Flight mission modeling based on BDI Petri net

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Abstract: Goals reasoning and management of pilot is a key issue to monitor pilot's behavior and intention. Traditional modeling methods are based on scenarios or situations, such methods will cause the covering problem due to redundancy and are incapable of depicting interactions among various goals and plans of pilot. Petri net integrated with belief, desire and intention (BDI) theory (BDI Petri net) is designed to solve this problem. Focusing on the BDI theory, goal states of agent are discussed firstly. Belief, desire and intention are modeled by places and transitions based on the Petri net theory. In order to simplify the network, colored token is introduced to depict various states of belief, and the hierarchy transition is applied to model the intention, together with tokens' flow demonstrating the interaction among various goals and relationship among belief, desire and intention. A search and rescue mission is used to validate the proposed method and the result indicates that the model can be used to monitor goals and behaviors of pilots.

Keywords: Petri net, belief, desire and intention (BDI) theory, flight mission modeling, agent.

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1. Introduction

Pilot may encounter many unexpected situations during the executing process, resulting in the exceeding workload for pilots and inability to settle them [1]. Designing an intelligent system to assist the pilots' decision is a key issue to improve operational effectiveness. To achieve this goal, the intelligent system should be able to reason and manage pilot's intention and give advice on the basis of task requirements. In addition, it should customize the display of information, monitor pilot's behavior, find out the problem ongoing and give warnings to the pilot in order to enhance the interactive capability between the pilot and the vehicle.

Plan and goal graph (PGG) is one of the key techniques in pilots' associate (PA) program, which is the first program adopting artificial intelligent technologies to enhance the operational capability of pilots [2–9]. The PGG

decomposes the mission by goals and plans from up to down and achieves the transformation from abstract goals to concrete plans. The summit nodes of the PGG are the most abstract goals, while the bottom nodes of the PGG are the atom actions executed by pilots. Taking the advantage of the PGG, pilots can command their behavior more precisely and engineers can take an insight into the process of mission to improve the interactive capability by providing the most urgent and mission-related information [10–13].

The PGG's advantage lies in the hierarchical description of goals and plans, but it fails to characterize the interactions between different goals and the sequences or inter-relationships of goals. Most of all, the PGG is static and unable to describe the dynamic process of the changing situation which may influence pilots' behaviors. Therefore, other modeling methods are deliberated to adopt in order to solve these problems.

Prevailing modeling methods include activity networks [14], state diagram and activity diagram [15], event-driven process chains [16], and Petri net [17]. In contrast with others, the advantages of Petri net can be listed as follows: clear semantics, strong logical description ability, and dynamics. And hierarchical modeling means can reduce the model's complexity and enable engineers to adopt top-down methods to build models. After 50 years of development, many advanced Petri nets such as colored Petri net [18,19], hybrid Petri net [20], stochastic Petri net [21,22] and fuzzy Petri net [22–24] have been created and widely used, but the applications focus on the unconscious process modeling. Human with goals makes decisions and changes minds based on his observation and knowledge of the outside world. Therefore, the methods listed above cannot simulate the deliberate behaviors of human.

The BDI model denotes an agent from perception concepts including belief, desire and intention these three basic elements [25–27]. Belief represents the knowledge sets of environment, other agents and the agent himself; desire represents the expected states or states that the agent wishes to keep; intention represents the selected plans or

actions of agent. The belief, desire and intention (BDI) model well defines the process of an agent's selecting action based on environment information and agent's desire. This paper integrates the BDI model and Petri net modeling methods, represents beliefs and desires by places, intentions by transitions with bottom subnet, and the dynamic process by the flowing colored tokens among different places so that the problem analyzed above can be solved.

The rest of this paper is organized as follows. Section 2 gives the basic definitions of the BDI model, discusses the different states of desire and the transformation mechanism. Section 3 integrates the BDI model into Petri net and provides related definitions. In Section 4, the BDI Petri net is applied to a search and rescue mission and the model is built in the ExSpect simulation environment. Section 5 draws the conclusions.

2. BDI model

2.1 Belief, desire and intention

During the formalization process of agents, the state of agents mind consists of belief, desire and intention. The ongoing researches of different BDI models are based on Cohen [28] and Rao [25], the key issues of which are to determine the goals of agents and the means to achieve them. These key issues refer to belief, desire and intention.

Belief is the agent's perception of the world, including the descriptive information of environmental characteristics, agent's functions, which is the basis of agent's deliberation. When pilots execute missions, the main beliefs consists of three kinds.

- (i) Environment information: weather, terrain, etc.
- (ii) Aircraft status: fault or malfunction, remaining fuel, etc.
- (iii) Other agents' beliefs: friend and foe.

Desire is the state set that agents expect to be or wishes to keep, initiating agents to plan and act. For example, the pilot's desire normally consists of mission completion, security maintaining and cooperation. If the flight plan is to fly from A to B , the expected state or desire of pilot is to make the plane in the coordinates of the point B . During the flight, pilot may encounter bad weather, mechanical failure or other unexpected situations affecting safe condition, and then the pilot's desire is to take actions to evade crashing.

These desires may conflict with each other, so some of them can exit concurrently and some must execute sequentially.

As described above, desires can be categorized into two classes.

- (i) $\text{maintain}(G, PreCon, C)$

A maintain desire represents a state that agent wishes

to keep. G is an identifier to distinguish different maintain desires, $PreCon$ denotes the trigger events that initiate the maintain desire G , C denotes the condition that the desire G wants to be true.

- (ii) $\text{achieve}(G, PreCon, S, F)$

An achieve desire represents a state that agent expects to be. G and $PreCon$ are the same as maintain desire. S is the expected state and represents the success condition. When S is true, the desire G suspends successfully. F is the failure condition. When F is true, the desire G suspends with failure.

Intention represents the plans and actions that accomplish desire and command agent's behavior. For example, in order to complete a mission, pilot needs to fly according to the pilot operation procedure and perform certain tasks in task areas. When the safe condition is violated, e.g., the emergence of the bad weather, the pilot needs to adjust course to fly around the dangerous area. Notably, in order to achieve a desire, the intention may include two or more plans. The completion of one plan denotes that the desire is achieved.

2.2 States of desire and transition mechanism

Agent's beliefs change with the perception of the world and conflict resides among some desires, so transitions between different desires occur when beliefs change. In the process of transitions, the agent firstly deliberates under current beliefs, then activates the desires with satisfied preconditions, adopts responding intentions and monitors the success or failure condition to determine whether to suspend the desires. When beliefs change (objective factors such as weather changes or subjective factors such as world changes due to agent's behavior), agent will revalidate the condition (precondition, success and failure conditions) and determine whether to suspend or continue. If the condition is violated, agent considers aborting the desires and switching to other desires.

Through the above discussion, the states of desire can be separated into three states: pending, activated, suspended, shown in Fig. 1.

Fig. 1 Desire states of pending, activated and suspended

2.2.1 Pending state

The agent deliberates based on beliefs about the world and

mission and determines whether to activate the desire. During the process, the results will differ depending on the category of desires.

(i) $\text{achieve}(G, PreCon, S, F)$

If $S = 0 \wedge F = 0$, then the state switches to activated;

If $S = 0 \wedge F = 1$, then the state switches to suspended;

If $S = 1$, then the state switches to suspended.

The three circumstances above denote that the agent finds that $PreCon$ is satisfied and initiates G , then checks success and failure condition to determine whether to activate or suspend the desire.

If $PreCon = 0$, then state switches to suspended.

This circumstance denotes that the precondition of the desire is not satisfied, the agent aborts the desire.

(ii) $\text{maintain}(G, PreCon, C)$

If $PreCon = 1 \wedge PreCon \models \neg C$, then the state switches to activated.

This circumstance denotes that the agent checks if the precondition will affect the state that the agent wants to keep and determine whether to activate or suspend.

If $PreCon = 0$, then the state switches to suspended.

This circumstance denotes that the precondition of the desire is not satisfied, and the agent aborts the desire.

2.2.2 Activated state

The agent selects a series of actions based on current beliefs to achieve or keep the states that desire holds.

(i) $\text{achieve}(G, PreCon, S, F)$

If $S = 0 \wedge F = 0$, then the desire holds in this state;

If $S = 0 \wedge F = 1$, then the state switches to suspended due to failure;

If $S = 1$, then the state switches to suspended due to success;

If $PreCon = 0$, then the state switches to suspended due to the unsatisfied precondition.

(ii) $\text{maintain}(G, PreCon, C)$

If $PreCon = 1 \wedge PreCon \models \neg C$, then the desire holds in this state due to the violated condition;

If $PreCon = 0$, then the state switches to suspended due to the unsatisfied precondition.

2.2.3 Suspended state

The agent checks the beliefs and determines to adopt another desire to pursue or to reactivate the current desire.

(i) $\text{achieve}(G, PreCon, S, F)$

If $S = 0 \wedge F = 0$, then the state switches to activated;

If $S = 0 \wedge F = 1$, then the agent shifts the state to another desire's pending state;

If $S = 1$, then the agent shifts the state to another desire's pending state;

If $PreCon = 0$, then the agent shifts the state to another desire's pending state.

(ii) $\text{maintain}(G, PreCon, C)$

If $PreCon = 1 \wedge PreCon \models \neg C$, then the state switches to activated;

If $PreCon = 0$, then the agent shifts the state to another desire's pending state.

We analyze types of desires and categorize desires into three states above. Notably, the difference in the transition mechanism between achieved and maintain desires lies in $PreCon$. Achieve desire is initiated when $PreCon$ is true and after that $PreCon$ may turn into false, but the maintain desire should guarantee that $PreCon$ always be true.

3. BDI Petri net

As analyzed above, the dynamic process of the BDI model can be depicted as Fig. 2. The perception of the outside world is input into the model to form belief sets of the agent. Belief sets are a kind of states, while desire sets are the expected states of the future of the agent. Beliefs and desires determine the intentions and the selection of plans. When plans are executed, agent affects the world as well as beliefs which drive the agent to move forward.

Fig. 2 Procedure of BDI model

Many works have devoted efforts on the formalization of the process [29–32], but rarely focus on applying modeling methods to depict the process. The Petri net theory includes four basic elements: places, transitions, arcs and tokens. Places represent states, transitions represent events or actions, arcs linking place and transition define the dynamic process, and tokens denote the current state of the model. Taking the advantage of the Petri net, we can develop the BDI Petri net to depict the dynamic process as Fig.2 shows. The definition of the BDI Petri net is given below.

Definition 1 Desire generates the function O_D : $\rho(Bel) \times \rho(Int) \rightarrow \rho(Des)$.

Definition 2 Intention generates the function I_I : $\rho(Bel) \times \rho(Des) \rightarrow \rho(Int)$.

Definition 3 Belief updates the function O_B : $\rho(Int) \rightarrow \rho(Bel)$.

Definition 4 The BDI Petri net is a seven-tuples:

$$\sum^j = (P_m^j, T_m^j, F_m^j, W_m^j, M_{om}^j, I_m^j, C).$$

(i) P denotes places and has three types: P_B , P_D and P_N , which stand for belief, desire and ordinary place. Desires have three states: pending, activated and suspended represented by P_{DP} , P_{DA} and P_{DS} ;

(ii) T denotes transitions and has two types: T_I and T_N , which stand for intention transition and ordinary transition. Intention transition consists of T_{IP} , T_{IA} and T_{IS} which denote intention under pending, activated and suspended states;

(iii) F defines the arcs linking places and transitions, $F \subseteq (P \times T) \cup (T \times P)$;

(iv) $N_m^j = (P_m^j, T_m^j, F_m^j)$ is the directed net and the underlying net of $\sum^j$, where j denotes the number of layers, m denotes N_m^j is an extension of T_m which is in the $j - 1$ layer;

(v) C is a finite set of colors, $C = \{c_1, c_2, \dots, c_k\}$ denotes different beliefs;

(vi) W defines weight functions on F and consists of O_D , I_I , O_B and W_N , where W_N is the ordinary function;

(vii) M_0 is the initial marking of $\sum$.

The triggering rules and initial marking [33] define the state changes in a model based on the BDI Petri. This paper focuses on the state changes modeling by applying the BDI Petri net. Therefore, the Petri net analysis methods such as reachability graph are not mentioned here and analysis of dynamic properties such as boundedness, safety and reachability can refer to [34,35]. The typical state transformation of a single desire modeled by the BDI Petri is depicted in Fig. 3. The meanings of symbols are as shown in Table 1.

Table 1 Meanings of symbols in Fig. 3

P/T	Type	Description
P_1	Ordinary place	State of observing
P_B	Belief place	Current beliefs
P_{DP}	Desire place	Pending state of desire
P_{DA}	Desire place	Activated state of desire
P_{DS}	Desire place	Suspended state of desire
T_N	Ordinary transition	Changes observed
T_{IP1}	Intention transition	
T_{IP2}	Intention transition	
T_{IS1}	Intention transition	
T_{IS2}	Intention transition	
T_{IA}	Intention transition

Fig. 3 State transformation of single desire modeled by BDI Petri

We illustrate how the desire generates the function O_D , intention generates the function I_I and belief updates the function O_B that affects the dynamic process of the model below.

For $\{P_1, P_B, P_{DP}, P_{DA}, P_{DS}\}$, supposing the initial marking is $M_0 = \{1, 0, 1, 0, 0\}$, it denotes the agent is observing and the desire is in the pending state. Under this circumstance, T_N is enabled, the agent observes that the world has changed and generates its own beliefs, and the marking transforms into $M_1 = \{0, 1, 1, 0, 0\}$. At this moment, T_{IP1} or T_{IP2} will be enabled and which one will be initiated depends on the token's color in P_B and I_I (the arcs linking P_B , P_{DP} and T_{IP1} , T_{IP2}), the intention transition has bottom subnet to denote the agent's plans and actions and the selection of plans and actions is also influenced by beliefs. When the plan or action has been achieved, O_D and O_B (the arcs linking T_{IP1} , T_{IP2} and P_1 , P_{DA} , P_{DS}) will change the world and the state of desire. Supposing T_{IP2} is initiated, the marking transforms into $M_2 = \{1, 0, 0, 1, 0\}$, and the agent observes the world has changed again making marking transform into $M_3 = \{0, 1, 0, 1, 0\}$. The model will continue according to the above rules.

BDI Petri net owns hierarchical bottom subnet, its inputs are beliefs and desires, outputs are the influence on outside world and state of desire, the function denotes the specific plans and actions of intention by bottom subnet.

4. Application of BDI Petri net in flight mission modeling

4.1 Mission scenario

To verify the functionality of the BDI Petri net, a search and rescue mission is selected. The description of mission scenario is as follows.

The search and rescue team is composed by two helicopters, and each heads to its own region to perform search and rescue missions. During the execution, pilots may encounter some events affecting the safety, such as enemy patrol aircraft appearing on the radar, helicopter malfunction and insufficient fuel, which require pilots to immediately return to the base until the problems are solved. If the fuel is still enough, then the pilot continues the search and rescue mission. When one of the search and rescue team finds survivors, the coordinate of survivors will be updated and pilot calls for cooperation to send the survivor back together.

4.2 Mission analysis and modeling

4.2.1 Mission analysis

The advantage of the BDI Petri net lies in the ability to depict the influence of the agent's desires on the operation procedure. Thus, before modeling, the types of desires must be determined. As described above, the most abstract desires of pilots can be categorized into four classes: (i) search survivor, (ii) rescue survivor, (iii) safety maintenance, (iv) cooperation, where (i), (ii), (iv) are achieve desires, while (iii) is the maintain desire.

The information that pilots need to observe is listed in Table 2.

Table 2 The observed information

Type	Description
state_arrival_search	Whether helicopter is in the search area
state_finded	Whether survivors are found
state_search_end	Whether search is done
state_arrival_base	Whether helicopter arrives at the base
state_enemy	Whether enemy helicopter appears
state_fault	Whether malfunction appears
state_fuel	Whether fuel is enough
state_survivor	Whether survivors are all on board
state_capacity	Whether helicopter is full
state_arrival_survivor	Whether helicopter arrives at survivors
state_request	Whether the request signal is sent
state_coordinate_survivor	The coordinate of survivors
state_mission	Whether pilot accepts the mission

Pilot's beliefs and desires are analyzed above, in the top layer of the BDI Petri net model, beliefs and desires are represented by places, and intentions are represented by transitions. The realization processes of intentions are represented by bottom subnets of transitions. We use the search survivor desire to analyze the interaction among beliefs, desires and intentions.

The formal definition of the rescue survivor desire is $achieve(Search, PreCon, S, F)$, where $PreCon$ is $state_mission$, S is the set of $\{state_search_end, state_finded\}$, F is the set of $\{state_enemy, state_fault, state_fuel, state_request\}$.

In the pending state of the search survivor desire, the pilot firstly checks $PreCon$ to judge whether pilot has accepted the mission. If the $PreCon$ is true, then the *search*

desire is activated. If one of the conditions in F is true, the situation denotes that it is not safe to carry out the desire. Then the state transforms into the suspended and waits for transforming into the pending state of the safety maintenance desire.

In the activated state, beliefs and desires command the selection of plans and actions based on intention generate function and the pilot begins to adjust the course to the search area. During the search tasks, the state could transform into the suspended state under the two circumstances below:

(i) One of the conditions in F is true, which denotes that the safety condition is violated or friendly helicopter has found survivors and called for cooperation, and the desire will be changed to safety maintenance or cooperation respectively, and the desire generates the function which begins to take effect.

(ii) One of the conditions in S is true, which denotes that the pilot has found survivors or the area is completely searched and no survivor is found. Under this circumstance, The belief updates function takes effect, and the search results will change the beliefs of pilot to make further decisions.

In the suspended state, the pilot checks all the conditions according to current beliefs to determine whether to reactivate search desire or transform into other desire.

4.2.2 Mission modeling

ExSpect (executable specification tool), jointly developed by Dutch Deloitte & Touche Bakkonist Companies and Eindhoven University, is a kind of process modeling tool that supports automatic and step by step simulation, and the analysis of simulation results through charts and other modes. It is widely used in maintenance support systems [36], manufacturing systems [37], system reliability analysis [38] and other areas of modeling. We model the search and rescue mission described above by using ExSpect and parts of the model are shown in Figs. 4–5.

In Fig. 4, four desires are search, safe, rescue and cooperate. Every desire has three states as shown in Fig. 1. Observe denotes that pilots are observing outside world, transition $State_change$ will change the Belief state of pilots. The search desire includes three states which are P_search , A_search and S_search . They are represented by places. The transition between two states of search desire such as $I_P_A_search$ denotes that the change of belief initiates state transition of search desire, and so as rescue, safe, cooperate desire. There are four desires, in order to represent the transition between two desires, three transitions are used in one desire. Take search desire as an example, it includes $I_S_T_search_1$, $I_S_T_search_2$, $I_S_T_search_3$ representing the transition to safe, rescue and cooperate.

Fig. 4 Top layer of search and rescue mission model

 Fig. 5 Bottom subset of I_{A_S} search intention transition

In Fig. 5, A_search denotes that search desire is activated, Course_correcting denotes that pilot is correcting course, enroute denotes that plane is on the right course, searching denotes that pilot is searching, S_search denotes that search desire is suspended. Transition Course_deviation denotes that plane is deviating from the right course, Course_right denotes that pilot is correcting course, Arrival denotes that plane has arrived, Enemy_show and Enemy_show_2 denote that pilot finds enemy, Fuel_shortage and Fuel_shortage_2 denote that fuel is not enough, Fault_show and Fault_show_2 denote that plane malfunctioned, Help_request and Help_request_1 denote that pilot needs help, Survival_find denotes that survival has found, Search_end denotes that pilot has finished search job.

Fig. 5 shows a simplified procedure of search intention. Making use of hierarchical modeling means of the Petri net, the detailed model of actions can be acquired by expanding the ordinary places like course_correcting shown in Fig. 5.

The running results show that tokens can flow freely according to the design and verify the effectiveness of the proposed methods of modeling based on the BDI Petri net.

5. Conclusions

In this paper, the problems of traditional modeling methods and Petri net are analyzed, with a focus on the inability to model the intentions of agents. We propose a new BDI Petri net which is a fusion of the Petri net and the BDI model, and verify the effectiveness by applying it to a search and rescue mission.

Besides the advantages of modeling intentions of agents, this method also allows the designer to adopt top-down means to model under the desire system and as a result, the size of model is reduced. The most promising application of the BDI Petri net is on the modeling behaviors of unmanned aerial vehicle (UAV) and multi-agent cooperation.

The model based on the BDI Petri net holds all the desires of agents, and the bottom subnet of intention transitions denotes the agent's plans and actions. If we reverse the directions of the arcs linking places and transitions, and introduce the fuzzy theory into the BDI Petri net, we can infer the pilot's desire or intention according to the occurrent actions on the basis of the current situation and judge whether the pilot's action will cause deviation from the normal procedure. This is one of the several promising paths for further research.

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