Conceptual Architecture for Remotely Piloted Operation Mode in Commercial Aircraft

LUO Yue, *WANG Miao**, *XIAO Gang*, *WANG Guoqing*

School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai 200030, P.R.China

(Received 15 March 2020; revised 4 April 2020; accepted 9 April 2020)

Abstract: With the increasing civil aviation passengers and the rapid development of aviation logistics, the study on remotely piloted operation (RPO) mode has received extensive attention. RPO mode constructs the piloting decision-making mode which involves the tripartite collaboration among airborne automatic/autonomous system, remote ground-based crews and air traffic control. In this paper, we describe the organizing architecture for commercial remotely piloted aircraft (CRPA) system and its components. Compared with the current operation mode, the new air-ground collaborative decision-making mode has been established with six different situations based on the type of the flight and the condition of the remote pilot. Taking airport surface operation as an experimental example, we model the airport surface operation process and compare the advantages and disadvantages between RPO mode and the current dual-pilot mode from the perspectives of time and operation coverage, and draw conclusions that RPO mode can basically cover the flight operations of the dual-pilot, improve the accuracy of pilot operations and greatly reduce response time by 48% in pre-flight inspection. The above research would be the foundation for the RPO development of commercial aircraft in China.

Key words: remotely piloted operations (RPO); commercial remotely piloted aircraft (CRPA); airborne automatic/autonomous system; flight process

CLC number: V323.11 **Document code:** A **Article ID:** 1005-1120(2020)02-0274-14

0 Introduction

It is known that the crew of civil airliners has evolved from the five-person operating mode that consists of a captain, a first-officer, a flight engineer, a navigator and a radio operator to the dual-pilot operating mode that only contains a captain and a first-officer. But the dual-pilot mode[1], which includes piloting operations, environmental monitoring, interactive driving, decision making and substitute for the incapacitated pilot, has never been changed since then. With continuous increase of civil aviation passengers and rapid development of aviation logistics, there has been a growing demand for pilots, but the high cost and long cycle of pilot-training make the aviation market in short supply. Therefore, the study on remotely piloted operation (RPO) mode for commercial aircraft has received extensive attention.

The future development trend[2] of commercial aircraft is shown in Fig. 1. Our research group has conducted relevant research on single pilot operations(SPO)[3] and started to gradually involve in the research and analysis on RPO mode. The flight organization and management process of commercial remotely piloted aircraft (CRPA) is to construct flight task and implement flight management in accordance with flight task requirements, flight plan arrangement and flight environment. Among them, the ground station, controlled by ground operaters; is responsible for the organization and management of flight planning, flight environment, flight situation, flight status and flight task. The airborne con-

*Corresponding author, E-mail address: miaowang@sjtu.edu.cn.

How to cite this article: LUO Yue, WANG Miao, XIAO Gang, et al. Conceptual architecture for remotely piloted operation mode in commercial aircraft[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2020, 37(2): 274-287.

http://dx.doi.org/10.16356/j.1005-1120.2020.02.009

trol system is responsible for flight environment information perception, flight status organization, airborne equipment management, flight environment report, flight status report and equipment operation status report. The air-ground data link is responsible for downloading flight information and reports as well as uploading flight instructions and flight assistance parameters.

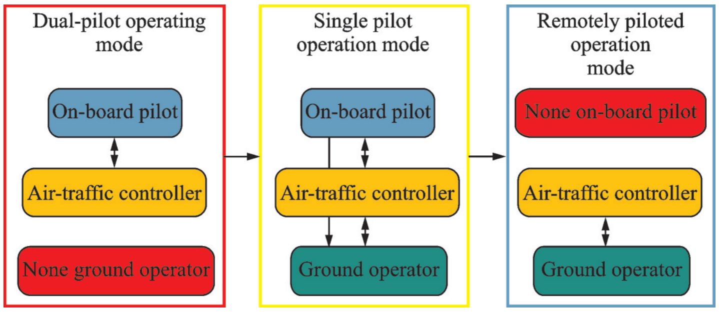

Fig.1 Future development trend of commercial aircraft

In this paper, we focus on the requirements for flight process organization of commercial aircraft, and adopt RPO mode, instead of the current dual-pilot mode, according to the flight environment and the target of unmanned driving. By constructing the piloting decision-making mode, which involves the tripartite collaboration-airborne automatic/autonomous system, remote ground-based crews, and air traffic control, we aim to realize the organization of flight process from the take-off airport to the destination airport, covering all flight phases, flight environments, meteorological conditions, airport requirements, system capabilities and states, and to meet the requirements for effective decision-making capabilities, costs, credibility, and safety goals of RPO mode[4]. By taking airport surface operation as an experimental example, we draw conclusions that RPO mode can basically cover the flight operations of the dual-pilot, improve the accuracy of pilot operations and greatly reduce response time.

1 Commercial Remotely Piloted Aircraft System

The significant difference between RPO mode and the current dual-pilot mode is that there is no pilot and cockpit on board in PRO mode. The data which is traditionally displayed in the cockpit instrumentation system passes through the command and control link (C2 link) to the ground station. Since there is no pilot to observe the information outside the aircraft through the porthole in the cockpit, in order to reduce the loss of visual information, several cameras need to be installed on the nose to monitor conditions outside in real time[5]. The data should be analyzed by airborne data fusion and intelligent analysis system, and the processed useful information will be transmitted to the ground station through C2 link and presented to the remote pilot. Affected by the bandwidth of C2 link and transferring costs of satellite, the original on-board video data will not be transmitted to the ground station, and the ground station can visualize the data through ground simulation software.

From the psychological point of view, the workload of remotely piloting is greater than that of piloting onboard. In order to reduce the workload of remote pilots, CRPA needs more automated equipment to assist remote pilots in piloting the aircraft to ensure flight safety, for example, surface operation automatic systems, off-board information monitoring and alarm systems, automatic take-off systems, and so on. CCAR Part 25 also states that pilots should use the airborne automatic system as much as possible when piloting. Moreover, to further reduce the workload of remote pilots and improve airspace utilization and flight safety, CRPA can fly autonomously in the traffic area authorized by air traffic control (ATC) through the airborne autonomous system. Therefore, with the assistance of the airborne automatic and autonomous system, the remote pilot only acts as a "remote co-pilot" to monitor the flight.

1.1 Remote ground-based crews

The CRPA's remote ground crews consist of three members: A remote pilot who is responsible for remotely piloting the aircraft and the safety of the flight, and has a sole control of the aircraft, a co-pilot who is the airline dispatcher and a backup remote pilot who takes charge of the aircraft when the remote pilot is incapacitated or off-duty. However, several remote pilots can control the aircraft to accomplish the flight task in different flight phases. For example, limited by C2 link, the latency of data transferring will increase when there is only one ground station be responsible for long distance flight. In order to accomplish the entire flight process smoothly, two or more ground stations are needed to work in turn, but only one takes charge of the aircraft at a time. Therefore, there is only one remote pilot of the CRPA's remote ground crews can control the aircraft, but the remote pilot may be replaced as the flight progresses[6].

1.2 Ground station of CRPA

The remotely piloted ground station of CRPA consists of a set of equipment for remotely piloting, including joystick, throttle, remote pilot and air controller communication system, remote pilot driving assistance system, remote pilot workload monitoring system, intelligent distribution system of human-machine functions, and remote pilot operation specification monitoring system, etc. The ground station is generally settled in a safe and closed place. A CRPA is consists of one or more ground stations, the number of which depends on the range of flight, the coverage of the communication chain, and the reliability of data transferring.

1.3 Command and control link

The command and control link provides the communication channel for remote pilots controlling CRPA through the ground station. The link includes radio line-of-sight (RLOS) and beyond radio line-of-sight (BRLOS). RLOS refers to the situation that the transmitter and receiver are within the coverage of the radio link and can communicate with each other directly, or when communicating through the terrestrial wired network, the transmitter is within the CRPA's radio range and could accomplish the transferring within the corresponding time range. BRLOS means that the transmitter and receiver cannot accomplish any configuration of RLOS. The ground station cannot accomplish the transferring within the corresponding time range under BRLOS unless it uses the help of satellite or other intermediary systems.

1.4 Communication with ATC

In the early stages of the development of CRPA, the operation of the existing ATC system should not be affected. So the general requirements for communication between air traffic controllers and remote pilots are the same as that for manned aircraft which operating in the same airspace. In addition to very high frequency (VHF) voice, there also include requirements for supporting air traffic control data links. However, it is also possible to adopt various alternative communication architectures, since the pilot is not on the plane. Regardless of which architecture is adopted, the function of air traffic control communication should meet the required communication performance specified for the airspace in which the CRPA operates.

1.5 Detecting and avoiding

Detecting and avoiding refers to the ability to observe or detect traffic conflicts or other dangers and to take appropriate actions. This capability is designed to ensure the safe execution of CRPA flights and enable full integration into all types of airspace with other airspace users. For CRPA, appropriate technology or programs are required to enable remote pilots to have similar abilities that pilots onboard got through one or more senses, like sight, hearing, touch, and related cognitive process. To ensure safety objectives for the operation of specific airspace, appropriate actions are needed to be taken to avoid dangers like potentially conflicting traffic in hazardous situations.

1.6 Air traffic management

The inclusion of CRPA into non-segregated airspace is a gradual process based on technological advances and the development of relevant procedures[7], thus the CRPA can be seamlessly integrated into manned aircraft transportafion. Consideration must be given to minimizing the risks to all airspace users when adding any type of airspace user into the existing air aviation system. Therefore, the state and the service provider under supervision should deploy the safety management principles and conduct relevant analysis when introducing the operation of the CRPA system[8-11], and these principles and analysis should reflect continuous progress of CRPA's system capability.

2 RPO Mode for Commercial Aircraft

Cockpit flight crew members, occupying the very important position in civil aviation transportation, need to rely on their own ability to cope with the changing flight environments and conditions, make reasonable decisions, operate the aircraft and safely accomplish flight tasks. If the workload of the crew does not match the number of crew members during the flight, the pilot may lose concentration and slack off, leading to catastrophic crashes. CCAR Part 25 and its appendices have specified airworthiness requirements for minimum flight crews, that is, the minimum number of crew members who can safely accomplish the flight task without excessive concentration or fatigue under the condition that the equipment configuration and layout of the cockpit have been determined. For a long time, this clause has been regarded as the first concerning human factors in the cockpit of civil aircraft.

Under the current dual-pilot driving mode, although both pilots have the ability to pilot the aircraft, only one is in charge of the flight operation, that is, the pilot flying (PF), who controls the aircraft according to the flight plan and monitors the flight path and deviation in real time. The other is the pilot monitoring (PM), who is responsible for assisting PF to accomplish navigation, communication, monitoring and other tasks to relieve PF's flight pressure, take the place of PF when PF is in abnormal state[12]. Therefore, in the dual-pilot driving mode, the two communicate with each other through languages, and body movements, to accomplish the flight task safely. CCAR Part 25 proposes that the "minimum flight crews" should be no less than two pilots, but the main pilot can only be one, since two pilots are not allowed to pilot the aircraft at the same time. That the key element of the design is allowing a single pilot to operate.

The reason for requiring at least two pilots in CCAR Part 25 is to make sure the probability of accident is no higher than 10^{-9}. As long as the reliability of air-ground data link meets 10^{-9} probability, the aircraft can be controlled by a single remote pilot from the ground station to accomplish the flight. There is a probability of 10^{-9} that pilots are both in an abnormal state under the dual-pilot driving mode. Unlike the pilot in the cockpit, in RPO mode, when the original remote pilot is incapacitated, the ground surveillance system first detects this condition and temporarily transfers control to the airborne automatic/autonomous system which is more intelligent and capable of handling such emergencies. It is similar to the automatic braking system and the automatic avoidance system of the car. Additionally, the airline can assign other remote pilots to take over the aircraft. The order of dealing with this emergency is that the airborne automatic/autonomous system, the backup remote pilot intervenes. Therefore, RPO research can only be carried out with the support of advanced airborne automatic/autonomous systems, and under the support of them as well as air-ground data link, the ground remote pilot can successfully accomplish the flight process while ensuring flight safety.

2.1 Organizing architecture of RPO mode

RPO mode for commercial aircraft establishes the cooperative mode of airborne automatic system, airborne autonomous system and remote pilot of airlines, aiming at meeting the requirements for flight capability and safety level of dual-pilot mode. Among them, the airborne automatic system, according to the standard flight procedures of the aircraft, can accomplish the nominal flight process by using the airborne automatic equipment, and there is no need for manual participation in decision-making, because it is executed according to the automatic procedures in the whole process, and it will switch into the ground manual piloting mode under the off-nominal flight.

Airborne autonomous system, based on the airborne intelligent sensing technology, can monitor other aircraft's operations in the airspace, build the current environmental awareness and airspace flight state prediction, and accomplish autonomous collaborative operation and management with the optimization of flight performance. It can realize the autonomous flight in the complex airspace environment. The remote pilot can obtain real-time airborne data and accomplish the remotely piloting of the aircraft through the ground station based on the communication link. He/she can also coordinate with ATC and the airline under the support of the ground automatic system. In order to meet the requirements for the current dual-pilot driving mode where one pilot is flying the aircraft and the other monitoring, the airline ground operators normally consist of two persons in the RPO mode: A remote pilot who is responsible for the remote piloting of the aircraft, and a dispatcher who monitoring the flight. The organizing architecture of RPO mode for commercial aircraft are shown in Fig. 2.

The goal of the RPO mode for commercial aircraft is to meet the requirements of the flight process organization and build four modes[13], includeing nominal flight operation and pilot healthy, off-nominal flight operation and pilot healthy, nominal flight operation and pilot incapacitated, and off-nominal flight operation and pilot incapacitated, based on the conditions of the flight environment and the ability state of the remote pilot. By the cooperation of airborne automatic/autonomous system and the remote pilot, the RPO mode could realize the organization of the flight process from the take-off airport to the destination airport, covering all flight phases, flight environment, meteorological condition, airport requirements, system capabilities and states. It can compete the decision-making ability, efficiency, effectiveness of the current dual-pilot mode, and realize cost, credibility, and security goals.

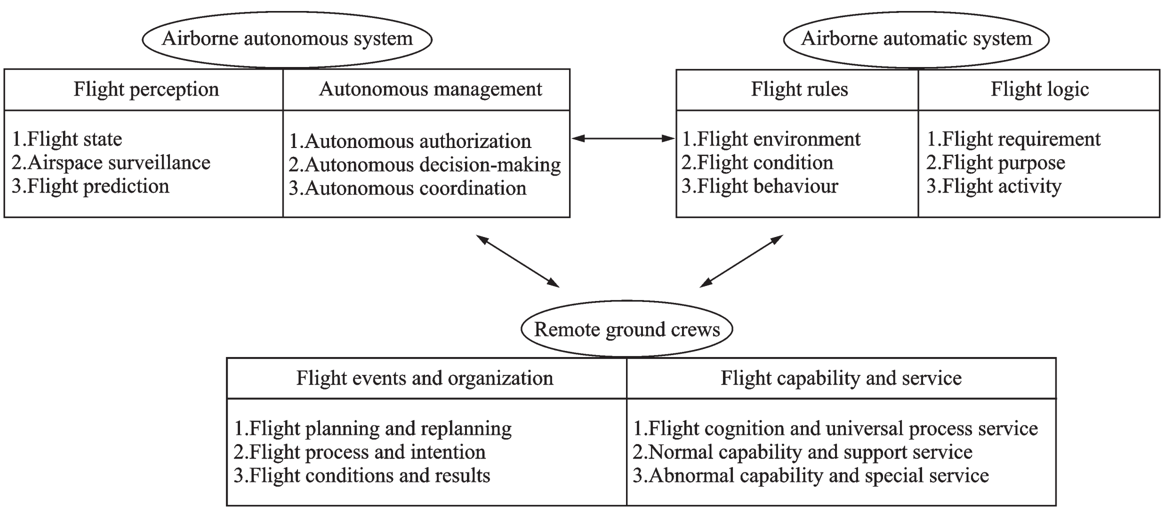

Fig.2 Organizing architecture of RPO mode for commercial aircraft

2.2 Air-ground collaboration system architecture

The main feature of the commercial RPO mode which is different from the dual-pilot mode is that it is based on the air-ground cooperative control organization mode with the air-ground data link. The RPO mode needs to rely on the ground remote pilot, in collaboration with the airborne automatic and autonomous system, to accomplish the flight, since there are no pilots on board. Moreover, the remote pilot is fully responsible for the safety of the flight under the condition that the air-ground data link is running normally. The ground remote pilot use the station to implement remote flight planning and re-planning, task planning, organization and management, which could effectively improve aircraft's capabilities of flight operating and processing, and achieve ground flight organization and management. The airborne automatic system could realize flight environment information collection, flight status organization and flight operation execution, as well as flight information perception and flight system management so as to reduce the need for pilot's capacities in controlling airborne equipment, and accomplish the nominal flight.

The airborne autonomous system can realize autonomous flight in the airspace authorized by ATC, including real-time trajectory optimization, real-time path adjustment within authorized airspace in the event of some emergency, etc., and there is no need to apply in advance to ATC, and just to send the changed route information to it. For example, during an approaching phase where the pilot's workload is heavy, the airborne autonomous system can sense the flight status of surrounding aircraft through the ADS-B system and obtain the flight path of them from ATC at the same time, then autonomously accomplish the flight based on the optimal track (for example, the lowest fuel consumption) and the aircraft's current status within the authorized airspace, and send the path information to ATC in real time to accomplish the autonomous flight. With the support of the airborne autonomous system, there is no need for the remote pilot controlling the aircraft most of the time, but only to monitor the ground thereby reducing the workload.

The air-ground data link provides high-speed data transferring to improve air-ground cooperation capabilities, support flight environment perception and task decision-making. The air-ground cooperation system architecture in RPO mode for commercial aircraft is shown in Fig. 3.

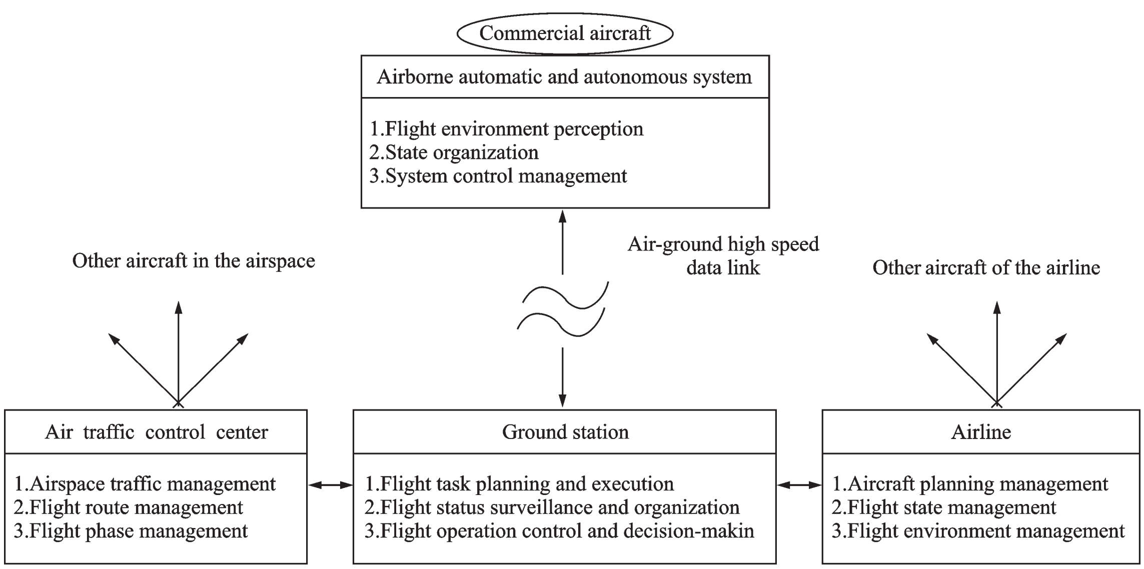

Fig.3 Air-ground cooperation system architecture in RPO mode for commercial aircraft

2.3 Air-ground collaborative decision-making mode

The important goal and premise of RPO mode for commercial aircraft is to cover the flight control process and safety guarantee of the current dual-pilot mode. An important feature of the dual-pilot mode is the human-human interactive decision-making mode, that is, the independent perception and interactive cognitive decision-making of the captain and the first officer, while the important feature of RPO mode is the human-machine interactive decision-making mode that means the ground remote pilot's abilities and cognition make interactive decisions with the rules and logic of machines (airborne automatic systems and airborne autonomous systems). Moreover, RPO mode requires collaborative decision-making with the machine based on whether the aircraft is nominally flying and whether the ground remote pilot is in normal abilities.

2.3.1 Air-ground collaborative decision-making architecture

According to whether the pilot participating in the flight decision-making, the aircraft flight process is divided into nominal flight process that does not require pilot decision and off-nominal flight process that require pilot decision. In a nominal flight that does not require pilot's participation in decision-making, the flight can be accomplished by the airborne automatic system or the airborne autonomous system, thereby ensuring, for example, the compliance of the actual flight path with the predicted flight path including error tolerance, and the compliance of flight operation and flight envelope. This can reduce the workload of the remote pilot. Healthy or incapacitated piloting ability is a description of whether the ground remote pilot is capable of controlling the aircraft during the flight, like the process when the ground remote pilot becomes ill or leaves post, or the system is maliciously operated.

The airborne automatic/autonomous system starts flying in the automatic piloting mode under the condition of nominal flight and the ground remote pilot has normal abilities. The remote pilot just need to accomplish relevant monitoring tasks. When the remote pilot is incapacitated as well as the nominal flight, the airline should dispatch another ground remote pilot to accomplish the surveillance of the aircraft. Under off-nominal flight, the ground remote pilot is responsible for the piloting and decision-making, and interacting with the air traffic controller through the ground network with the assistance of the airline dispatcher to accomplish off-nominal flight task.

The core technology of the RPO mode for commercial aircraft is to establish the human-machine interactive decision-making ability of air-ground collaboration, covering the current dual-pilot man-man interactive decision-making mode, as shown in Fig. 4.

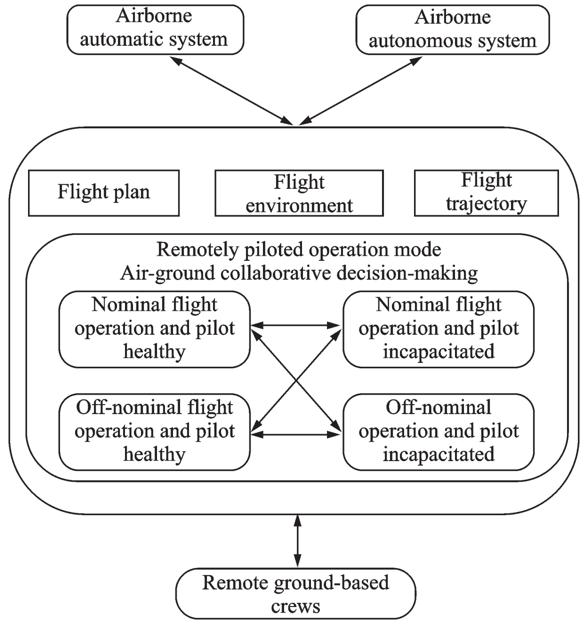

Fig.4 Air-ground collaborative decision-making architecture

2.3.2 Air-ground collaborative method

Since the ground remote pilot in the RPO mode is the only operator who controls the aircraft flight, his/her piloting ability and physical condition are important for safe flight. Ground intelligent monitoring equipment can be used to monitor the ground remote pilot's piloting specification in real time to determine whether the aircraft is in a normal piloting state. At the same time, the cognitive human-machine interface[14] is used to monitor the pilot's physical status in real time to determine whether the pilot is in a healthy state, whether the pilot's operation is normal and whether there is a malicious and hazardous piloting behaviour[15]. The last one is particularly important for the RPO mode. The ground surveillance system must contain the hazardous piloting judgment function. When the ground remote pilot is in a malicious and hazardous piloting state, the system will alert and notify the airline management department in real time to ensure flight safety.

Aiming at the pilot's piloting specification and physical status, the RPO mode for commercial aircraft can dynamically adjust the controller of the aircraft to ensure flight safety. As shown in Fig.5, it includes six situations, and the air-ground collaborative method is explained as follows.

	Nominal flight	Off-nominal flight
Remote pilot healthy	The first situation The airborne automatic and autonomous system executes control procedures to complete the flight mission and the remote pilot could just monitor the flight. Remote pilot has a complete control of the aircraft and is responsible for the safety, and the airline dispatchers can be responsible for the dispatch of multiple aircraft at the same time.	The second situation The remote pilot controls the aircraft and communicates with airlines, and air traffic controllers with the assistance of the airline dispatcher to complete the off-nominal flight. Remote pilot has a complete control of the aircraft and is responsible for the safety and the dispatcher must provide one-on-one assistance, acting as the "remote co-pilot".
Remote pilot incapacitated (passive)	The third situation The airborne automatic and autonomous system executes control procedures to complete the flight mission and the remote pilot could just monitor the flight. Remote pilot has a complete control of the aircraft and is responsible for the safety and the dispatcher must provide one-on-one assistance.	The fourth situation The backup remote pilot controls the aircraft and communicates with airlines and air traffic controllers with the assistance of the airline dispatcher, to complete the off-nominal flight. The backup remote pilot has a complete control of the aircraft and is responsible for the safety and the dispatcher must provide one-on-one assistance.
Remote pilot abnormal (initiative)	The fifth situation The ground monitoring system warns the remote pilot that the operation is abnormal, and if the malicious operation is continued, the system will cut off the current remote pilot control, and the airborne automatic and autonomous system executes control procedures to assist the backup remote pilot. The backup remote pilot has a complete control of the aircraft and is responsible for the safety and the dispatcher must provide one-on-one assistance.	The sixth situation The ground monitoring system warns the remote pilot that the operation is abnormal, and if the malicious operation is continued, the system will cut off the current remote pilot control, and the backup remote pilot controls the aircraft and communicates with airlines and air traffic controllers with the assistance of the airline dispatcher, to complete the off-nominal flight. The backup remote pilot has a complete control of the aircraft and is responsible for the safety and the dispatcher must provide one-on-one assistance.

Fig.5 Air-ground operation authorization of RPO mode

Input: Remote pilot's physical status P, flight type F, time threshold T

Initialization: Perform_flightMission = True

Algorithm description: While (Perform_flightMission):

If Remote pilot's physical status P = healthy ‖ flight type F = nominal flight, **then**

Do Airborne automatic and autonomous system executes control procedures to complete the flight mission

Do Remote pilot monitors the flight

Do Airline dispatcher one-to-many assistance

Elseif Remote pilot's physical status P = healthy ‖ flight type F ! = nominal flight, **then**

Do Remote pilot takes charge of the aircraft

Do Airline dispatcher provides one-to-one assistance

Elseif Remote pilot's physical status P = incapacitated, then:

Do Ground surveillance system detects and confirms

Do Transfer control to the airborne automatic and autonomous system

Do Airborne automatic and autonomous system handles the emergency situation

Do Backup remote pilot takes charge of the aircraft (backup = true)

If Access time $t \leqslant$ time threshold T ‖ backup = true

Do Backup remote pilot takes charge of the aircraft

Do Airline dispatcher one-to-one assistance

Else

Do Start the prefabricated emergency procedure based on the flight process and stage

End while

The six situations shown in Fig.5 are based on the premise that the communication of air-ground data link is normal. If the communication is not smooth, the ground remote pilot cannot normally control the aircraft and is not responsible for the flight safety. At this time, the aircraft automatic system will take control of the aircraft, under the guidance of the control program, and automatically start the emergency landing planner program. It will automatically find the nearest airport in the navigation database, and use ADS-B to send out the emergency code to make other aircraft. The aircraft accomplish the emergency landing process in accordance with the automatic program settings.

3 Modeling of RPO Mode

In this part, we model the six situations mentioned above, establishing the collaborative mode among the airborne automatic/autonomous system, remote ground-based crews and ATC. Taking airport surface operation as an example, we study the organization of airport surface traffic process, model the airport surface operation process, and finally analyze and compare the advantages/disadvantages between RPO mode and the current dual-pilot mode from the perspectives of time[16] and operation coverage.

3.1 Modeling of authorization situation

Based on flight types and pilot's piloting specification and physical status, there are six authorization situations in RPO mode, as shown in the Fig.5.

We take the fifth situation as an example. When the remote pilot is in an abnormal piloting state (hazardous operating subjectively) and the aircraft is in the nominal flight process, the ground surveillance system detects the malicious operation and warns the remote pilot that the operation is hazardous. If the malicious operation is continued, the system will cut off the current remote pilot's control and transfer it to the backup remote pilot. At this time, the airborne automatic and autonomous system executes the control procedures to control the aircraft, and the backup remote pilot monitors the flight process and is responsible for the flight safety.

Moreover, the dispatcher must provide one-on-one assistance to the aircraft, and other aircraft previously assigned by him/her will be transferred to other dispatchers of the airline. The dispatcher's role at this time is the "remote co-pilot" of the aircraft, and is responsible for communicating with airlines and air traffic controllers to assist the backup remote pilot. The entire process described above is shown in Fig.6.

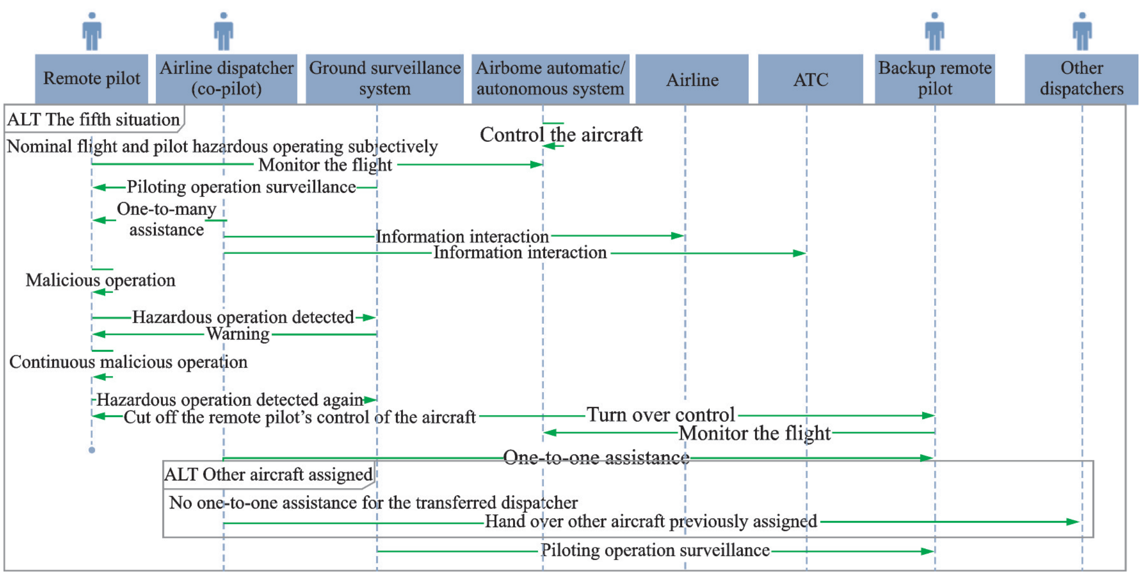

Fig.6 Sequence of the fifth situation

3.2 Modeling of airport surface operation

Airport surface operation is an important part of CRPA's flight process. In the composition of flight infrastructure, such as airlines, airspaces, satellites and airports, airport resource (terminal airspace) capability and surface operation effectiveness are the core capabilities and important components of CRPA flight process organization and operation. Especially in metropolitan airports with high-density take-offs and landings, the capacity, efficiency, certainty and safety of the airport surface operations affect not only the aircraft's objective demand. but also the transport capacity and efficiency of the whole region.

Airport surface management is established on the basis of airport surface capability, providing guidance, surveillance and management of surface operation through the cooperation among remote ground-based crews, the airborne automatic/autonomous system and ATC. Therefore, airport surface traffic operation and organization provide airport surface guidance system, establish taxiing process monitoring, construct and implement traffic situation decision-making management[17], enhance aircraft taxiing efficiency, airport runway throughput, improve airport arrival and departure flow, and realize airport surface traffic integrating organization and management.

Based on the above organizational structure of airport surface traffic process, the traditional dual-pilot operations will be assigned to the remote pilot, the airline dispatcher and the airborne autonomous/automatic system, to establish the cooperation mode among remote ground-based crews, airborne automatic and autonomous system and ATC. First, we establish the status diagram of CRPA from preparations for take-off to final taxiing, as well as the emergency that needs change flight plan, to describe status transition information, as shown in Fig. 7.

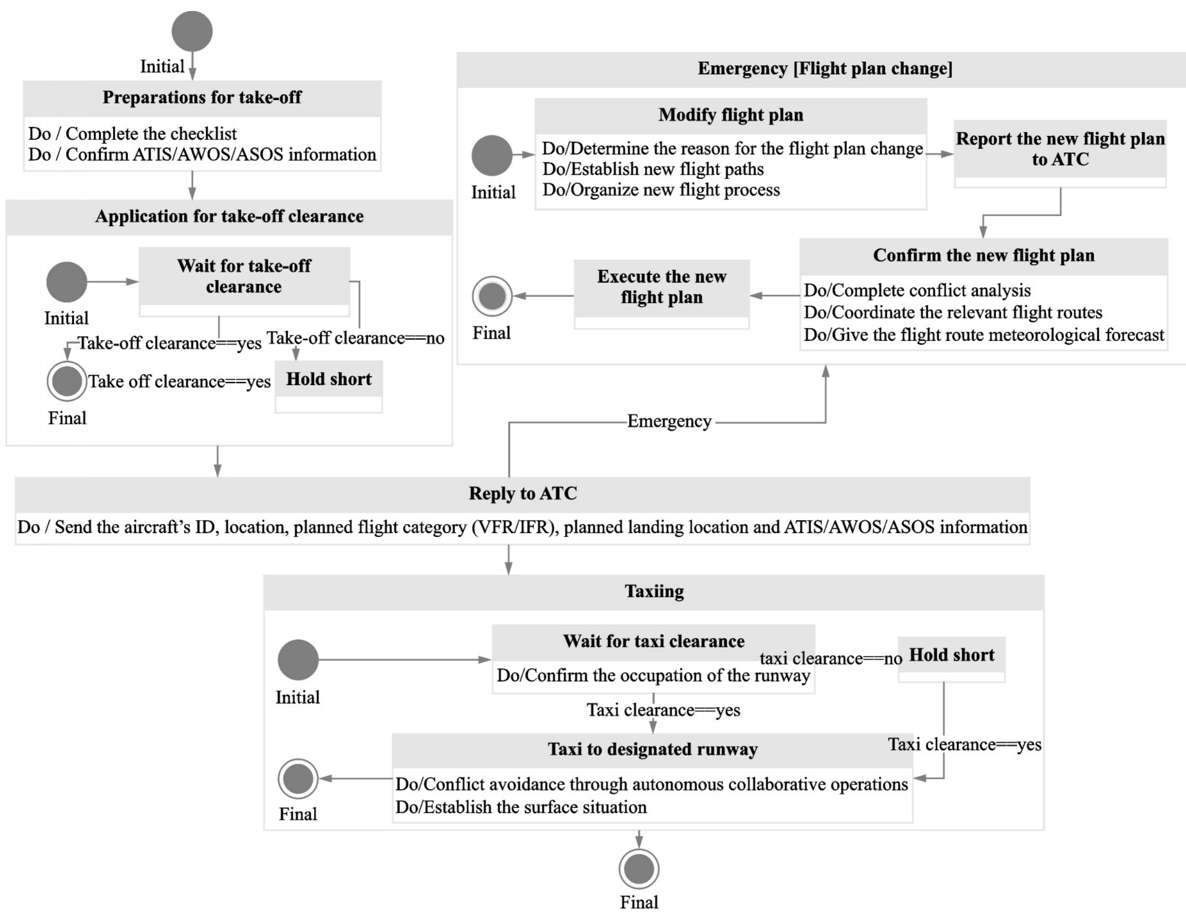

Fig.7 Status of CRPA in airport surface operation

Based on the above description for airport surface operation process under RPO mode, combined with the air-ground collaborative decision-making architecture which involves a tripartite collaboration, remote ground-based crew, airline and ATC, and with the support of airborne automatic/autonomous system, the remote ground-based crew could accomplish surface operation process in the ground station through C2 link. At this time, the airline dispatcher, as the "co-pilot" of the aircraft, will take charge of surface operation monitoring and provide one-to-one assistance, so that the remote pilot could focus on piloting. With the support of ADS-C and surface trajectory-based operations(STBO), in case of conflicts during taxiing, the airborne autonomous system negotiates avoidance autonomously to reduce the stop and start frequency of the aircraft, so as to reduce the workload of the remote ground-based crew and to improve efficiency.

When the original route needs to be changed due to weather hazards, the remote pilot proposes the change according to the new weather forecast provided by ATC. The airline dispatcher, as the co-pilot, will receive the current flight status, determine the reason for the change of flight plan, organize new flight process, establish new flight paths, and identify new flight objectives based on suggestions proposed by the remote pilot, and finally submit it to ATC. ATC accomplishes the airspace conflict analysis, provides flight route meteorological forecast, coordinates relevant flight routes and determines the new flight management based on the new path, then sends it to airborne automatic system and the remote pilot. With the one-on-one assistance of the airline dispatcher, the remote pilot determines the latest flight plan and transmits instructions to the airborne automation system via C2 link. The entire process described above is shown in Fig. 8.

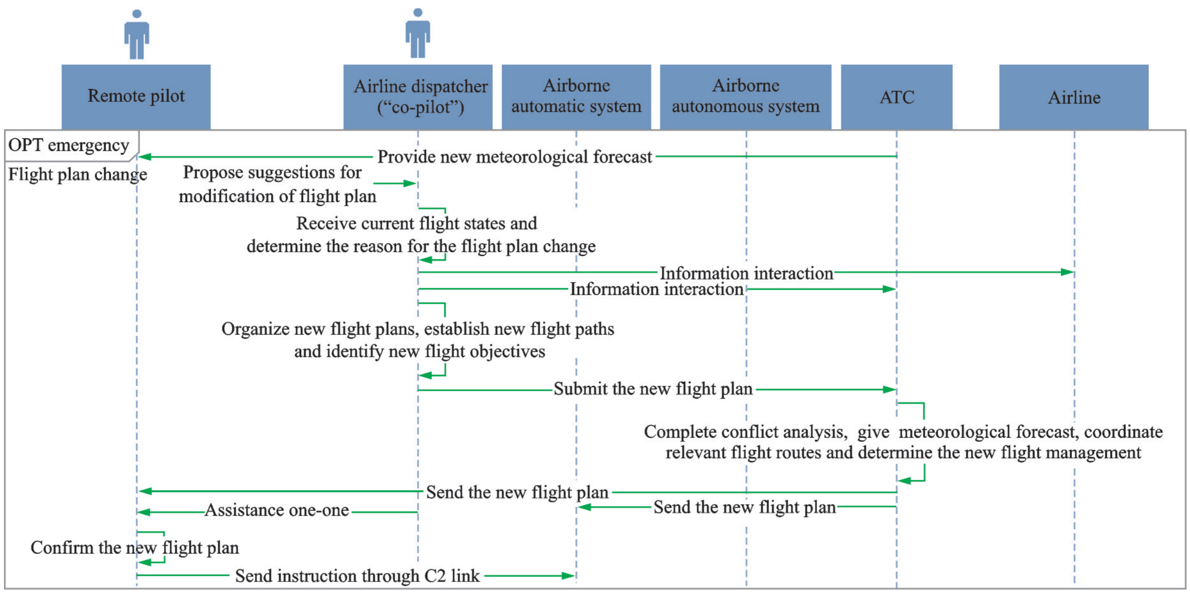

Fig.8 Sequence of flight plan change

3.3 RPO mode and dual-pilot mode comparison

In order to accelerate the integration of CRPA into the existing ATC system and minimize the effects on the existing ATC's working mode and information processing program, the communication method between CRPA and ATC system is that CRPA works as a repeater, which is the same as that of manned aircraft. In this method, the amounts of communication time between remote pilot and ATC will increase (defined as 2 s), among which the time for passing through C2 link is defined as 1.5 s, and the time for passing through the air-to-air data link is defined as 0.5 s. For example, the pre-flight inspection under RPO mode is applied by a remote pilot. The airborne automatic system conducts the pre-flight equipment inspection according to the checklist, and then transmits the results to ATC through air-to-air data link. The airborne automatic system takes about 10 s for inspection and data transferring takes 0.5 s. Under the traditional dual-pilot mode, the checklist is manually accomplished, and costs 2 min, and the pilot, the co-pilot, and ATC are required to participate at the same time, which will increase the workload of all the participations.

If the off-nominal emergency occurs during the flight, the remote pilot, with the assistance of the airline dispatcher, will take CRPA as a communication relay node to communicate with the air traffic controller. The advantage of this is that CRPA's airborne automatic/autonomous system could also accomplish communication task with ATC or airline even if C2 link is lost, as well as accomplish the emergency processing procedure in an automatic and autonomous manner.

We take the pre-flight inspection as an example. Operations under the traditional dual-pilot mode will be re-assigned to the airborne automatic/autonomous system, the remote pilot and the airline dispatcher to establish a collaborative mode, which basically covers the flight operations of the dual-pilot, as shown in Figs. 9, 10. In addition, we calibrate each operation and the response time over different communication links, and then accumulate the time. The time comparison for each step is shown in Fig. 11. It is found that the whole process costs 5 min and 20 s in the dual-pilot mode, while only 2 min and 54 s in RPO mode. It can be seen that when the airborne automatic system replaces some functions of the traditional co-pilot, it can shorten about 48% of the flight operation time in pre-flight inspection and greatly improve the pilot operation accuracy.

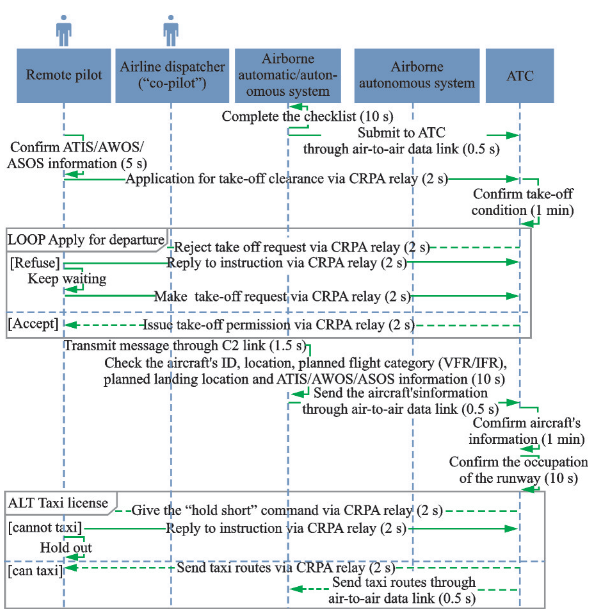

Fig.9 Pre-flight inspection of RPO mode

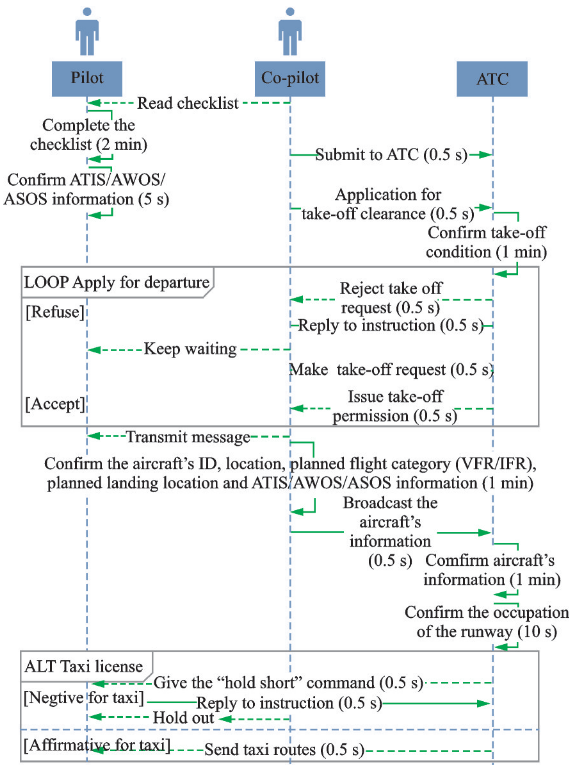

Fig.10 Pre-flight inspection of dual-pilot mode

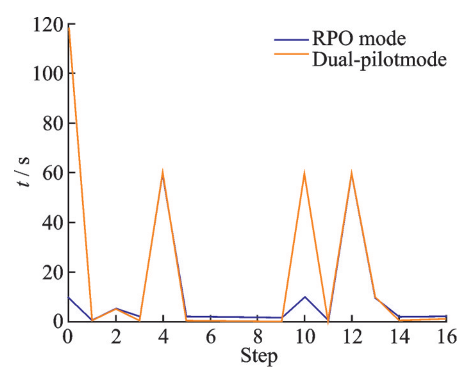

Fig.11 Operation and response time comparison

4 Conclusions

This paper describes the system architecture for CRPA system and its components. We study the air-ground collaboration system architecture of RPO mode, and propose an air-ground collaborative decision-making mode. Finally, we model different situations based on flight types and pilot's piloting specification and physical status. Taking surface operation as an experimental example, we compare the advantages and disadvantages between RPO mode and the current dual-pilot mode from the perspectives of time and operation coverage, and draw conclusions that RPO mode can basically cover the flight operations of the dual-pilot, improve the accuracy of pilot operations and greatly reduce response time.

References

[1] MCLUCAS J L, DRINKWATER F J, LEAF H W. Report of the President's task force on aircraft crew complement[R].USA: USA Government, 1981.

[2] LIM Y, BASSIEN-CAPSA V, RAMASAMY S, et al. Commercial airline single-pilot operations: System design and pathways to certification[J]. IEEE Aerospace and Electronic Systems Magazine, 2017, 32(7): 4-21.

[3] WANG M, XIAO G, WANG G Q. Research on single pilot operation (SPO) mode technology[J]. Acta Aeronautica et Astronautica Sinica, 2020, 41(4): 323541. (in Chinese)

[4] WASHINGTON A, CLOTHIER R, NEOGI N, et al. Adoption of a Bayesian belief network for the system safety assessment of remotely piloted aircraft systems[J]. Safety Science, 2019, 118: 654-673.

[5] STANTON N A, HARRIS D, STARR A. The future flight deck: Modelling dual, single and distributed crewing options[J]. Applied Ergonomics, 2016, 53: 331-342.

[6] MACHUCA J P, MILLER M E, COLOMBI J. A cognitive task analysis-based evaluation of remotely piloted aircraft situation awareness transfer mechanisms[C]//Proceedings of International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support. New Orleans, USA: IEEE, 2012: 179-182.

[7] ZIELIŃSKI T, MARUD W. Challenges for integration of remotely piloted aircraft systems into the European sky[J]. Scientific Journal of Silesian University of Technology: Series Transport, 2019,102: 217-229.

[8] THOMAS E, BLEEKER O. Options for insertion of RPAS into the air traffic system[C]//Proceedings of the 34th Digital Avionics Systems Conference (DASC). Prague, Check: IEEE/AIAA, 2015: 5B4-1-5B4-14.

[9] CAPELLO E, DENTIS M, GUGLIERI G, et al. An innovative cloud-based supervision system for the integration of RPAS in urban environments[J]. Transportation Research Procedia, 2017, 28: 191-200.

[10] JIANG T, GELLER J, NI D H, et al. Unmanned aircraft system traffic management: Concept of operation and system architecture[J]. International Journal of Transportation Science and Technology, 2016, 5(3): 123-135.

[11] LIU Y, SUN J Z, LI H. Supervision and norm discussion on civil unmanned aerial vehicle[J]. Journal of Nanjing University of Aeronautics & Astronautics, 2017,49(S1): 152-157. (in Chinese)

[12] EVANS S, RADCLIFFE S A. The annual incapacitation rate of commercial pilots[J]. Aviation, Space, and Environmental Medicine, 2012, 83(1): 42-49.

[13] NEIS S M, KLINGAUF U, SCHIEFELE J. Classification and review of conceptual frameworks for commercial single pilot operations[C]//Proceedings of the 37th Digital Avionics Systems Conference. Piscataway, NJ, USA: IEEE Press, 2018.

[14] SPRENGART S M, NEIS S M, SCHIEFELE J. Role of the human operator in future commercial reduced crew operations[C]//Proceedings of the 37th Digital Avionics Systems Conference. London, UK: IEEE/AIAA, 2018: 1-10.

[15] SUN R, ZHANG Y C, HU M H. Fuzzy logic based UAV suspicious behavior detection[J]. Transactions of Nanjing University of Aeronautics& Astronautic, 2016, 33(6): 721-725.

[16] TIAN Y L, WANG C Q, XIONG P S, et al. Structured simulation platform architecture for fighter cloud operations[J]. Journal of Beijing University of Aeronautics and Astronautics, 2019, 45(10): 1938-1945. (in Chinese)

[17] RILEY J M, ENDSLEY M R. Situation awareness in Hri with collaborating remotely piloted vehicles[C]// Proceedings of the Human Factors and Ergonomics Society Annual Meeting. [S.l.]: SAGE, 2005: 407-411.

Acknowledgements This work was supported by the National Program on Key Basic Research Project (No. 2014CB744903), the National Natural Science Foundation of China (Nos. 61973212, 61673270), the Shanghai Industrial Strengthening Project (No. GYQJ-2017-5-08), the Shanghai Science and Technology Committee Research Project (No. 17DZ1204304), and the Civil Aviation Pre-Research Projects and Shanghai Engineering Research Center of Civil Aircraft Flight Testing. The authors would like to acknowledge the following people for their assistance: GONG Ke, XUE Zoutao, WU Xia, LIU Xiaoniao, QI yuqian, all with the Advanced Avionics and Intelligent Information Laboratory (AAII), School of Aeronautics and Astronautics, Shanghai Jiao Tong University.

Authors Ms. **LUO Yue** received her B. S. degree in Automation Engineering from Nanjing University of Aeronautics and Astronautics Nanjing, China, in 2019. She is currently a postgraduate at School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai, China. Her research interests include remotely piloted operations (RPO) mode for commercial aircraft and flight test data processing.

Dr. **WANG Miao** received B.S. degree in information management and information technology form Shengda Economy Trade College of Zhengzhou University in 2004, M.S. and Ph.D. degrees in computer science and technology from the Northwestern Polytechnical University in 2008 and 2013, respectively. From February 2013 to April 2017, he had been an engineer of China Aeronautical Radio Electronics Research Institute, and the Science And Technology On Avionics Integration Laboratory. He joined in Shanghai Jiao Tong University in July 2019, where he is an assistant research fellow of the School of Aeronautics and Astronautics and the Advanced Avionics and Intelligent Information (AAII) Laboratory. His research is focused on avionics system, data mining and safety.

Author contributions Ms. **LUO Yue** established the model of remotely piloted operations (RPO), conducted the analysis and wrote the manuscript. Dr. **WANG Miao** designed the architecture of commercial remotely piloted aircraft system and provided valuable suggestions on the revision and improvement of the manuscript. Prof. **XIAO Gang** participated in the coordination of the study and reviewed the manuscript. Prof. **WANG Guoqing** contributed to the discussion and background of the study. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: ZHANG Bei)

商用飞机远程驾驶模式的概念架构

罗 悦，王 淼，肖 刚，王国庆

(上海交通大学航空航天学院，上海200030，中国)

摘要：随着民用航空客运量的不断增加和航空物流的快速发展，商用飞机远程驾驶(Remotely piloted operations, RPO)模式的研究受到了广泛的关注。远程驾驶模式通过构建机载自动/自主系统、远程地面机组和空中交通管制的三方协作架构来共同完成飞行驾驶决策。本文首先对商用远程驾驶飞机系统的组织架构及其组成部分进行了描述；然后建立了新型的空地协同决策模式，并根据飞行类型和远程飞行员的身体状况划分了六种不同的情况；最后，我们以机场场面运行过程为例，将机场场面运行过程进行建模并从时间和操作覆盖度的层面对比分析RPO模式和目前双人制机组之间的优缺点，分析得出RPO模式基本上能够覆盖双人制的飞行操作，可以提高飞行驾驶操作精度并在飞行前检查中缩短了48%的操作时间。通过上述内容研究，为我国商用飞机开展远程驾驶研究奠定了一定的技术基础。

关键词：远程驾驶模式；商用远程驾驶飞机；机载自动/自主系统；飞行过程