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Intrusion Detection in Aviation Terminal Region Petri Net with Non-arc and Unchanged Library

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Abstract

Due to the complex structure and the large number of the running aircrafts in the application of the intrusion detection in terminal regions, the defense conflict dangers and the influence on aviation safety exist in such terminal region. Therefore, Petri net framework with non-arc and unchanged library is constructed in this paper to propose the terminal intrusion detection scheme. Firstly, the aviation operation structure of the terminal region is analyzed and the constraint model of the terminal region is constructed as the terminal intrusion detection basis according to Petri net model framework; secondly, the aviation constraint model of the terminal region constructed thereby and the principle of non-arc and unchanged library are adopted to establish the terminal intrusion detection control strategy, and the control decision is made according to the transition activation for the aviation instructions; finally, the experimental analysis of the practical cases shows that the proposed terminal intrusion detection scheme can effectively handle the terminal intrusion detection problem and reduce the workload of the controllers.

***Keywords**: Non-arc; Unchanged library; Petri net; Intrusion detection*

1. Introduction

Along with the rapid progress of the aviation industry brought by the technological development, both the aviation passenger density and the flight density in the aviation terminal region are gradually increased year by year. Meanwhile, the structures of the aviation terminal regions also gradually become complex, so the poor constraint and control strategies can easily cause serious flight accidents and other air crash accidents which directly threaten the life safety of the passengers. The improvement of the defense effect of the intrusion detection in aviation terminal region is deeply researched in many literatures. In literature [1], the basic hybrid control theory is adopted to establish the three-dimensional flight profile of the aviation terminal region and accordingly predict the four-dimensional flight path, and the flight conflict is taken as the research emphasis for evaluation and analysis; then, relevant control strategy is improved so as to improve the evaluation accuracy of the terminal region, but the conflict defense is not specially researched in this algorithm. In literature [2], the aviation terminal region is monitored in a real-time manner and the dynamic mathematical flight model is combined to predict the flight path, and meanwhile the reasonable flight conflict prevention strategy is adopted; but the intrusion prevention problem is not researched in this algorithm for the aircraft carrier terminal airspace. In literature [3], the arrival stack ordering method is adopted to research the prevention strategy of the aviation terminal region and meanwhile the

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reasonable effective dispatching mechanism is also adopted. Only the airspace intrusion prevention or the ground intrusion prevention is unilaterally considered in the terminal defenses in the above literatures, but the comprehensive consideration of the airspace intrusion prevention and the ground intrusion prevention has more significant practical value. Therefore, the terminal region model is established in this paper on the basis of Petri net theory to obtain the running characteristics of the aircrafts in the terminal region, and then the corresponding control regulations are adopted to constrain the aircrafts so as to obtain the safe flight control strategy, thus realizing the comprehensive intrusion prevention of the aviation terminal region.

2. Model Establishment

Based on relevant flight safety requirements and the corresponding control regulations for the aircrafts (airplanes) in the aviation terminal region, the constraint model used for ensuring the safe flights of the aircrafts in the aviation region terminal can be established. Some prohibited actions under the control regulations of the aviation terminal region are usually expressed as upper control limits or weighting identifications and such expression can form linear inequality model constraint, such as $\mathbf{l} \cdot m \le \mathbf{b}$. In the previous inequality constraint, $\mathbf{l}$ is the weighting matrix identification of the constraint; m is the identification vector; $\mathbf{b}$ is the weighting constant identification. The model mainly includes the following three constraints:

Constraint 1: On the basis of the flight control purpose, the landing safety of an aircraft is regarded as the main objective and only one aircraft is allowed in the approach area at the moment. Such control regulation can be modelled as follows:

$$m(p_0) \le 1 \tag{1}$$

Constraint 2: On the basis of the flight control purpose, the safety of the aircrafts in the waiting area is regarded as the main objective, and only n aircrafts can be allowed to stop in the waiting area:

$$\begin{cases} m(p_1) \le n, m(p_4) \le n \\ m(p_6) \le n, m(p_{12}) \le n, m(p_{13}) \le n \end{cases} \tag{2}$$

Under the inequality model constraints as defined above, some prohibited states are not allowed to appear in the aviation terminal region. But when the runway and the approach segment are empty, multiple aircrafts may request for taking off or landing at the same time. In order to avoid such conflict, the following flight priority control strategy is designed. If the running mathematical model of the aircrafts is N, then the values of the transitions $t \in T$ regarding this model are all positive values $pr(t)$. Therein, if $pr(t_i) > pr(t_j)$ ($t_i, t_j \in T$) is true, then the priority of transition t_i is higher than that of transition t_j.

Constraint 3: On the basis of the flight control purpose, when an aircraft enters the core part of the aviation terminal region, the following model constraint can be added for the grade classification of the aircrafts:

$$pr(t_2) > pr(t_3) > pr(t_6) > pr(t_{12}) > pr(t_{13}) \tag{3}$$

3. Control Strategy

3.1. Unchanged Library Control Strategy

For the three inequality model constraints as defined above, the unchanged library principle is adopted in this paragraph to establish the aircraft flight controller [8]. The basic thought of this scheme is to realize the closed-loop control coverage of the inequality control constraints based on the unchanged invariant. The process can be specifically described as follows:

When control library p_c executes the addition operation, the controlled Petri net can be adopted for all inequality model constraints to initialize the constraint model:

$$m_0(p_c) = \mathbf{b} - \mathbf{l}m \tag{4}$$

Control library p_c and incidence matrix $\mathbf{D_c}$ can be correspondingly generated during the constraint transition process, wherein $\mathbf{D_c}$ can be calculated according to incidence matrix $\mathbf{D}$ of the controlled object:

$$\mathbf{D_c = -lD} \tag{5}$$

In the instance of model constraint 1, the unchanged library strategy of the flight controller can be specifically described as follows:

Process 1: (Library set) Determine library set P_s, incidence matrix $\mathbf{D}$ of the controlled object and transition constraint set T_s.

Process 2: (Initial identification) Add library control p_c and obtain the following initialized identification according to Formula (4): $m_0(p_c) = 1$.

Process 3: (Incidence matrix) Obtain incidence matrix $\mathbf{D_c}$ according to Formula (5): $\mathbf{D_c}$=[1 1 1 1 1 -1 -1 -1 -1] .

Process 4: (Process synthesis) Obtain incidence matrix $\mathbf{D_c}$ according to the above process and synthesize the model controller, as shown in Figure 1.

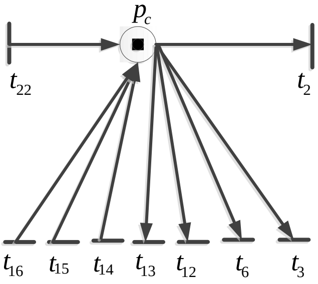

Figure 1. Unchanged Library Strategy

3.2. Non-arc Strategy

In practical application, it is more or less difficult to adopt the constraint priority strategy and the unchanged library strategy for the flight control process. The improvement method is to execute the non-arc improvement strategy of the control constraint. The improvement thought is to avoid the existence of the transition inconsistent with the given model constraints.

For the non-arc based constraint transition activation process adopted thereby, the input of the library set of constraint transition t is set as $P_{in} = \{p_i \mid p_i \in {}^*t\}$. Meanwhile, P_1 and P_2 are also assumed as $P_1 = \{p_k \mid p_k \in {}^*t\}$ and $P_2 = \{p_j \mid p_j \in {}^*t\}$, wherein P_1 is the input library set without any non-arc, and P_2 is the input library set with non-arc. $P_{in} = P_1 \cup P_2$ can be obtained according to the above definition. Therein, $w_{b(p_j,t)}$ refers to the weight value of the non-arc existing between library p_j and constraint transition t; $b(p_j,t)$ refers to the non-arc existing between library p_j and constraint transition t. If any $m(p_i)$ is more than the forward connectivity weight value thereof and the non-arc connectivity weight value of existing constraint transition t is more than identification number p_j, then constraint transition t is in the transition activation state; or else, constraint transition t is in the transition inactivation state.

$$E(t)= \begin{cases} 1,\left(\forall p_i : m(p_i) \ge w_{pre(p,t)}\right) \wedge \left(\forall p_j : m(p_j) < w_{b(p_j,t)}\right) \\ 0, \exists p_j : m(p_j) \ge w_{b(p_j,t)} \end{cases} \tag{6}$$

In the instance of model constraint 3, the specific design process of the non-arc based controller mentioned above is as follows:

Process 1: Transition value $pr(t_2)$ is the maximum value, so transition t_2 has the highest relative priority. Namely, when transition t_2 is in the activation state, such transition processes as t_3 , t_6 , t_{12} , t_{13} are all in the inactivation state, wherein the condition for the above activation state of the transition process is $m(p_1) \ge 1$. Therefore, the activation state of the transition processes t_3 , t_6 , t_{12} , t_{13} can be effectively controlled according to $m(p_1)$ value , thus to execute the non-arc design.

Process 2: The non-arc design process based on the design principle of Process 1 is specifically described by the network connection diagram as shown in Figure 2. This figure is the non-arc design for model constraint 3.

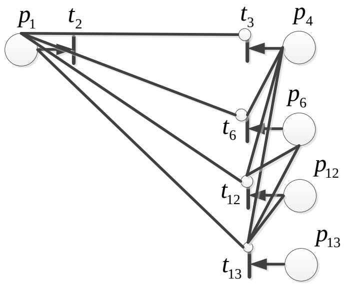

Figure 2. Addition of Non-Arc Constraint

4. Control Decision Instruction

In order to effectively prevent the flight conflict accidents in the aviation terminal region, the decision instruction control strategy of the transition state is designed in this paragraph [9]. With simple and easy operation, such instructed flight control mode for the terminal region can be used to effectively prevent the terminal intrusion problems.

Definition 2: (Control instruction) For the flight control and constraint models for the aviation terminal region, the control instruction can be defined as $\{fly, wait\}$, wherein fly refers to the instruction used for allowing the aircraft concerned to execute the next operation and $wait$ refers to the flight instruction ---- Wait. The following mapping can be defined according to the flight instruction control of the aircrafts:

Mapping 3: Transition state set E of the aviation terminal model constraints and flight instruction control set N have the following mapping relation: $\lambda : E \mapsto N$, wherein the mapping rule can be expressed as follows: if current state of transition t is 1, then the corresponding instruction control is fly ; if current state of transition t is 1, then the corresponding instruction control is $wait$. Specifically, the above mapping relation is as shown in Table 1.

Table 1. Instruction Control Model

Transition State	Instruction Control
$E(t)=1$	*fly*
$E(t)=0$	*wait*

According to the instruction control model as shown in Table 1, the leading lights can be effectively controlled and the instruction decisions can be automatically made for waiting lights, *etc*. The specific process is as follows:

Process 1: Establish aircraft flight model N for the whole aviation terminal region;

Process 2: On the basis of the above established aircraft flight model N of the terminal region, establish the mathematical models of constraints 1~3 and the aircraft flight model with the instruction control for the aviation terminal region.

Process 3: Determine the identification of current library according to the actual conditions.

Process 4: Determine the activation identification state (1 or 0) of the constraint transition according to the constraint transition activation strategy designed above.

Process 5: On the basis of the aircraft flight instruction control mapping, determine the aircraft flight instruction: fly or $wait$.

Process 6: Transmit the instruction control symbol to the aircraft concerned, and return to Process 3.

5. Case Analysis

In order to verify the feasibility of above instruction control strategy, the case of the flights in the terminal region as shown in Figure 1 is taken as the research object.

Step 1: Establish the flight model N for the aviation terminal region as shown in Figure 1;

Step 2: Adopt the established aviation terminal region model N and combine constraints 1~3 to establish the constraint model of the terminal region, and then establish the aviation terminal region model with instruction controller;

Step 3: Based on such flight information detection tools as radar, identify current scene state m. For the case as shown in Figure 1, the identifications of current scene state are as follows: $m(p_0)=1$, $m(p_1)=1$, $m(p_4)=1$, $m(p_{12})=1$ and $m(p_{13})=1$, and other state identifications are all 0;

Step 4: Determine the constraint activation state (1 or 0) according to the constraint transition activation principle and state identification m; meanwhile, determine the constraint transition states of current scene specifically as follows: $E(t_2)=0, E(t_3)=0, E(t_{12})=0, E(t_{13})=0, E(t_{15})=1$;

Step 5: Determine the aircraft instruction control according to the mapping relation between the constraint transition states of current scene and the aircraft instruction control. For the case as shown in Figure 1, the instructions received by aircrafts 1, 2, 4 and 5 in current scene are all $wait$, namely: aircrafts 1, 2, 4 and 5 are in waiting state, and the instruction received by aircraft 3 is fly, namely: this aircraft is in flight state.

Step 6: Return to Step 3, and determine the state identification of current scene according to the information collected by such tools as radar after aircraft 3 finishes the landing operations; further update the constraint transition as follows: $m_1(p_1)=1$, $m_1(p_4)=1$, $m_1(p_{12})=1$, $m_1(p_{13})=1$, $m_1(p_{15})=1$, wherein other state identifications are all 0;

Step 7: Determine the transition activation conditions as 1 or 0 according to state identification m_1 and the constraint transition activation conditions; further determine current scene transition as follows: $E(t_2)=1$, $E(t_3)=0$, $E(t_7)=0$, $E(t_{12})=0$ and $E(t_{13})=0$;

Step 8: Further determine the aircraft instruction control according to the mapping relation between various transition activation states and the aircraft instruction control; for the case as shown in Figure 1, the instruction co Step 9: control of aircraft 1 in current scene state is fly and the instruction control of aircrafts 2, 4 and 5 is $wait$.

Step 9: Return to Step 3, and update the identification of current scene state as m_2 according to the information collected by such tools as radar when aircraft 1 flies to the approach area and glides to the end of the runway but aircrafts 2, 4 and 5 are still in waiting state, as shown in Figure 3; then, further update the constraint transition as follows: $m_2(p_0)=1$, $m_2(p_4)=1$, $m_2(p_{12})=1$, $m_2(p_{13})=1$ and $m_2(p_{15})=1$, wherein other state identifications are all 0.

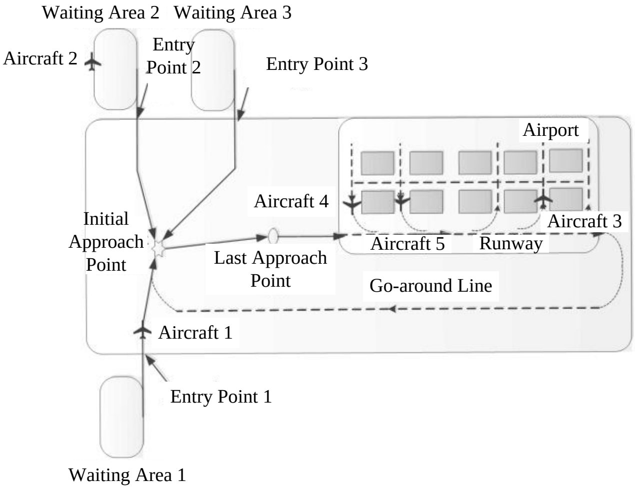

Figure 3. Aircraft Landing

Step 10: Determine the constraint activation conditions as 1 or 0 for the case as shown in Figure 1 according to the constraint transition activation condition and state information identification m ; meanwhile, determine the transition condition of current scene as follows: $E(t_2)=0$, $E(t_3)=0$, $E(t_6)=0$, $E(t_7)=0$ and $E(t_{14})=1$;

Step 11: Determine the aircraft instruction control according to the mapping relation between the aircraft instruction control and various constraint transitions. In the case as shown in Figure 1, the control instruction received by aircraft 1 in current state is fly and the control instruction received by aircrafts 2, 4 and 5 is $wait$, wherein the cyclic process is executed till aircraft 1 leaves away from the runway and enters the taxiway;

In order to further verify the above control strategy, the terminal region experiment system is established according to the operation conditions of the aviation terminal region, as shown in Figure 7. Specifically, such system is the computer simulation platform designed for the aviation terminal region with the structure similarly as shown in Figure 1, and such platform can be adopted for the terminal region control strategy simulation in order to verify the feasibility of the proposed algorithm, thus to avoid the flight accidents probably caused by direct application. Therefore, such system has important research value.

Figure 4 shows the flight instruction control scheme made for inequality constraint 1, and the specific scheme is as follows: aircraft A003 is executing the approach landing process according to the unchanged library control principle, aircrafts A001 and A002 are waiting for airspace for landing, and aircrafts A004 and A005 are waiting for taking off in the ground taxiway. The following flight control regulation can be verified: only one aircraft is allowed to exist in the approach area and the runway at the same moment.

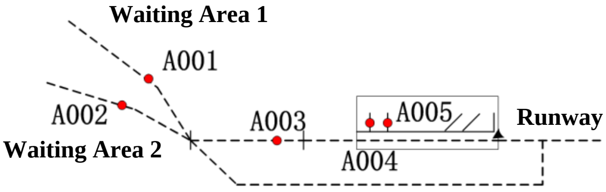

Figure 4. Schematic Diagram of Simulation (1)

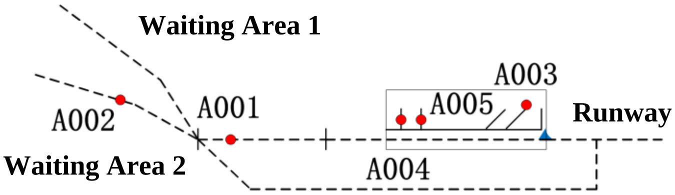

Figure 5. Schematic Diagram of Simulation (2)

For the control model based on constraint priority grade in the simulation diagram as shown in Figure 8, aircraft A003 has landed on the runway at that moment, and if the non-arc principle is adopted for control, then we can know that aircraft A001 has flight priority. Therefore, aircraft A001 will start to execute landing operation after receiving relevant instruction fly, aircraft A002 will still wait for landing in the waiting area, aircrafts A004 and A005 will wait for taking off in the taxiway. The following flight control regulation is verified: the aircrafts entering the core aviation terminal region must be provided with flight priority.

6. Conclusion

This paper aims at researching and designing the flight model of the aircrafts in the aviation terminal region in order to establish the aviation terminal region model based on Petri net and meanwhile establish the model constraints thereof according to the control regulations f the aviation terminal region. Moreover, the non-arc and unchanged library principles are combined to determine the instruction control scheme of the aviation terminal region. According to relevant case analysis, the model and the instruction control strategy can not only ensure the safe flight of the aircrafts in the terminal region, but also effectively reduce the workload of the controllers.

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