shortest length that the aircraft must occupy in the taxiing process. The source nodes correspond to the actual physical path of the airport whilst the arc merely indicates the connection relation between the resource nodes. The aircraft only taxis in the nodes and spends no time taxiing on the arc. The aircraft can only taxi in the direction of arc arrow. The unidirectional arc indicates taxiing from one source node to another node, while the bidirectional arc indicates interlink of both resource nodes.

III. ALGORITHM DESIGN

Different from disorderly and random movement of ground traffic vehicles, the aircrafts move orderly under the strict control of controllers, and the ground controller gives instructions for aircrafts according to the flight plan. Any aircraft on the airport surface must take off or land according to the orders scheduled by the controller, i.e. the aircrafts must taxi in a sequence on the airport surface. Therefore, the priorities of aircrafts may be classified against the flight plan. Firstly, route planning shall be made for an aircraft with high priority and then made for an aircraft with low priority. The lately-planned route must follow the existing route, and can be only planned at the free time windows of each taxiing road section. By setting the taxiing priorities and planning the routes as per the priorities for the aircrafts, route planning for one aircraft each time will reduce the difficulties of the problem significantly; moreover, during route planning, the free time windows of all taxiing road sections can be searched so that surface traffic is evenly distributed to ensure overall optimization of route planning results.

Route planning is a process that the aircraft searches the free time widows in each taxiing road section as per the priorities, just like the traffic signal lights indicate the accessibility of the road. The route planning is a process of the aircraft selecting the road to access according to the instruction from the traffic signal lights. It is a complicated distributed solving process. Multi-Agent System (MAS) is a kind of distributed artificial intelligence system, which is good at finishing the overall system task by behaviors, such as interaction, cooperator and completion among the agents [11]. The agent is a kind of intelligent body which can accomplish the task independently and can cooperate with each other. The centralized solution to the problem of the free time window graphs using the MAS can be transferred into the distributed solution to the route problems on airport surface by interaction and cooperation among the agents. This way simplifies the difficulties of the problems and is easy to realize the algorithm.

A. Design of MAS Structure

The MAS structure for route planning of aircrafts on airport surface is illustrated as in Fig. 3. Three kinds of agents are designed using the hierarchical system structure: namely route management Agent, resource node Agent, aircraft Agent and one environment object. The route management Agent is the core of the system, responsible for management of MAS operation. The resource node Agent corresponds to the taxing resources nodes in the taxiing resource graph. And the aircraft Agent corresponds to all aircrafts for which route planning will be made. The environment object provides a living environment for the Agents, and records the connection relation between Agents and takes responsibilities for the communication and interaction among the Agents. The airport model and routing task (including start time, start and end points of taxiing, priorities, etc.) are the MAS's input information. The taxiing route planning of each aircraft is the output information of the system.

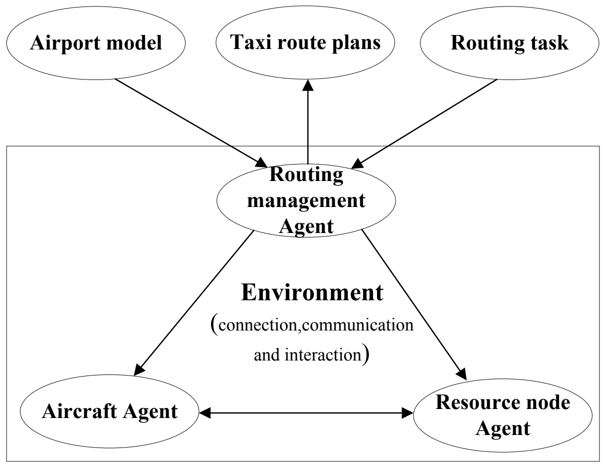

Fig. 3: MAS structure of aircraft taxiing route planning

B. Design of Agent

Design of Agent aims to define the functions and attributes of each kind of agents and determine the interaction, cooperation and completion relations among the Agents.

(1) Route Management Agent

Route management Agent is a core Agent of the system, responsible for starting and managing the whole MAS as well as outputting the route planning results. The route management Agent generates the Agent of all the resource nodes and sets the attributes of the resource node Agent. The first aircraft Agent (i.e., initial aircraft Agent) is generated in the aircraft priority order according to the route planning tasks, and then placed in to the corresponding resource node Agent of route start point (i.e., initial resource node Agent) to management and supervise the interaction and communication process among the Agents and finally output the route planning results.

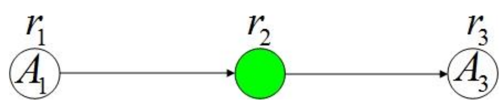

Fig. 4: MAS status of aircraft taxiing route planning

(2) Aircraft Agent

The aircraft Agent lives in the resource node Agent and has the survival ability, reproductive capability and mature and genetic attributes. The aircraft Agent will always survive when the resource node Agent status is in green (i.e. when the current time window is free). The aircraft will die immediately after it receives the information that the status of resource node Agent is changed into red (i.e. when the current time window is utilized). The aircraft Agent only has the ability to reproduce after it matures. The mature time of the aircraft agent is dependent upon the mature time attribute of the resource node agent where it lives; namely, it needs different taxiing times corresponding to the different road sections that the aircraft passes through. The aircraft Agent will take the initiative to check the adjacent resource node Agent in accordance with the connection attribute of the current resource node Agent after it matures. The aircraft Agent will immediately reproduce a descendant to occupy the resource node Agent if it discovers the status of resource node Agent is changed into green. When the aircraft Agent received the information that the resource node Agent is changed into green after it matures, it also will immediately reproduce a descendant to the resource node Agent that sends such information. The mature time of aircraft Agent must be prior to the time when it receives the information that the status of resource node Agent status is changed into green before it can reproduce a descendant to the resource Agent. A conflict of synchronous resource exchange will occur when both times are equal. In Fig. 4, if A_1 has been mature before receiving the r_2 sent information that the status is changed into green, then A_1 will immediately reproduce a descendant to r_2; if the mature time of A_1 and the time of receiving the r_2 sent information that the status is changed into green are equal, then A_1 will not reproduce a descendant to r_2, or otherwise, the conflict of synchronous resource exchange will occur. The genetic attributes have recorded the current route information of the aircraft Agent (including the resource node that has been passed through by it and the time window occupied by it).

C. MAS Operational Process

The MAS will generate an initial aircraft Agent in the initial resource node Agent when it begins operation. With the gradual reproduction, growth and death of the initial aircraft Agent, traversal for free time windows of all resource nodes is achieved. The optimal route of the aircraft is then obtained when the aircraft Agent is reproduced to corresponding resources node Agent of the taxiing endpoint （ending resource node Agent) and thus this route planning process ends. The next initial aircraft Agent will be generated in the order of priority to continuously repeat such process till all routing tasks are finished. The detailed operational process is described as follows:

(1) Route management Agent generates all resource nodes Agent according to the airport taxiing resource map;

(2) The route management Agent selects the current aircraft with the highest priority to generate an initial aircraft Agent and place it into the initial resource node Agent according to the routing task;

(3) Upon the beginning time of the routing task, the initial aircraft Agent begins a life journey of growth, maturation, reproduction and death till it reproduces a descendent to the ending resource node Agent to ends this routing process. The genetic information of aircraft Agent in ending resource node Agent is recorded to obtain the optimal route plan; and the status occupancy attribute of resource node Agent that the aircraft Agent passes through is reset (namely, the free time window is updated);

(4) The aircraft Agent cannot reproduce a descendent to the resource node Agent which has been recorded in the genetic information, so as to prevent repeated access to the road sections from forming a loop;

(5) During the routing process, the route management Agent will generate an initial aircraft Agent again when the status of initial resource node Agent is changed into green again if the initial aircraft Agent dies (the status of initial resource node Agent is changed into red). This can ensure traversal of all free time windows and the optimal solution can be found for every routing because the firstly-accessed free time window is not supposed to give the optimal routes finally, and even the feasible routes cannot be obtained;

The route management Agent selects the next aircraft to be planned for route planning and outputs all aircraft's optimal route plans till all routing tasks are accomplished.

IV. Simulation Experiment

A. Experimental Design

The model and algorithm established in this paper are validated by taking a domestic hub airport as an experimental object. Assuming that the flight schedule is as shown in Table 1, where the routing tasks of each aircraft (start point, end point, beginning time and priority for taxiing) are shown. In order to simulate and validate the route planning tasks of a large number of aircrafts during the approaching and departure processes, it is assumed that an aircraft rejoins the route planning task queue after it arrives at the destination. In order to compare with the route planning algorithm that firstly sets a fixed taxiing path and then dynamically allocates the taxiing time, a pre-selected taxiing path set is set for each aircraft. The number of pre-selected taxiing paths is k=3, as shown in Table 2.

Table 1: Flight Schedule

Taxi priority	Flight number	Operation type	Start time	Start point	End point
1	CA4224	Departure	12:20:20	gate10	Runway02
2	SC4436	Arrival	12:20:40	Runway02	gate1
3	CA3978	Departure	12:21:00	gate9	Runway02

4	MF1293	Arrival	12:21:20	Runway02	gate2
5	CZ3413	Departure	12:21:40	gate8	Runway02
6	3U8986	Arrival	12:22:00	Runway02	gate3
7	HU7317	Departure	12:22:20	gate7	Runway02
8	FM9307	Arrival	12:22:40	Runway02	gate4
9	CA4108	Departure	12:23:00	gate6	Runway02
10	3U8670	Arrival	12:23:20	Runway02	gate5

Table 2: Pre-selected Fixed Path Set for Aircraft

Flight number	Preselection fixed-path set
CA4224	gate10-E10-D11-A10-A9-A8-A7-A6-A5-A4-A3-A2-A1-F-Runway02 gate10-E10-B10-B9-B8-B7-B6-B5-B4-B3-B2-B1-D1-F-Runway02 gate10-C9-C8-C7-C6-C5-C4-C3-C2-C1-E1-D1-F- Runway02
SC4436	Runway02-J-A7-A6-A5-A4-A3-A2-D2-E2-gate1 Runway02-J-D8-B7-B6-B5-B4-B3-B2-E2-gate1 Runway02-J-D8-E8-C7-C6-C5-C4-C3-C2-gate1
CA3978	gate9-E10-D11-A10-A9-A8-A7-A6-A5-A4-A3-A2-A1-F-Runway02 gate9-E10-B10-B9-B8-B7-B6-B5-B4-B3-B2-B1-D1-F-Runway02 gate10-C9-C8-C7-C6-C5-C4-C3-C2-C1-E1-D1-F-Runway02
MF1293	Runway02-J-A7-A6-A5-A4-A3-D3-E3-gate2 Runway02-J-D8-B7-B6-B5-B4-B3-E3-gate2 Runway02-J-D8-E8-C7-C6-C5-C4-C3-gate2
CZ3413	gate8-E9-D9-A8-A7-A6-A5-A4-A3-A2-A1-F-Runway02 gate8-E9-B8-B7-B6-B5-B4-B3-B2-B1-D1-F-Runway02 gate8-C8-C7-C6-C5-C4-C3-C2-C1-E1-D1-F-Runway02
3U8986	Runway02-J-A7-A6-A5-A4-D4-E4-gate3 Runway02-J-D8-B7-B6-B5-B4-E4-gate3 Runway02-J-D8-E8-C7-C6-C5-C4-gate3
HU7317	gate7-E8-D8-A7-A6-A5-A4-A3-A2-A1-F-Runway02 gate7-E8-B7-B6-B5-B4-B3-B2-B1-D1-F-Runway 02 gate7-C7-C6-C5-C4-C3-C2-C1-E1-D1-F-Runway02
FM9307	Runway02-J-A7-A6-A5-D5-E5-gate4 Runway02-J-D8-B7-B6-B5-E5-gate4 Runway02-J-D8-E8-C7-C6-C5-gate4
CA4108	gate6-E7-D7-A6-A5-A4-A3-A2-A1-F-Runway02 gate6-E7-B6-B5-B4-B3-B2-B1-D1-F-Runway02 gate6-C6-C5-C4-C3-C2-C1-E1-D1-F-Runway02
3U8670	Runway02-J-A7-A6-D6-E6-gate5 Runway02-J-D8-B7-B6-E6-gate5 Runway02-J-D8-E8-C7-C6-gate5

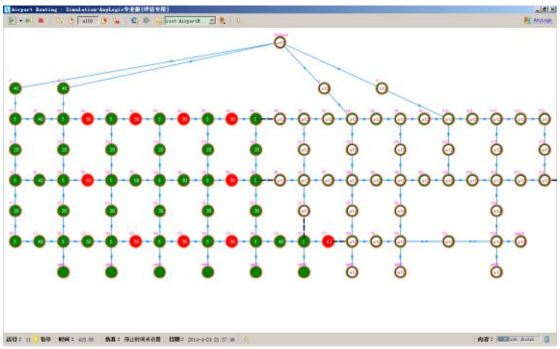

Fig. 5: MAS operational process for aircraft taxiing route

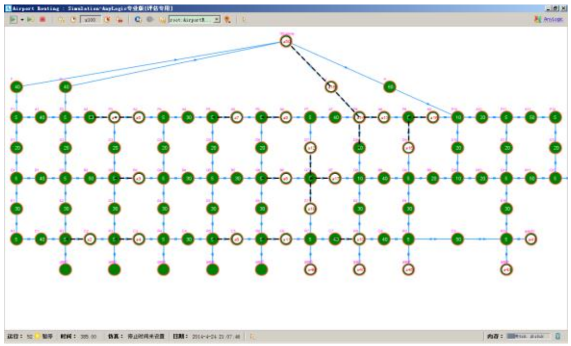

Fig. 6: Simulation of aircraft taxiing route planning results

The development for the aircraft taxiing route MAS proposed in this paper is realized with Anylogic 7.0 as a platform. Anylogic remains the only professional agent based modeling tool[12].Anylogic provides an active objects class for designing various Agents, provides an environment object to realize the interaction and the communication between the Agents, and significantly simplifies the MAS development difficulty. The operational process interface of aircraft taxiing routes planning MAS is illustrated as in Fig. 5. The red node indicates the current time window is not free in the resource node agent; the white node indicates the resource node Agent has been occupied by the reproduced aircraft Agent; the black dotted line indicates the resource node Agent that the aircraft Agent may occupy in the next reproduction. All aircrafts will conduct a simulative operation according to the obtained optimal routes after all aircraft route planning tasks are accomplished, as shown in Fig. 6. The black dotted line in the figure indicates the movement direction of aircraft Agent. With the MAS of aircraft taxiing route planning, we can intuitively observe the route planning process; with the aircraft taxiing simulation using the output route plans, we can observe various taxiing waits of the aircrafts in order to avoid the taxiing conflicts. The overall planning and simulation process are very imaginative and intuitive.

B. Result analysis

To simulate the taxiing activities of a large number of aircrafts on the airport surface, as for the routing tasks given in Table 1, it is assumed that the aircraft returns to the starting point and rejoins the simulation queue after it arrives at the destination to repeat the routing tasks for one to six times. .A comparison is made between the free time window routing algorithm proposed in this paper and the fixed pre-selected taxiing path routing algorithm. The number of paths are taken as k=1,2,3 respectively. The average taxiing times of the aircraft corresponding to two algorithms are given in Figure 6. It can be seen from the figure that, when k=1, the results given by the fixed pre-selected taxiing path routing algorithm are the worst. This is because it will cause some taxiing road sections are excessively crowded and jammed when all the aircrafts select one fixed shortest path to taxi. The average taxiing time improves as the number of paths (k) increases, however, it is unable to exceed the lower limit given by the free time window routing algorithm. This is because the fixed pre-selected path routing algorithm only uses a part of taxiing resources on the pre-selected path for planning, while the free time window routing algorithm makes full use of all taxiing resources, making the traffic on the airport surface can be evenly distributed.

The percentage of taxiing time reduced by the free time window routing algorithm compared with the fixed pre-selected path routing algorithm when k=3 is shown in Figure 7. It can be seen from the figure that, the percentage of taxiing time reduced by the free time window routing algorithm increases with the increase in number of aircrafts. It can save up to 19.6% taxiing time when there are 60 aircrafts. This is because the more aircrafts taxi simultaneously on the airport surface, the more at, the more their mutual influence is; and the more severe jamming on the fixed pre-slected taxiing path is, the more taxiing waits for avoiding conflicts appear; while the free time window routing algorithm makes the traffic on the airport surface be evenly distributed, preventing severe congestion on part of road sections, and thus the advantage of saving taxiing time is reflected more obviously.

HPZ820 work station (6-core CPU, dominant frequency 2.0GHz, 4G RAM) is applied for experiment. Through multiple tests, any aircraft's optimal route can be calculated out within 1.5s by using the MAS-based free time window routing algorithm.

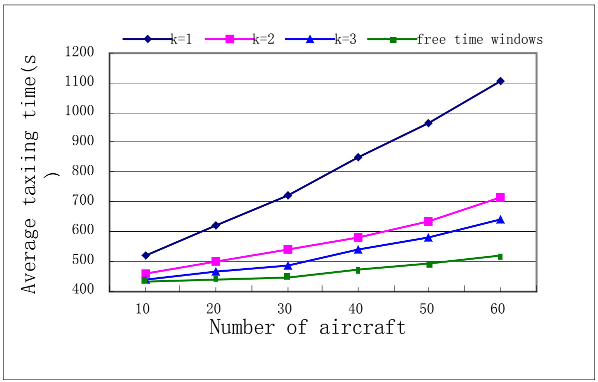

Fig. 7: Average taxiing times given by two algorithms for route planning

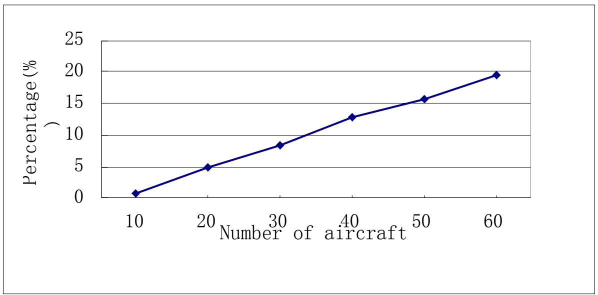

Fig. 8: Percentage of taxiing time saved by the free time window algorithm

ACKNOWLEDGMENT

(1)This paper proposes that the taxiing resource graph is used to model the taxiing zone on the aircraft surface, which fully describes the taxiing process of the aircrafts on the airport surface and reduces the complexity of model.

(2)The operation characteristics of the aircafts on the airport surface are analyzed. The order of priority is set for the aircrafts according to the flight schedule and route planning is made in sequence according to the order of priority. The route to be planned later only can be planned by using the free time windows of the taxiing road section and route planning shall be made only for one aicraft each time. It reduces the difficulty and gives consideration to the routing optimization at the same time.

(3)The designed multi-agent system can find out the optimal solution in order of priority, with vivid and visual route and simulation processes.

(4)Compared with the method of taxiing route on a fixed path, route planning method based on multi-agent system can obviously reduce average taxiing time of aircrafts, and improve the overall operation efficiency of the airport surface.

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