Computers & Industrial Engineering 112 (2017) 238–245

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

A control policy for scheduled traffic flow system

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ARTICLE INFO

Article history:
Received 11 April 2016
Received in revised form 10 August 2017
Accepted 16 August 2017
Available online 18 August 2017

Keywords:
Air transportation
Conflict resolution
Air traffic control
Trajectory planning

ABSTRACT

This paper presented a modeling methodology with the aim of controlling flight flow. By incorporating minimum safety separation time, it was demonstrated that the control of air traffic flow in the terminal control area can be regarded as the planning of different departure queues in each fix. The jet route control model for different scenarios were put forward by formulating various types of constraints emphasized in the air traffic control rules. The inherent relationships for different system variables were acquired and the proposed optimization models were applied to coordinate several different departure air traffic flows in the specified fixes. In addition, some key features of the presented system optimization model were discussed. The proposed max-plus system model has been validated using real traffic flow data and some relevant experimental results were reported. Moreover, the influence of different factors such as temperature, weight, as well as aircraft climbing mode on the system optimization performance were also analyzed which demonstrated the validation of the presented system model.

1. Introduction

Air traffic volume all over the world continues to rise rapidly in recent years, especially in some developing countries. As a result, the most urgent task for the airport and air traffic management agency is to increase air traffic system capacity and decreasing controller workloads (Corver & Aneziris, 2015). At the same time, air traffic flow optimization regulation methodology with better performance can also play an important role to bear on this problem as the sky becomes saturated, which was brought up by the NGATS (Next Generation Air Transportation System) and the SESAR (Single European Sky Air Traffic Research System) aimed at improving the performance of existing air traffic system infrastructure (Centre, 2010; Harry, Richard, & Michael, 2006; Schuster & Ochieng, 2014). Besides, NGATS and SESAR are implemented in a different way compared with traditional system operation mode. It can expect that the trajectory-based air traffic system operation mode will play a greater role in future air traffic control (Besada, Frontera, Crespo, Casado, & Lopez-Leones, 2013). As for the multiple aircraft tactical control, the aircraft maneuvers which are involved in the conflict resolution are based on aircraft's future trajectory. Usually, the related flight parameters or historical track data are used to estimating aircraft's location for a specified time interval (Sahawneh, Mackie, Spencer, Beard, & Warnick, 2015; Yong, Han, & Park, 2015). The term control policy presented in this paper is referred to the actions that air traffic controllers take when the flight take-off time is acquired in advance(Ruiz, Piera, Nosedal, & Ranieri, 2014). Generally speaking, there are three types of methods used for aircraft conflict detection on the whole (Kuchar & Yang, 2000). Correspondingly, there are two types of methods used for conflict resolution, which are known as pair-wise strategy and global strategy. The former refers to partial aircrafts involved in flight conflict for a specified aircraft. On the contrary, the latter refers to all aircrafts involved in flight conflict (Kuchar & Yang, 2000).

Prior to our work, some studies presented constraint programming model for trajectory optimization problem (Nicolas Barnier, 2011). The conflict resolution algorithm using causal modeling was also put proposed (Ruiz et al., 2014). A variety of mathematical optimization models have been examined, such as the mixed-integer linear programming algorithm and genetic algorithms (Durand, Alliot, Noailles, Belin, & Camichel, 1996; Omer, 2015). Moreover, some optimal control approaches were also adopted to solve this problem by setting corresponding cost functions (Alliot, Durand, & Granger, 2000; Clements, 1999; Matsuno, Tsuchiya, Wei, Hwang, & Matayoshi, 2015; Pallottino, Feron, & Bicchi, 2002; Raghunathan, Gopal, Subramanian, Biegler, &

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http://dx.doi.org/10.1016/j.cie.2017.08.022

Samad, 2006; Tang, Chen, & Li, 2016; Vela et al., 2010) Additionally, the interaction between the costs due to ground-holding regulations and the costs due to en-route air traffic control was also derived based on traffic forecasts (Lehouillier, Soumis, Omer, & Allignol, 2016). The schedule recovery problem of aircraft flow using two-stage heuristic algorithm was also put forward. Consequently, the integrated recovery procedure was proposed (Boysen & Fliedner, 2011; Chen, Yan, & Chen, 2010; Zhang, Henry Lau, & Yu, 2015). All the aircraft conflict resolution tasks are currently carried out by air traffic controllers, and these contribute significantly to their workloads. Therefore, it is very necessary to develop a decision support system with greater level of automation for air traffic controllers at the strategic level aimed at satisfying the increasing air traffic flow demand and reducing the workloads of controllers at the tactical level.

In fact, numerous systems arise in daily life like physical system, biological system, as well as economical systems can be grouped into two categories: continuous variable dynamic system and discrete event dynamic system. As a result, the system sate evolution dynamic can be modeled by specified mathematical models such as differential or difference equations (Menon, Sweriduk, & Bilimoria, 2004). Besides, the system that contains only synchronization can be described by max-plus linear model proposed in this paper. For air traffic control system composed of man, aircraft and air route, its states change depend on the occurrence of discrete events instead of continuous variable, In other words, the system dynamic is dominated by the time process or the clock ticks (Rong, Geng, Valasek, & Ioerger, 2002). Due to the complex characteristics of air traffic flow in the airspace, the air traffic system models that reflect its behavior are difficult to build. This constitutes the main work of this paper and some attempts using max-plus model to build system model have been implemented in many areas (Goverde, Bovy, & Olsder, 1999; Olsder, 1993). In this paper, we developed a max-plus system modeling methodology for air traffic system. As an automated support tool for decision making on traffic flow management, these models can be used by air traffic managers and controllers.

The organization of this paper is as follows. Firstly, the max-plus theory is briefly reviewed and single jet route constraints in air traffic system are introduced. Some system analysis technologies of air traffic flow are also put forward. Next, air traffic system with multiple jet routes constraints is presented to characterize the dynamics of system operation. The max-plus optimization cost function and a realistic simulation situation is demonstrated in Section 4 and Section 5. Finally, some concluding remarks and indications of future work are reported.

2. Construction of the single jet route system model

The max-plus model offers a solution for the air traffic flow model construction using linear difference equations. We firstly give some basic definitions of max-plus theory and then present some initial results. In short, there are only two basic operations in the max-plus algebra, which are denoted by symbols '$\oplus$' and '$\otimes$', respectively. For the meaning of two computation symbols ($\oplus$) and ($\otimes$), the readers can refer to the following reference (Baccelli, Cohen, Olsder, & Quadrat, 1992) for more details. To obtain the algebra model of air traffic system, we should determine the location through which flight number need to be counted firstly. A basic unit of the air traffic system is composed of three parts, which can be denoted by an input boundary, a specified air route length, as well as an output boundary. Taking single jet route consists of m sub-segments $s_1, s_2, \ldots, s_m$ as an example, at a coarse grain, we can regard each sub-segment $s_k (k = 1, 2, \ldots, m)$ as a 'machine' which is used to process specified tasks with different property as illustrated in Fig. 1. Consequently, several flight conflicts in the air traffic system along a specified air route can be regarded as the serial tasks (Gruzlikov, Kolesov, Skorodumov, & Tolmacheva, 2017; Oliveira, Carvalho, Junior, & Sato, 2008).

Moreover, we assume that the predefined nominal trajectory of each aircraft on the jet route follows a specified order. That is, if we use symbol n to represent the total number of aircrafts $p_1, p_2, \ldots, p_n$ involved for a particular jet route, then the specified order means that each sub-segment has n aircrafts assigned to it and each aircraft accepts the service provided by m sub-segments. In addition, we call the process provided by each sub-segment service activity and there are two types of shared resources in the system, that is, sub-segment and aircrafts. We call the cases that aircraft arrived at entrance of a specified sub-segment or sub-segment begins offering service for a specified aircraft input (Cohen, Eacute, Gaubert, & Quadrat, 1999). On the contrary, we call aircraft leaves a specified sub-segment or sub-segment finishes the service activity for aircraft output. In the following section, we will give a detailed description of the model building of air traffic system using max-plus algebra put forward above. A typical nominal operation of the air traffic system follows a time schedule with a specified period. In our framework, each sub-segment is denoted by $s_1, s_2, \ldots, s_m$ as indicated above. Other basic elements of the air traffic system are the control points where the aircrafts are authorized to enter a generic node by the real-time traffic controller (Dias, Maia, & Lucena, 2015).

Furthermore, the operation of air traffic system also refers to different types of characteristic locations such as holding locations which are used to 'store' aircrafts temporarily. As a result, the number or layouts of various holding locations have great impact on the control of aircraft flows in the airspace. Therefore, it is necessary to incorporate their property for the system model building. We denote by b_i the 'capacity' of s_i in the jet-route. In this case, the jet route can be regarded as a 'flexible coupling serial system' for $b_i \geqslant 2$. From another perspective, we can transform the original system with 'capacity' into m sub-queues $L_i (i = 1, 2, \ldots, m)$ in which each sub-segment contains only one queue by combining each specified sub-segment with the corresponding 'storage capacity' on the basis of the 'first come first service' principle (Qi & Li, 1995). In other words, the original sub-segment is extended virtually and its length is prolonged by incorporating the influence of 'storage capacity'. In this way, the max-plus system model for the jet route can be described as follows by incorporating pseudo sub-segment queue $s_j^{(i)} (j = 1, 2, \ldots, b_i - 1)$ and equivalent transformation:

$$\begin{cases} \boldsymbol{X}(k) = \boldsymbol{A}(k) \otimes \boldsymbol{X}(k-1) \\ \boldsymbol{Y}(k) = \boldsymbol{C}(k) \otimes \boldsymbol{X}(k) \end{cases} \tag{1}$$

where

$$\begin{cases} \boldsymbol{X}(k) = [\boldsymbol{X}^{(1)}(k), \boldsymbol{X}^{(2)}(k), \ldots, \boldsymbol{X}^{(m)}(k)]^T \\ \boldsymbol{X}^{(i)}(k) = [\boldsymbol{X}_1^{(i)}(k), \boldsymbol{X}_2^{(i)}(k), \ldots, \boldsymbol{X}_{b_i}^{(i)}(k)]^T, \quad (i = 1, 2, \ldots, m) \\ \boldsymbol{Y}(k) = [\boldsymbol{Y}^{(1)}(k), \boldsymbol{Y}^{(2)}(k), \ldots, \boldsymbol{Y}^{(m)}(k)]^T \end{cases} \tag{2}$$

and $\boldsymbol{X}_j^{(i)}(k)$ denotes the time instant at which aircraft p_k departs from $s_j^{(i)}$ in queue L_i and $\boldsymbol{Y}(k)$ is the time instant at which p_k flies out the specified jet route. More specifically, the two time variables above mentioned involves a serials of actions taken by air traffic controllers or system dispatchers in order to ensure air traffic sys-

Fig. 1. The division of single segment in air traffic system.