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A dynamic air traffic model for analyzing relationship patterns of traffic flow parameters in terminal airspace

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ABSTRACT

This paper provides a special view on air traffic flow parameters and presents certain influences from airspace to traffic flow characteristics. Based on statistics on measurement radar data within terminal airspace, we obtain time distributions and interrelationships of the basic parameters, and accordingly divide traffic flow states into 3 phases: free flow, mild-controlled and strong-controlled flow. Through analyzing characteristics shown in different phase states, as well as aircraft performing in real airspace operations, we establish dynamic models to describe potential behaviors including following, holding and maneuvering, while programing them into simulation tools. Relationship patterns are validated by comparison analysis on the similar simulation results against measurement data. Taking air route adjustment as simulation example, we conduct experiments on airspace elements that may have effects on traffic flow, with further discussing on possible reasons.

1. Introduction

The air traffic congestion, along with its companions including flight delay, operation safety and environmental pollution, has affected the quality of industry development and efficiency of economic growth, not to mention bringing great inconveniences and costs to people's lives. Large numbers of flights emerging in airport terminal airspace bring too much traffic pressure to Air Traffic Controllers (ATCs), while aircraft flying on the complex networks of air routes have different movements, like climbing, declining, converging, crossing or overtaking, all making this area be the place where air congestions happen frequently, and be the highlight that we focus on.

Several studies in last decades have developed air traffic flow theory, especially in air traffic flow modeling. Inspired by LWR model [25,26,38], Menon et al. [32] and Bayen et al. [3] proposed a new Eulerian network model using macroscopic traffic parameters. The computation complexity of this model relies on the physical size of airspace while not the numbers of aircraft, which is different from the microscopic model considering individual trajectory or behavior [2]. After that, stochastic factors were added in and therefore the model could be used to make short predictions for air traffic flow [33]. With specifically modifying the state variables (flow rate instead of volume) and control variables (time in trail) for terminal area, Bai and Menon [1] proposed an optimal flow control approach based on Eulerian model, while reducing the numerical difficulties and simple to be implemented in real time. Since the Eulerian PDE (partial differential equation) network model has non-closed equations, Cell Transmission concept [7] was then introduced in by Robelin et al. [39] and Sun and Bayen [45] by time-varying equations instead of continuous model, as well as the aggregate flow model [44] and its disaggregation method [46].

Instead of aggregate traffic flow modeling, number of studies were focusing on the modeling of air traffic behaviors either. In terms of aircraft dynamics, a three-dimensional point-mass aircraft model considering the kinematic characteristics is proposed by Williams [50] to obtain the optimal trajectories using a Legendre pseudo-spectral method. Liu and Hwang [27] introduced a stochastic linear hybrid system to describe the dynamics of an aircraft with changing flight modes, which has two different discrete-state transition models depending on the availability of flight plans, including the Markov transition model and state-dependent transition model. From separation maintaining point of view, mostly centered around are the conflict detection and resolution models. A thorough overview and classification of these models was presented by Kuchar and Yang [23], while more recently, the reader

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Nomenclature

$P_i(t)$	Position of aircraft i at time t
$v_i(t)$	Speed of aircraft i at time t
$a_i(t)$	Acceleration of aircraft i at time t
$\gamma_i(t)$	Heading of aircraft i at time t
$\Delta\gamma_i(t)$	Deviation angle of aircraft i at time t
$a_{\max}(k)$	Maximum deceleration of aircraft type k
$T_i(t)$	Estimate time of passing holding fix
Δt_i	Time from metric to hold fix for aircraft i
ξ_i	Binary variable if holding is needed
t_h	Actual time of passing holding fix
P_i^{ta}	Tangent point for aircraft i
P_i^{o}	Postposition converging point for aircraft i
ϕ	Special intersect angle
T'	Time from holding fix to converging point
T''	Time to fly by specific straight segment
v_i^{tg}	Speed of aircraft i at tangent point
a_i^{tg}	Acceleration of aircraft i at tangent point
M	Metric point
P	Holding fix
D	Distance from metric to converging point
d	Distance from holding fix to converging point
T^{io}	Time needed for inbound or outbound
W	Maneuvering fix
δ	Intersect angle of the air routes
P^o	Converging point
U	Intersection between air routes and the circle
r	Radius of the circle
T_i^{hold}	Holding time for aircraft i
r_i^{io}	Radius of the turning circle for aircraft i
ω_i^{io}	Angular speed for aircraft i
γ_i^{dev}	Heading of aircraft i in the deviation phase
γ_i^{rec}	Heading of aircraft i in the recovery phase
V_k	Initial speed for aircraft type k
A_k	Initial acceleration for aircraft type k
P_{node}	Relative coordinate of each *node*
T_{random}	Random rate in exponential distribution
T_{node}	Arrival rate at each *node*

is referred to [5,47,40]. With the improvement in simulation techniques, air traffic models were proposed and modified with respect to specific scenarios and constraints. For instance, a method for designing models of the air traffic merging techniques vectoring and point merge is described and validated with fast-time simulation [17]. In [48], the authors studied the aircraft following phenomenon in the air freeways and proposed the corresponding microscopic model with respect to the route type of single layer. Based on hybrid dynamic characteristics of traffic flow, Zhang et al. [51,52] established the generalized arrival model for terminal airspace by means of the stimulation–reflection mechanism.

There also has been much discussion on air traffic parameters in the literature, such as dynamic density or complexity. As an air traffic metric, the concept of dynamic density was proposed by Laudeman et al. [24] and its measurement and prediction methods were taken into consideration by Kopardekar and Magyarits [22]. Furthermore, Hilburn [15] elaborated the detailed cognitive complexity metrics, while Klein et al. [21] simplified them to analyze the dynamic airspace configuration. Studies by Delahaye and Puechmorel [8] and Delahaye et al. [9] assessed the intrinsic metrics of air traffic complexity. Based on data-driven approach for air traffic flow modeling using historical data, Marzuoli et al. [31] provided valuable insight on airspace complexity at the level of large-scale three dimensional flow networks. However, there has been less discussion on the interrelationships of parameters of traffic flow, which could be seen much in the literature of vehicle traffic flow theory. See for instance Kerner and Rehborn [18,19], Helbing et al. [13,14] and the references therein.

In this paper, motivated by the analysis of the identified relationship patterns of air traffic flow parameters from measurement data, a dynamic model is developed capturing realistic aircraft behaviors in terminal airspace. Based on the simulation of the model subject to more complicated scenarios, more complete relationship patterns of air traffic flow are further addressed, which accordingly could be implemented into air traffic forecast, air traffic modes identification, sector capacity/complexity assessment for instances. Similar applications could be seen in studies e.g., [43,4,34,20].

This paper is outlined as follows: in Section 2 the time distributions and interrelationships of air traffic flow parameters are derived from measurement radar data. Section 3 introduces the dynamic models we developed to capture the normal following, holding and maneuvering behaviors of individual aircraft. Based on these models, in Section 4 simulation experiments are conducted using NetLogo tool with variables from real practice, while results from both measurement data and simulation experiments are compared and analyzed. Finally, the conclusions and future work are presented in Section 5.

2. Measurement data

2.1. Time distributions

The measurement radar data (from Sept. 11th to 16th in year 2012) for 144 hours come from Guangzhou International Airport, which include information (e.g., longitude, latitude, flight level, ground speed, heading, flight number, SSR code, etc.) of every 16 seconds for each aircraft within radar coverage. Through data clean, integration and transformation, these data turn to be suitable for air traffic flow study. Data clean mainly includes: eliminating the duplicate records and over flights that have little influence on terminal operation, and filling missing records by averaging adjacent ones. Data integration includes: taking records of flights that fly along converging air routes (such as *GYA-AGVOS* and *TAN-AGVOS*) according to flight schedules that day. The reason why we focus on converging air routes is that this kind of routes seen widely in terminal airspace normally has great influences on operation, especially for separations, which is quite different from vehicle traffic flow focusing on one-way road ([37,12], just to mention some). It is not appropriate to take each air route separately into consideration. We could also see much discussion on converging air routes for like conflict detection [6] and resolution [36]. Therefore, the records of converging air routes mentioned above are put together and used in data transformation next that mainly includes transforming the longitude and latitude of radar tracks into distances to the converging point (*AGVOS*). Then we take 5 minutes as the unit time and perform a statistical analysis on the parameters, Volume, Flow, Speed and Density, as follows.

Considering the data type and operation mode in air traffic, it is necessary for us to explain how we define and calculate these parameters, in order to distinguish them from the same ones as in vehicle traffic.

a. Volume (n): the number of aircraft emerging in the observing area. By flight number and SSR code, individual aircraft could be selected within the radar data of target time.