2010 3rd International Conference on Computer and Electrical Engineering (ICCEE 2010)
IPCSIT vol. 53 (2012) © (2012) IACSIT Press, Singapore
DOI: 10.7763/IPCSIT.2012.V53.No.2.13

Decision-making Method for Control of A-SMGCS Taxiway Centre Line Lights

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Abstract—For automatic decision-making on the control command of A-SMGCS (Advance Surface Movement Guidance and Control System) taxiway centre line lights in line segment, Petri net based approach is proposed. Firstly, the dynamic operation model for taxiway line segment is established based on Petri net, and the corresponding marking control regulation is defined. And then, the controller synthesis for the operation model is fulfilled based on the local incidence matrix approach and it can prevent the model from evolving into forbidden states. Furthermore, the control command decision-making method and corresponding algorithm are provided based on the state of transition. Finally, an example on the decision-making of control command for taxiway centre line lights demonstrates the effectiveness of this approach.

Keywords- A-SMGCS; taxiway centre line lights; Petri net; control command decision-making

1. Introduction

A-SMGCS (Advanced Surface Movement Guidance and Control System) is a system providing routing, guidance and surveillance for the control of aircrafts and vehicles on airport surface. A-SMGCS acquires precise location information through multiple sensors, and avoid confliction through automatic control of guidance lights. The objective of this system is to support safe, orderly and expeditious movement under all traffic density, visibility level and complex condition [1].

Traditionally, the guidance of aircraft movement on airport surface is fulfilled by two kinds of method: One is the command of air traffic controller, and the other is the follow-me car. However, the first method relies on huge amount of radio talk and can not accommodate the increasingly busy surface traffic. The second method restricts the aircraft independent move speed. In the A-SMGCS fourth implementation level, it is proposed that aircraft movement needs to be guided by automatically controlled guidance lights. Thus, comparing with traditional airport surface operation, safety and efficiency of this level will be greatly upgraded.

Many existing research results about guidance of aircraft on airport surface are reported. In 2000, an advanced taxiway guidance system (ATGS) has been designed, equipped in Atlantic City international airport by FAA. The ATGS provides guidance to aircrafts through simultaneously controlled taxiway edge lights and centre line lights. Questionnaire in this project indicates pilots are more apt to accept the guidance of centre line lights [2]. An airfield ground lights automation system (AGLAS) is designed for Leipzig/Hall airport by Bumiller in 2002, which achieves the work state monitor and automatic switch of lights [3]. The applicability of automatic control for guidance lights through computer system is demonstrated by Kevin [4].Nowadays, although many design proposals [5-7] on airport surface guidance lights control have been provided by FAA, and also some guidance light control systems of different design method exist, the final decision-making relies

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mostly on air traffic controllers. This approach is easily constrained by personal experience, and increases the workload of air traffic controllers, especially during busy period. Thus, it is necessary to achieve automatic decision-making on the control command of guidance lights, following the real-time aircraft operation state on airport surface.

In this paper, we report our research on automatic decision-making for the control command of taxiway centre line lights. This paper is organized as follows. After a brief discussion of taxiway centre line lights operation process, the control architecture based on hybrid control theory is proposed in Section Ⅱ. The Petri-net (PN)-based operation model for taxiway line segment is provided in Section Ⅲ. The marking control regulation of PN-based operation model is introduced in Section Ⅳ. Section Ⅴ presents implementation method for control command decision and related decision-making algorithm for taxiway centre line lights. Section Ⅵ gives a case study. Then, a conclusion and some future work suggestion are drawn in Section Ⅶ.

2. Taxiway centre line lights operation process and its corresponding control architecture

In A-SMGCS fourth implementation level, for airport surface operation, air traffic controllers just require ordering the pilot manipulate aircraft to follow the centre line lights front. At the same time, the stop bar lights work together to ensure the safety of aircraft movement.

Taxiway centre line lights exert its function and make aircrafts pertain safe separation among each other. There are two kinds of centre line lights control methods: one is the single light-based control method, the other is the lights segments-based control method. For the location precision of aircrafts and the time delay on lights control can not satisfy control requirement, the single light-based control method is difficult to fulfill. Thus, lights segments-base control method for centre line lights is always adopted. In this control method, numbers of neighboring centre line lights form a lights segment and they are linked into the same electronic circuit physically.

Example1. The taxiway centre line lights operation situation in A-SMGCS fourth implementation level is demonstrated in Figure 1. Z_i , Z_{i+1} are two neighboring intersections. $\mathrm{S}_\mathrm{B}^i (1 \le i \le 5)$ are centre line lights operation segments. When aircraft a_1 is about to enter segment S_B^3 , the centre line lights belonged to this segment will be turned on. Thus, aircraft a_1 can be guided into this segment. Similarly, when aircraft a_1 is about to leave operation segment S_B^4 , the centre line lights belonged to this segment will be turned off.

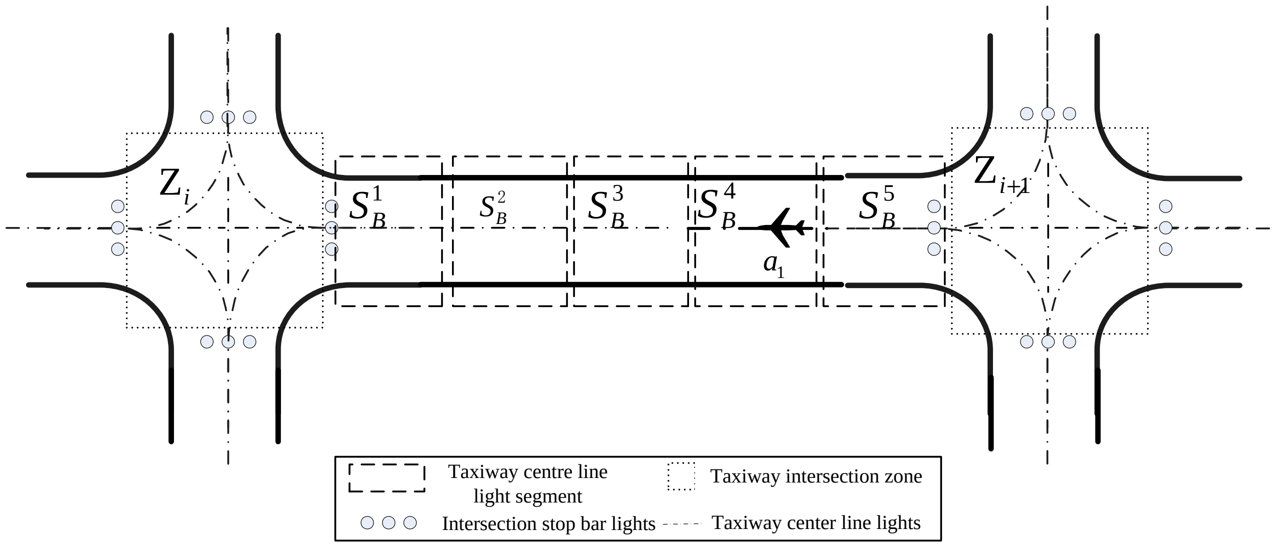

Fig.1. The operation scenario of taxiway centre lights in A-SMGCS

Operation process of centre line lights is an interactive process between continuous aircraft movement and discrete lighting control command, which belongs to the research category of hybrid control theory. The control architecture for taxiway centre line lights based on hybrid control theory has been proposed in Figure 2.

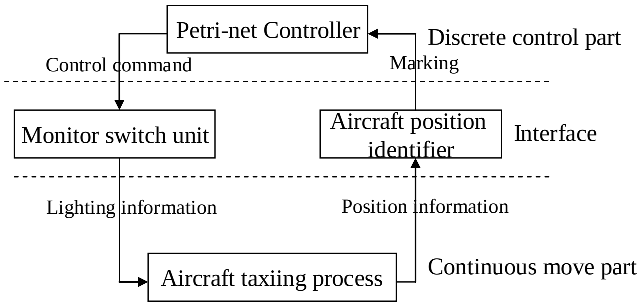

Fig.2. Control architecture for taxiway centre line lights

In Figure 2, Petri-net controller interacts with continuous aircraft state through aircraft position identifier. The control command can be transformed in monitor switch unit and the result can drive the switching of centre line lights instrument. For the essential role of Petri-net controller in the control architecture, we mainly study its design process and related decision-making method in this paper.

3. Petri net-based taxiway line segment operation model

Definition 1: Taxiway line segment operation model based on Petri net can be defined as $LPN = (P, T, \boldsymbol{Pre}, \boldsymbol{Post}, \boldsymbol{M_0})$. Place p_{∇}^{j}、${}^{'}p_{\nabla}^{j} \in P$ represent the same centre line lights segment, but they can represent operation state of different aircraft movement directions, and ∇ is the name of taxiway line segments, j is the sequence number of centre line lights segment in the same line segment. Transition $t_{\nabla}^{i-j} \in T$ represents movement that aircrafts move from segment S_{∇}^{i} to S_{∇}^{j}; $\boldsymbol{Pre}$ is the pre-incidence matrix; $\boldsymbol{Post}$ is the post-incidence matrix; $\boldsymbol{M_0}$ is the initial marking, representing the initial state of taxiway line segment operation.

Example2. Taking the taxiway line segment between intersection $\mathrm{Z}_i, \mathrm{Z}_{i+1}$ in Figure 1 as an example, and we assume that it allows two different movement directions in different period, Z_i to Z_{i+1}, and Z_{i+1} to Z_i respectively. The PN-based operation model is presented in Fig. 3. In this model, places p_{B}^{i} and ${}^{'}p_{\mathrm{B}}^{i}$ represent the same centre line lights segments $\mathrm{S}_{\mathrm{B}}^{i}$ （$1 \le i \le 5$）; transitions t_{B}^{i-j} （t_{B}^{j-i}） （$1 \le i \le 5$, $1 \le j \le 5$）represent aircrafts move from $\mathrm{S}_{\mathrm{B}}^{i}$ （$\mathrm{S}_{\mathrm{B}}^{j}$） to $\mathrm{S}_{\mathrm{B}}^{j}$ （$\mathrm{S}_{\mathrm{B}}^{i}$）. The dashed arrowheads represent links among PN-based models for taxiway line segment and its neighboring intersections.

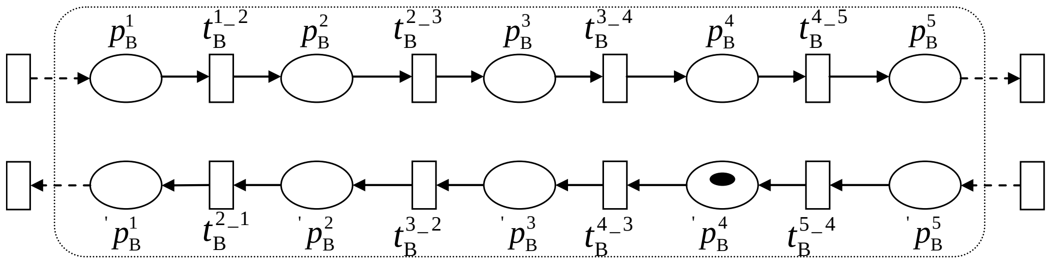

Fig.3. Petri net operation model for taxiway line segment

4. Marking control regulation

Definition 2: Marking control regulation for PN model is defined as prohibited states, which can be denoted as the weight-addition of marking less than an upper limit and represented as $\boldsymbol{L} \cdot \boldsymbol{m} \le \boldsymbol{b}$. $L_{q \times n}$ is the weight matrix, and $\boldsymbol{b}$ is the limit vector, q is the number of inequality, n is the number of places in model.

According to taxiway operation control rules, following constraints included in the marking control regulation can be established:

Constraint 1: Since place p_{∇}^{j} and ${}^{'}p_{\nabla}^{j}$ represent the same centre line light segment and at most only one aircraft can be allowed to occupy the segment at one time, the constraint for the marking of p_{∇}^{j} and ${}^{'}p_{\nabla}^{j}$ is as follows:

$$m(p_{\nabla}^{j}) + m({}^{'}p_{\nabla}^{j}) \le 1$$

Constraint 2: To ensure safe separation between aircrafts, two neighboring centre line light segments can not be occupied by aircrafts at the same time. The constraint for marking of two neighboring places is as follows:

$$m(p_{\nabla}^{j}) + m(p_{\nabla}^{j+1}) \le 1$$
$$m({}^{'}p_{\nabla}^{j}) + m({}^{'}p_{\nabla}^{j+1}) \le 1$$

Constraint 3: For line segment between two taxiway intersections, only aircrafts of the same movement direction can be allowed to occupy. Constraints for the marking of places in the same line segment are as follows (k is the number of lights segment in the same taxiway line segment):

$$m(p_{\nabla}^{j}) + m({}^{'}p_{\nabla}^{i}) \le 1$$
$$(i = 1, 2, \ldots \mathrm{k};\ j = 1, 2, \ldots \mathrm{k};\ i \ne j),$$

5. Decision-making method for the control command of taxiway centre line lights

5.1. Petri net controller synthesis for PN model based on local incidence matrix

For PN model whose marking control regulation is of the form $\boldsymbol{L} \cdot \boldsymbol{M} \le \boldsymbol{b}$, Moody provides a controller synthesis method based on the place invariant [14]. However, this method is not applicable for us for it needs the entire incidence matrix of the PN model. Method based on local incidence matrix is adopted in this paper.

Definition 3: For supervisory control goal restricting the reachable markings of a PN model, such that $l^{\mathrm{T}} m \le b$, places corresponding to non-zero elements in l form a set and is defined as constraint place set, denoted by $P_s = \{p_i \in P \mid l^{\mathrm{T}} m = \sum_{i=1}^{n} l_i m(p_i) \le b \ \ for\ \ l_i \ne 0\}$。

Definition 4: The input transition set of constraint place set is defined as ${}^{*}P_s = \{t \mid t \in {}^{*}p_i \ \ for \ \ p_i \in P_s\}$; The output transition set of constraint place set is defined as $P_s^{*} = \{t \mid t \in p_i^{*} \ \ for \ \ p_i \in P_s\}$; The constraint transition set is defined as $T_s = {}^{*}P_s \bigcup P_s^{*}$.

Definition 5: The incidence matrix which is corresponding to the subnet formed by P_s 、 T_s and the related arcs is defined as local incidence matrix and denoted by $C(l)$.

Algorithm 1[15]**:** Petri net controller synthesis algorithm based on local incidence matrix

Step1: For control goal $l^{\mathrm{T}} m \le b$, determine the constraint place set P_s and the constraint transition set T_s;

Step 2: Determine the local incidence matrix according to definition 5

Step3: Compute incidence matrix for controller place p_c and denote it as $C(p_c)$. $C(p_c)$ is composed of $C(p_c)|_{T_S}$ and $C(p_c)|_{T \backslash T_S}$. $C(p_c)|_{T_S} = -l^{\mathrm{T}} C(l)$ represents the local incidence matrix for column included in set T_s, while $C(p_c)|_{T \backslash T_S} = \boldsymbol{0}_{1 \times |T \backslash T_s|}$ represents the other columns in incidence matrix.

Step 4: Compute the initial marking $m_0(p_c)$ for the controller places p_c using the formula:

$$m_0(p_c) = b - l^{\mathrm{T}} m_0(p_i), \quad p_i \in P_s.$$

Remark: Since the controller place p_c and its link relation with other transitions in the plant can be determined by $C(p_c)|_{T_S}$, we can use $C(p_c)|_{T_S}$ to substitute $C(p_c)$ and simplify the algorithm complexity.

5.2. Control command decision-making for centre line lights based on the transitions state

For PN model in Figure 4 after controller synthesis through algorithm 1, if the output transition of place p_{∇}^{i} is controlled enable, then, it is the situation that the aircraft in place p_{∇}^{i} can be permitted to enter the place p_{∇}^{j}. Thus, we can make the centre line lights in its output place turn on and issue clearance command. In addition, when place p_{∇}^{i} is marked, it represents the situation that aircraft leaved place p_{∇}^{k}. Since the marking control regulation includes the constraint that two neighboring places can not be marked at the same time, place p_{∇}^{k} and p_{∇}^{i} of the plant can not be simultaneously marked. Thus, when place p_{∇}^{i} is marked, the transition t_{∇}^{k-i} is disable, and we can make the centre line lights in its input place turn off and issue stop command.

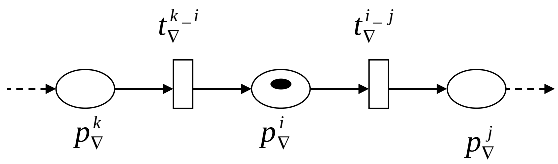

Fig.4. Part of Petri net operation model for taxiway line segment

Definition 6: For PN model of taxiway line segment, the state set of transition t_{∇}^{i-j} is defined as $E_{\nabla}^{i-j}=\{\mathrm{ena},\mathrm{dis}\}$. Symbol "ena" denotes that transition t_{∇}^{i-j} is controlled enable, while "dis" is disable.

Definition 7: The control command set for centre line lights is defined as $U=\{\mathrm{on},\mathrm{off}\}$. Symbol "on" denotes that centre line lights in the same lights segment must be turn on, while "off" denotes turned off command.

Mapping function 1: Mapping function between E_{∇}^{i-j} and U can be denoted by $\Pi: E_{\nabla}^{i-j} \mapsto U$. When the state of transition t_{∇}^{i-j} is "ena", the control command for centre line lights in place p_{∇}^{j} is "on". When the state of transition t_{∇}^{i-j} is "dis", the control command in p_{∇}^{i} is "off".

Algorithm 2: Control command decision-making algorithm for taxiway centre line lights

Phase1: Off-line Petri net controller synthesis using algorithm 1 for taxiway line segment operation model.

Phase2: On-line control command decision for centre line lights.

Step1: determine the marked place set $P_M=\{p \mid M(p)\neq 0, p\in P\}$;

Step 2: determine the post-transition set for P_M, and denoted by $T_M=\{t_i\in T \mid t_i\in p_i^{*}\ \ for\ \ p_i\in P_M\}$;

Step3: determine the pre-transition set of P_M, and denoted by $T_M^{'}=\{t_i\in T \mid t_i\in {}^{*}p_i\ \ for\ \ p_i\in P_M\}$;

Step4: determine state for $t\in T_M \cup T_M^{'}$, according to the transition enable condition in PN model and definition 6;

Step5: determine the control command for centre line lights using mapping function 1;

Step6: output control command set.

6. Example Illustration

Taking the PN model in Figure 3 as an example, we determine the control command for taxiway centre line lights.

Phase 1: Off-line Petri net controller synthesis.

For constraint $m(p_{\nabla}^{j})+m(p_{\nabla}^{j+1})\leq 1$ （$1\leq j\leq 5$）, when $j=3$, $m(p_{\mathrm{B}}^{3})+m(p_{\mathrm{B}}^{4})\leq 1$. The constraint place set $P_s=\{p_{\mathrm{B}}^{3},p_{\mathrm{B}}^{4}\}$, constraint transition set $T_s=\{t_{\mathrm{B}}^{2-3},t_{\mathrm{B}}^{3-4},t_{\mathrm{B}}^{4-5}\}$, $l=[1,1]^{\mathrm{T}}$. The local incidence matrix is

$$\mathrm{C}(l)=\begin{array}{c c} & \begin{array}{ccc} t_{\mathrm{B}}^{2-3} & t_{\mathrm{B}}^{3-4} & t_{\mathrm{B}}^{4-5} \end{array} \\ \begin{array}{c} p_{\mathrm{B}}^{3} \\ p_{\mathrm{B}}^{4} \end{array} & \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \end{array}$$

The structure for controller place p_c can be determined in matrix

$$C(p_c)|_{T_S}=-l^{\mathrm{T}}C(l)=\begin{array}{c c} & \begin{array}{ccc} t_{\mathrm{B}}^{2-3} & t_{\mathrm{B}}^{3-4} & t_{\mathrm{B}}^{4-5} \end{array} \\ p_c & \begin{bmatrix} -1 & 0 & 1 \end{bmatrix} \end{array}$$

The initial marking of p_c is

$$m_0(p_c)=b-l^{\mathrm{T}}m_0(p_i)=1$$

For other constraints in the marking control regulation, the design process of controller place is the same as the above process. Plant after Petri net controller synthesis is illustrated in Figure 5. For clarity, some controller places and arcs have been omitted.

Phase2: On-line control command decision-making.

Step 1: determine marked place set $P_M = \{{}^{'}p_{\mathrm{B}}^{4}\}$

*Step*2: determine post-transition set of P_M and it is denoted by $T_M = \{t_{\mathrm{B}}^{4-3}\}$.

Step 3: determine the pre-transition set of P_M and it is denoted by $T_M^{'} = \{t_{\mathrm{B}}^{5-4}\}$;

Step 4: For transition set $T_M \cup T_M^{'}$, according to the transition enable condition and definition 6, we can determine: transition t_{B}^{4-3} is controlled enable and its state is "ena"; t_{B}^{5-4} is disable and its state is "dis";

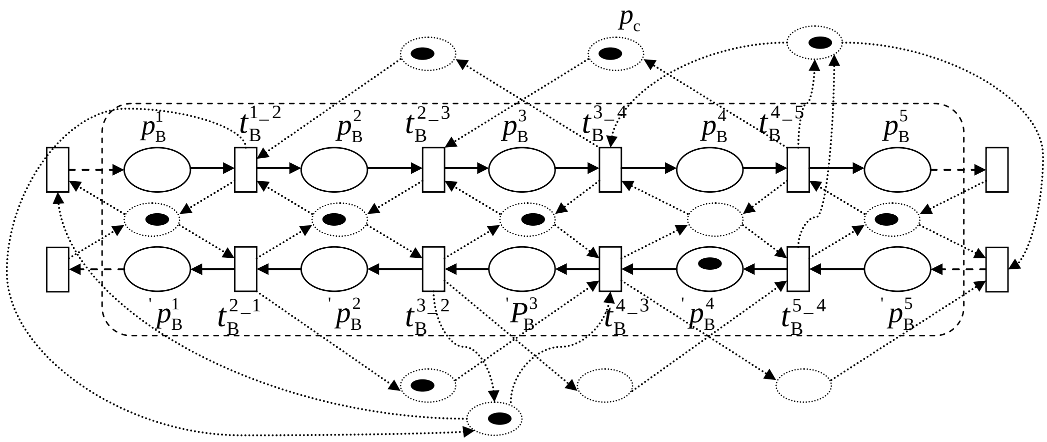

Fig.5. Petri net model for taxiway line segment after controller synthesis (For clarity, some controller places have been omitted)

Step 5: Using mapping function 1, we can determine the control command for centre line lights in place p_{∇}^{3} is "on"; the control command for centre line lights in place p_{∇}^{5} is "off".

Step 6: Output control command set U.

7. Conclusion

This paper proposes an automatic decision-making method on the control command of taxiway centre line lights. The method has the following advantages: on the one hand, the control process of taxiway centre line lights is studied using hybrid control theory, reflecting the intrinsic characteristic of the control process; on the other hand, the control command decision-making algorithm is based on the synthesized plant, which can guarantee taxiway operation safe and achieve automatic decision-making process. Research in this paper will contribute to the automatic control of taxiway centre line lights in A-SMGCS. Forthcoming research work will mainly focus on the transformation from control command to concrete control action and the design of aircraft location identifier.

8. Acknowledgments

The authors would like to thank the anonymous reviewers whose comments have helped us to improve the presentation of the paper. This research is supported in part by National Science Foundation of China 60879011 and Innovation Foundation of Jiangsu Province for college students CXZZ11_0221.

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