

Modeling and Analysis of Gate to Gate Flight Process Based on SysML in Commercial Aircraft



Hongyu Li, Miao Wang , Gang Xiao, Guoqing Wang, Bei Tian, and Zihang Chen

Abstract The design and development of commercial aircraft is a complex system engineering. At present, operational scenario analysis is gradually used for aircraft function identification and requirement capture. In the analysis process, the time dimension factors of the aircraft in civil aviation operations must be considered, that is, the complete process of aircraft operation must be defined. Guided by the idea of system modeling, this paper presents research on the modeling method of Gate to Gate flight process. The basic elements and hierarchical division of flight process models are constructed. Finally, the paper proposes the method and procedure of establishing Gate to Gate model based on SysML. Based on the previously proposed method and a complete description of commercial aircraft operation process, this paper establishes a summary behaviour model of aircraft's Gate to Gate flight process, covering the preparation before takeoff, push back, taxi out, taxi before takeoff, takeoff roll, takeoff, climb, ocean-based cruise, land-based cruise, descent, approach, final approach, landing, taxi after landing, and taxi to aircraft stand. SysML is used to model the flight process, which includes aircraft itself, ATC, AOC, airport tower and other models. The model is drawn to form Use Case diagrams, Activity diagrams, State Machine diagrams, and Sequence diagrams under each flight phase. The model mainly focuses on the collaborative process between aircraft and various

H. Li · M. Wang (✉) · G. Xiao · G. Wang · B. Tian · Z. Chen
Shanghai Jiao Tong University, Shanghai, China
e-mail: miaowang@sjtu.edu.cn

H. Li
e-mail: lihongyu39@sjtu.edu.cn

G. Xiao
e-mail: xiaogang@sjtu.edu.cn

G. Wang
e-mail: wang_guoqing@careri.com

B. Tian
e-mail: tianbei@sjtu.edu.cn

Z. Chen
e-mail: chenzihang_jy@sjtu.edu.cn

stakeholders, such as the collaborative interaction process between aircraft and ATC, AOC, as well as the collaborative interaction process between aircraft and airport tower during the takeoff and landing phase. This paper provides a method to describe the flight process systematically and graphically. It can also be used as an exploration of function identification and requirements capture methods.

Keywords Flight process · SysML · Behaviour diagram · Commercial aircraft

1 Introduction

Modern civil aircraft development is a highly complex multi-system integration project, which is characterized by numerous subsystems, complicated cross-linking between systems, technology intensive, and cross-disciplinary. How to systematically analyze the functional requirements of civil aircraft has always been an important task of civil aircraft design and development. Analysis methods based on document management are a thing of the past. Today, model-based systems engineering (MBSE) ideas are widely used in civil aircraft design to support activities such as capturing, analyzing, and verifying system requirements.

The design process of civil aircraft is a top-down, layer-by-layer decomposition based on user needs. Therefore, the premise of accurately grasping the functional requirements is to be able to obtain accurate and complete top-level use cases, and gradually expand into sub-use cases, which ultimately correspond to the needs and functions of civil aircraft. The MBSE method is now widely used in the field of aircraft design, and there are many researches using SysML for functional analysis and logic design [1]. Research literature [2] has carried out the functional design and logic verification of flight control system according to the demand-function-logic-physics system engineering method. Paper [3] proposed a MBSE method to analyze and design critical safety systems for aircraft. The MBSE method has been successfully applied in the practice of several projects of Boeing and Airbus [4].

In the above-mentioned related research, the top-level use cases on which requirements analysis relies are generally from a single running scenario, and system-level functional requirements are analyzed from the scenarios [5]. The top-level use cases from this source are likely to cause imperfect requirements capture. Therefore, it is necessary to consider the complete flight process of the aircraft and build a multi-dimensional flight environment and scene. In recent years, scene analysis has gradually been used to identify aircraft functions and capture requirements. The analysis process must consider the time dimension of the aircraft being put into civil aviation operation, that is, the complete process of aircraft operation must be defined. In the initial stage of civil aircraft design, the aircraft is considered under the civil aviation operation and management system. Taking the complete operation process of the aircraft as a scenario, it can ensure the close integration of requirements and functional design in the development life cycle.

In the first section of this paper, based on the complete description of civil aircraft flight process, the basic elements of constructing a summary model of aircraft Gate to Gate process are proposed, covering the entire operation process under the current civil aviation management system. In the second section, based on SysML, a summary model of the Gate to Gate process covering the basic elements is established, the Use Case, Activity, State Machine, and Sequence diagram in each operation phase are formed and further analyzed.

2 Gate to Gate Flight Process

The basic requirement for establishing a Gate to Gate flight process summary model is to cover the basic operation process and scenarios of aircraft under current civil aviation management system. Guided by the regulations of civil aviation management, according to the different flight missions under time dimension of civil aviation operation, the whole flight process of aircraft is subdivided into several phase.

Since this article builds a summary model, the basic elements contained in the model are required to be complete, but at the same time it should be concise and clear. Each flight process contains a large amount of information transmission, collaborative decision-making, and operation interaction. Therefore, when using SysML behaviour diagrams to describe, we should select the parts that help complete the requirements capture.

The Gate to Gate flight process model established in this paper focuses on collaborative decision-making with various participants and the state changes of key aircraft systems. The following is a detailed analysis from the three aspects of participants, system composition and flight process.

2.1 Participants

When modelling the Gate to Gate flight process, the first thing to determine is the members who are mainly involved in the flight scenario. According to the current civil aviation operation and management system, and the general procedures for aircraft operation, as well as airline operation and control regulations, the entire flight process is sorted out. Participants of Gate to Gate flight process model refer to all members participating in the flight scenario, including the aircraft, airlines, airports, air traffic control, etc.

Aircraft. The aircraft includes the aircraft's own equipment and systems, and the flight crew which is responsible for completing the aircraft's driving and manoeuvring. According to the current civil aviation regulations, usually the flight crew consists of two or more pilots. Specific to the distribution of responsibilities, it is divided into captain and co-pilot. When considering the division of labour in flying

an aircraft, it is generally divided into PF and PM, that is, pilot-flying and pilot-monitoring. The PF is mainly responsible for driving and manoeuvring the flight, and the PM is mainly responsible for the status monitoring of the flight. Specific to each flight phase, according to the requirements of different airlines and different types of aircraft, the cockpit areas of the two are different [6].

Airlines. The airline part involved in Gate to Gate flight process model mainly refers to the airline's operation control centre (AOC). The AOC can realize the integration of airline resources, complete the tasks including flight dispatch, maintenance, ground support, crew deployment, etc., is the core of the airline's command. Specific to the Gate to Gate flight process model, the AOC mainly involved in this article includes flight dispatch and ground support. The airline is responsible for organizing the initial flight plan of the aircraft flight and participating in the modification and adjustment of the real-time flight plan during the flight. At the same time, when the aircraft is in the pre-flight preparation phase on the ground, the airline's ground crew need to assist the flight crew to complete the pre-flight inspection and pushing back.

Airports. The airports part of Gate to Gate flight process model mainly includes deliver control center (DEL), ground control center (GND) and tower control center (TWR) in airport control. Among them, the DEL needs to make a comprehensive judgment based on the flight plan, airport flow and route weather, destination airport status and other information, issue a release permit to the aircraft, and allow the aircraft to complete the flight plan. GND is responsible for scheduling management and permit issuance of aircraft in surface operation, according to the traffic conditions of the airport surface and the sorting queues for entry and exit, the aircraft is issued with permission to launch and start the engine, and directs the aircraft to complete the surface taxi according to the route. The TWR is mainly responsible for the command and dispatch of aircraft entering and leaving the port, including directing the departing aircraft to enter the runway, issuing the take-off permission, and issuing the landing permission to the incoming aircraft.

Air traffic control. The air traffic control part of the model is mainly composed of area control center (ACC) and approach control center (APP), and is responsible for providing air traffic control services, flight information and warning services in specific flight areas. Area control areas generally refer to high-altitude control areas, and approach control areas are the connection between the tower control area and the area control area. APP is responsible for sequencing landing aircraft and adding routes to departing aircraft.

2.2 System Composition

The purpose of establishing a Gate to Gate flight process summary model is to perform aircraft function identification and requirements capture, so it is not perfect to obtain only the aircraft-level requirements. In the summary model, the participating

aircraft will be further decomposed to analyze the functional requirements of the key systems.

In addition to distinguishing the concept of human-machine and dividing the model into pilot and aircraft, the aircraft model established in this paper also subdivides the typical systems and equipment to form the system components of the model. The system composition includes the system involved in the whole flight process, which is obtained by subdividing the participating subjects layer by layer.

2.3 Division Method

For civilian aircraft, the fundamental mission of the aircraft is to fulfill the transportation needs, which is reflected in the ability, performance and effectiveness of flight. The flight process of aircraft is the application of capability, performance and effectiveness.

Taking current civil aviation operation and management system as a reference, the entire flight process is divided into: preparation before takeoff, push back, taxi out, taxi before departure, takeoff roll, takeoff, climb, ocean-based cruise, land-based cruise, descent, approach, final approach, landing, taxi after landing, sliding into the parking space. There are obvious flight tasks or status transition signs between each phase, and they are closely connected with the front and back phases, forming the whole process from flight preparation to flight completion. The definition and division of each phase are introduced as follows.

Preparation before takeoff. The preparation before take-off starts with the flight plan, and also includes the direct preparation work after the crew arrives at the aircraft stand. The main mission of the participants in this phase is to negotiate to formulate a flight plan. At the same time, the crew needs to complete the safety check, ground preparation and information acquisition, and finally apply for clearance to DEL.

Push back. After obtaining the clearance, the crew can begin preparations for push back. After applying for GND permission, the crew can complete push back of the aircraft and start engine with the help of ground crew. The phase ends with the aircraft reaching the stop line and engine keeping the idle stable.

Taxi out. The taxi-out phase refers to the phase in which the aircraft moves from the stop line to before the taxi area. During the phase, the crew needs to complete the preparations for taxiing, and apply to GND for taxiing instructions.

Taxi before takeoff. The phase refers to the process of the plane taxiing in the taxi area of airport surface. Depending on the situation, the crew may need to taxi to a specific area for de-icing operations. Or the crew needs to follow the GND commands to cross the runway. After taxiing, the aircraft should wait outside the runway for instructions.

Takeoff roll. The takeoff roll phase is defined as the time when the aircraft enters the flight runway until the aircraft completes the acceleration roll and retracts the landing gear in the air. The division is based on the relevance of the series of actions of crew after take-off. At the same time, the participants in the stage also have TWR,

which is responsible for issuing take-off instructions to the aircraft at the beginning of the phase.

Takeoff. To ensure the continuity of previous phase, the aircraft had retracted its landing gear at the beginning of take-off phase. Therefore, the main content of take-off phase is that the crew applies to APP for departure instructions, and at the same time completes the post-takeoff inspection. This phase can be regarded as the transitional phase between takeoff roll and climb.

Climb. The climb phase refers to the process until the aircraft rises to the cruising altitude. Generally, after take-off, the operation of aircraft is handed over to the autopilot system, so the subsequent few phases of crew operation activities are less, and the proportion of collaborative decision-making with ATC will increase. The control unit of the aircraft during the climb phase was transferred from APP to ACC.

Ocean-based cruise. The cruise phase will be divided into ocean-based and land-based depending on where the aircraft is located. Among them, ocean-based cruise refers to the cruise flight process of an aircraft crossing the ocean. The characteristic of this phase is that there are basically no navigation facilities in the ocean area. Therefore, when the aircraft is flying in the ocean area, its navigation and communication methods have changed greatly. To put it simply, during the cruise in the ocean area, aircraft rely more on HF or satellite communication, and the control mode is switched from radar control to procedure control.

Land-based cruise. The flight environment of aircraft during the land-based cruise phase has not changed much, because the radar stations and communication stations below the route are relatively dense. The aircraft will still fly under radar control. The collaborative decision-making between aircraft and ACC during the cruise phase usually includes application to change altitude, application to change routes, and ACC control handover.

Descent. Generally speaking, when flying to 80 nautical miles before the descent apex, the aircraft must begin preparations for descent. In addition to the necessary adjustment of flight status, it is also necessary to obtain the landing conditions of the destination airport. The descent phase ends after the control of aircraft is transferred from ACC to APP.

Approach. The whole landing process is divided into several small phase. Among them, the approach phase refers to the flight activities in the area controlled by APP. At this phase, the aircraft needs to complete preparations and inspections before approaching. The APP needs to sequence the arrival of aircraft in the area, and issue an approach command to each aircraft.

Final approach. In the final approach phase, control of the aircraft will be transferred to the airport's TWR. This is also the last phase of aircraft in the air during the entire flight. In addition to completing the pre-landing inspection at this stage, the crew needs to decide whether to go around based on the airport environment. TWR needs to grant landing permission to the aircraft based on the air traffic above the airport and surface.

Landing. For aircraft that require manual approach, more operations need to be completed by crew during the landing phase. The main content of this phase is to slow down the aircraft. At the same time, there is a control handover process. When

the aircraft decelerates and leaves the runway, it needs to be transferred from TWR to GND.

Taxi after landing. Before leaving the runway, the crew needs to apply to GND for taxi instructions. In addition to the necessary system control required by the flight manual during the taxi phase after landing, the rest of the content is basically the same as the flow during the taxi phase before take-off.

Taxi to aircraft stand. After leaving the taxi area of airport, the aircraft will enter the aircraft stand. According to the airport situation, the ground crew can choose to assist in entering stand. After completing the shutdown of the system, the entire flight process has also been completed, and the fifteen phases will constitute the Gate to Gate flight process.

Each phase model should include multiple participants such as aircraft, ATC, AOC, etc., and should cover air-ground collaborative interaction, aircraft-ATC-AOC, etc. Take the approach phase as an example, that is, when the aircraft descends to an excessive level until the landing checklist is completed before the aircraft is landed, the process should include the operation of the aircraft's local pilot under normal procedures, pilot and APP and TWR. Collaboration and interaction, as well as the handling and release of route conflicts under abnormal conditions, decision-making for approach and go-around, etc.

3 Modeling Based on SysML

Based on the above analysis of summary model, the basic elements required by it have been determined, and the start or end signs of each phase have been divided. The next step is to complete the summary model based on SysML behaviour diagram. Use Enterprise Architect software to complete the MBSE-based system model building and integration, establish a unified standard Gate to Gate model, build the model of basic participants and system components, with Activity, Use Case, Sequence and State Machine diagram [7], [8].

The characteristics and modelling methods of four behaviour models are introduced below, taking the take-off phase as an example. In order to better show the details, we reconstructed some models with Visio.

Activity diagram. Activity diagram can clarify the specific flow of a use case, such as the flow of take-off phase. In the take-off phase, the work of aircraft and ATC consists of a series of activities. In the activity diagram, two partition are drawn respectively, corresponding to the workflow of aircraft and APP. The model usually includes a basic branch and one or more alternative branch. The switching of branch needs to use a control node [9], 10, 11 (Fig. 1).

An activity diagram is a dynamic view that illustrates the sequence of actions and events that occur over time. Activity diagrams can express the flow of information and instructions through behaviours, and pay attention to how objects are accessed and modified during the execution of behaviours, and can express more complex control logic. Taking the take-off phase activity diagram as an example, the figure

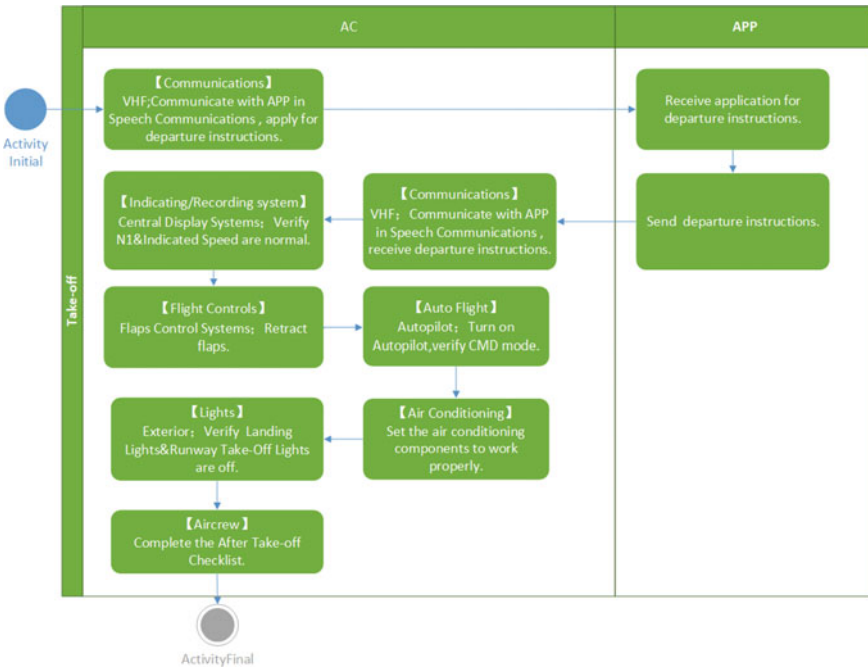


Fig. 1 Activity diagram during take-off phase

can clearly show the collaborative decision-making and information transmission process between aircraft and APP, and also describes the operations that flight crew within the aircraft needs to complete or the status changes in the key systems after take-off.

Sequence diagram. Sequence diagram is the same as activity diagram, expressing the dynamic view of system. Each participant can interact with each other through operation calls and asynchronous signals. Compared to activity diagrams, sequence diagrams focus more on expressing three types of information: the order in which actions are performed, which participants will perform which actions, and which structures trigger which actions (Fig. 2).

Sequence diagram uses lifelines to model the aircraft and APP, and uses messages between the lifelines to model the interaction between participants, which is convenient for describing various interactive behaviours and interactive executions. As shown in the figure, the left side is the time sequence of aircraft's behaviour during the take-off phase, and the right side is APP. The sequence diagram is more intuitive in expressing the execution order of behaviour and activities.

State Machine diagram. State Machine diagram also describes the dynamic behaviour information of system. The difference is that State Machine focuses on how the structure in system changes state according to events that occur over time. The concept of state is difficult to formally define. In summary model, the state will

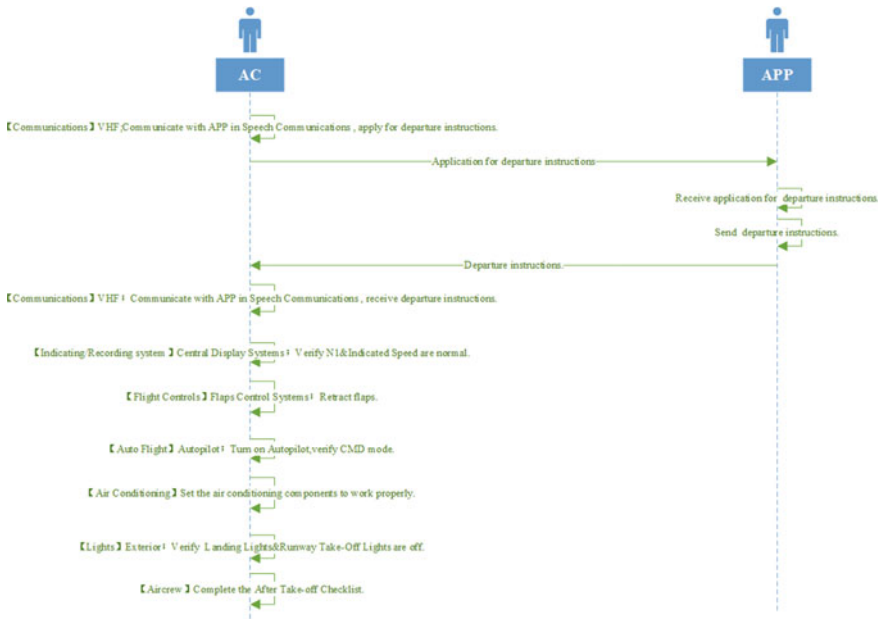


Fig. 2 Sequence diagram during take-off phase

be specifically defined according to different flight phases and environments, and the situation of system (Fig. 3).

State Machine is slightly different from activity diagram and sequence diagram, showing the state change process. There is no state transition in the take-off phase, so there is only one block diagram in the figure. In other phases, the State Machine has different complexity according to the activities, and there are judgment conditions between each state. The current summary model only takes the aircraft as main

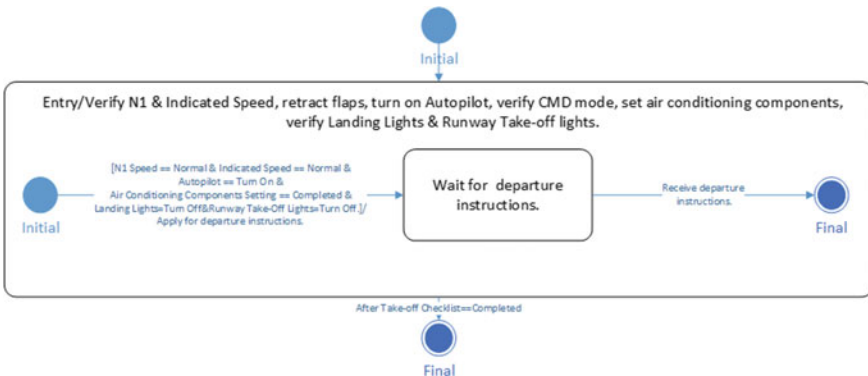


Fig. 3 State Machine diagram during take-off phase

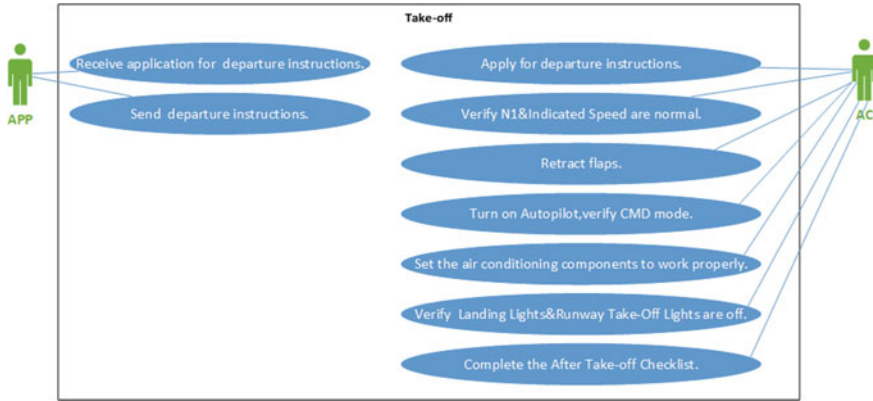


Fig. 4 Use Case diagram during take-off phase

body, and in a more detailed model, the key system of aircraft will have its own State Machine diagram to show the state of key system, in order to analyze the function and requirements of system.

Use Case diagram. Use Case diagram is different from the above three diagrams and is a situation diagram of system. Specifically, Use Case diagram can explain the service information provided by system, that is, all externally visible services. Each Use Case diagram contains several use cases, and each use case is associated with the executor who triggered and participated in the use case (Fig. 4).

The figure shows all use cases involving the aircraft and APP during the take-off phase. At some phases, there are multiple executions or participants in a single use case. The Use Case diagram also supports the rapid screening of use cases where the current participant participates in all stages. The existence of Use Case diagram can clearly show the relationship between behaviour and participants.

Model of flight phase. Taking the take-off phase as an example, the above content introduces the characteristics and modelling methods of four behaviour diagrams in detail. Due to space limitations, the remaining 14 phases will not be introduced one by one. Only some special behaviour diagrams are introduced below Fig. 5.

The first is the sequence diagram at push back phase. As mentioned above, during the push back phase, the crew needs to apply to GND for a start clearance. The GND needs to make judgments based on the flight plan and traffic conditions. If the situation permits, the aircraft can be pushed back directly. If the situation is not allowed, the aircraft needs to wait on the bridge until the GND grants permission. The logic of this part is a little more complicated, and the loop judgment structure in the behaviour diagram needs to be used. As shown in the figure below, the middle part shows the negotiation process between the crew and the GND.

The following figure is a Use Case diagram of taxi out phase. There are many behaviours and activities included in this phase, so we divide this into several processes. As shown in the figure, all use cases are listed and included in the process.



Fig. 6 Use Case diagram during taxi out phase

adjusts the radio to the new frequency. At the same time, if the pilot has a need to adjust the aircraft’s altitude or speed, they also need to apply and negotiate with ACC. The above process is reflected in the activity diagram, that is, it has become an interactive activity across multiple partition. The transmission of information is shown in the interactive behaviour, representing the negotiation between the crew and ACC (Fig. 8).

The Activity diagram in the approach phase mainly shows the collaborative decision-making process between aircraft and ATC. Aircrew need to obtain permission from ACC when descending. And obtain permission from APP when approaching. This process is mainly achieved through VHF voice communication (Fig. 9).

The following figure is State Machine diagram of taxi to aircraft stand phase. At this phase, several states are divided, so the structure of State Machine diagram is slightly complicated. During taxiing, there is a possibility that the aircraft needs to cross the runway. Therefore, in the State Machine, there are judgment modules and sub-states. Generally, the input, execution, and output of states need to be described, and transition conditions need to be set between different states (Fig. 10).

Based on the SysML behaviour diagram, the 15 phases of Gate to Gate flight process are modeled. Analyzing the above models, we can find that the Use Case

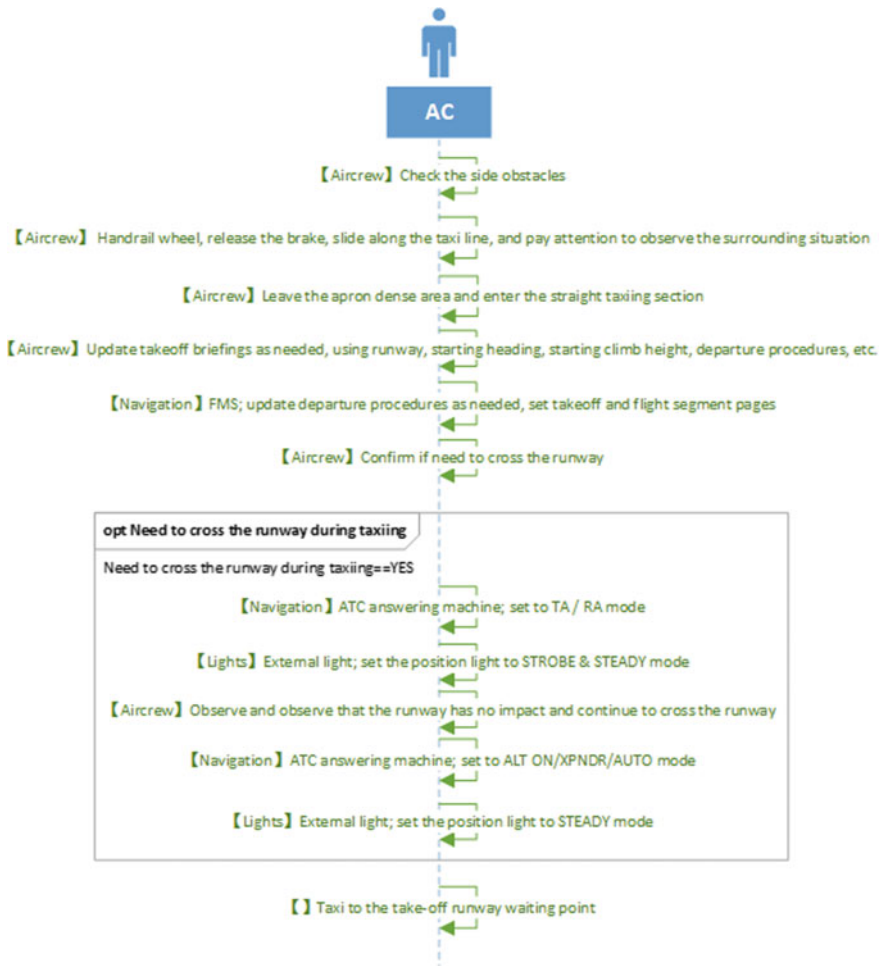


Fig. 7 Sequence diagram during taxi phase

diagram can obtain the behaviour activities that the participants need to participate in or perform during the full operation process. It can provide the sequence of actions required by each participant in a specific stage, and the State Machine can show the status changes and conditions of the aircraft or critical system. Therefore, the SysML behaviour diagram can meet the requirements of establishing a summary model of Gate to Gate flight process, and supports the analysis of functions and requirements of aircraft and key systems.

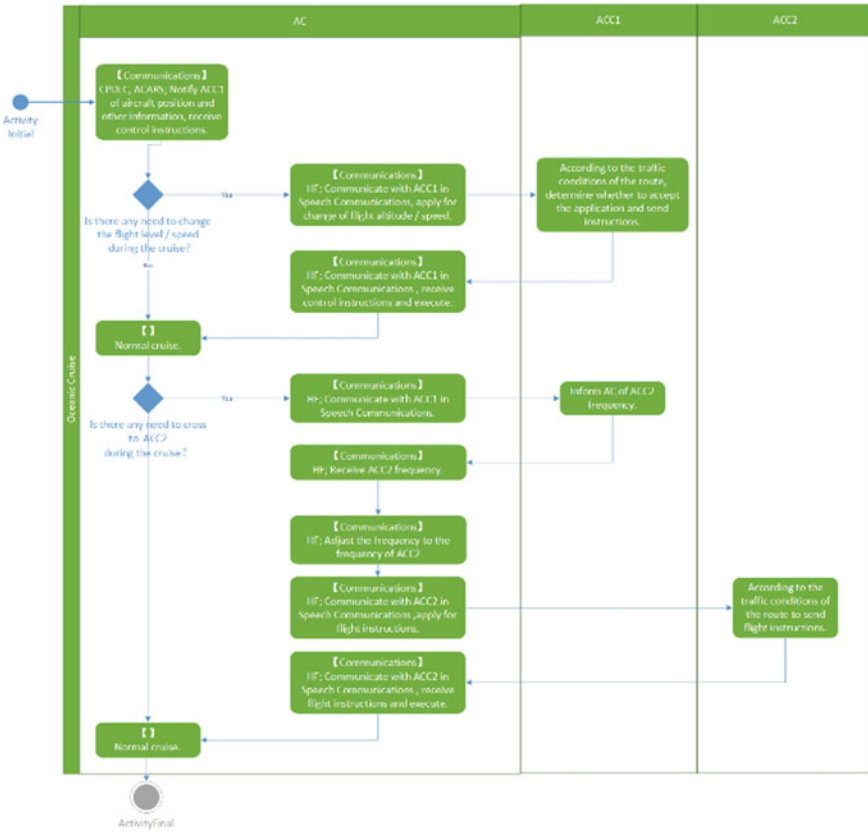


Fig. 8 Activity diagram during ocean-based cruise

4 Conclusion

In this article, we first analyze the basic elements required for the summary model, clarify and subdivide the parties including aircraft, air traffic control, airlines, etc., and divide the key components and systems of aircraft. At the end of the first section, the Gate to Gate flight process is defined. Then, based on the idea of system modeling, the model is established at the system level of aircraft, and the SysML behaviour model is built around the key systems involved in the flight process of aircraft. It can be obtained by analyzing the model that the behaviour diagram can provide a method for describing the flight process systematically and graphically, and can also be used as an exploration of function identification and requirement capture method in aircraft design process.

The work involved in this article is still insufficient. The first is that key systems are not the basis of behaviour model. To focus on the key system, it will take a large amount of work and require that relevant standards can be formulated in advance.

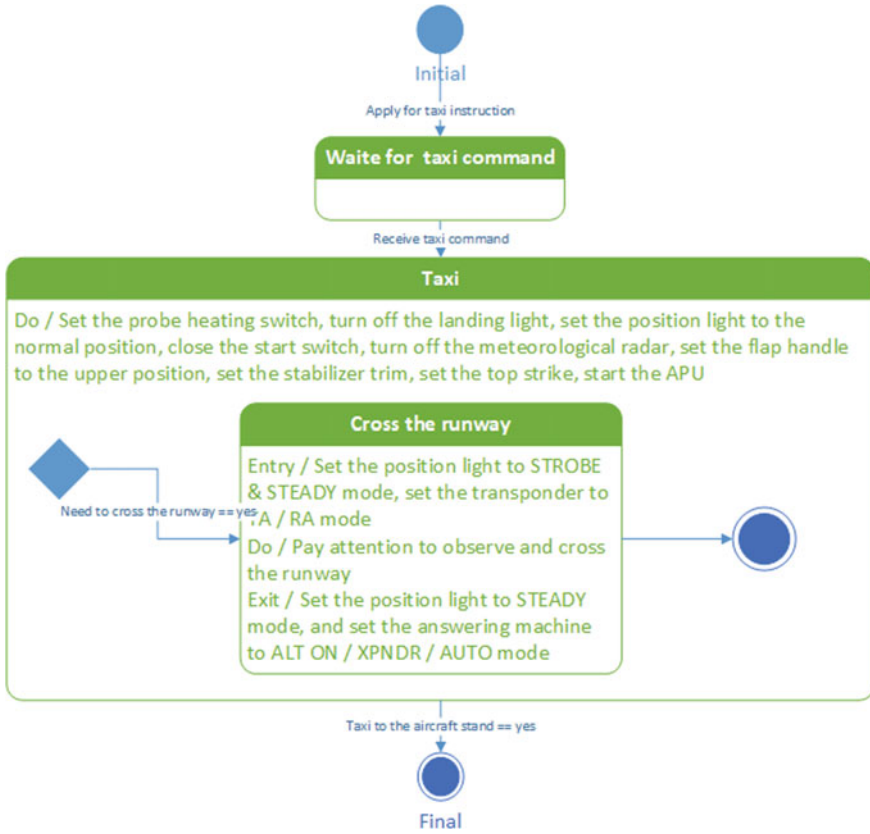


Fig. 10 State Machine diagram during taxi to aircraft stand phase

Acknowledgements The project is supported by National Program on Key Basic Research Project (2014CB744903), National Natural Science Foundation of China (61673270), New Young Teachers Launch Program of Shanghai Jiaotong University (20X100040036), Shanghai Pujiang Program (16PJD028), Shanghai Industrial Strengthening Project (GYQJ-2017-5-08), Shanghai Science and Technology Committee Research Project (17DZ1204304) and Shanghai Engineering Research Center of Civil Aircraft Flight Testing.

References

1. Qiao WF, Li ZQ, Huang S, Yao ZC (2015) Research on model-based integrated design of civil aircraft. *Aviat Manufact Technol* 2015(04):72–77
2. Xu YZ (2018) Application of model-based requirements-function-logic-physical system engineering method in aeronautical system design. *Chinese Aeronaut Soc. Proceedings of the 8th China aeronautical society youth science and technology forum 2018*: 1386–1391

3. Zhang SJ, Li ZQ, Hai XH et al (2018) Design of safety critical system for civil aircraft based on MBSE. *Chin Sci: Tech Sci* 2018(3):299–311
4. Mei Q, Huang D, Lu Y (2018) Design method of civil aircraft functional architecture based on MBSE. *J Beijing Univer Aeronaut Astronaut* 2019 45(05): 1042–1051
5. Ren BX, Lu Y, Fu S, Huang D (2019) Identification and confirmation of civil aircraft functional requirements based on MBSE. *Syst Eng Elect Technol* 41(09): 2016–2024
6. Zhu HY (2019) Research on the evaluation method of the minimum crew workload of civil aircraft. *Int Combust Engine Parts* 2019(08):185–187
7. Lenny D (2014) *SysML distilled: A brief guide to the systems modelling language*, 1st edn. Addison-Wesley Professional
8. Graves H, Bijan Y (2011) Using formal methods with SysML in aerospace design and engineering. *Ann Math Artif Intell* 2011(63):53–102
9. Friedenthal S (2015) *A practical guide to SysML: the systems modeling language*, 2nd edn. Morgan Kaufmann
10. Weikiens T (2008) *Systems engineering with SysML/UML*. Burlington: Morgan Kaufmann SMG Press, pp 18–22
11. Holt J, Perry S (2008) *SysML for systems engineering*, 2nd edn: A model-based approach[M]. London: The Institution of Engineering and Technology, pp 121–222