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THE STUDY OF UNMANNED AERIAL VEHICLE FLYING QUALITIES FLIGHT TEST METHOD BASED ON TIME-DELAY EVALUATION

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Abstract

With the rapid development of Unmanned Aerial Vehicle (UAV) technology, how to evaluate flying qualities of UAV based on time-delay has become the hot topic for engineers. It is known that time-delay of UAV is closely and directly correlated with flying qualities, which will affect not only the level of flying qualities evaluation, but also the performance of UAV. In this paper, the composition elements and the magnitudes of time-delay were analyzed and the definition of time-delay for UAV was proposed firstly. Then, in order to determine the relationship between time-delay and flying qualities, the control modes of UAV were introduced generally, including autonomous, semi-autonomous and remote control. Different control modes have different requirements on flying qualities and time-delay, especially flying qualities in remote control mode was strongly influenced by time-delay. According to the analysis of relationship between time-delay and flying qualities, criteria of objective and subjective evaluation for time-delay were given based a lot of data from ground tests and Modified Cooper-Harper Rating method for UAV was designed for UAV flying qualities evaluation, which consider UAV flying qualities including three basic elements: safety, task performance and degree of satisfaction. Moreover, in order to demonstrate the criteria, the closed-loop test mission were designed and implemented both in ground and flight test during UAV landing phase, when pilots landed UAV as well as evaluated time-delay and flying qualities. The flight test showed that the value of time-delay corresponds with evaluation of flying qualities, which indicates the validity of the proposed criteria for UAV flying qualities evaluation.

Keywords: Unmanned Aerial Vehicle, Flight Test, Time-Delay, Flying qualities, Evaluation Criteria

1. Introduction

With rapid development of UAV technology, the concept of UAV flying qualities is accepted by aviation after more research and flight tests of larger and medium UAV carried out. However, in term of safety, mission effectiveness and control load, Unmanned Aerial Vehicle (UAV) flying qualities is still to be developed, and its concept is almost the same with manned aircraft flying qualities. Also UAV flying qualities refer to the evaluation of operation satisfaction by UAV pilot/operator during the whole process of UAV mission and task completion [1]. However, due to composition characteristics of UAV, UAV flying qualities is unique, on which time-delay is one significant influence factor. Currently, UAV flying qualities is still under research and there are more research achievements about time-delay, but most of them are limited to how to measure and compensate time-delay. Although there are less research on relationship between time-delay and flying qualities of UAV and no UAV time-delay evaluation criteria based on flying qualities [2,3,4,5]. One reason is that the composition and control mode of UAV are different from manned aircraft, which makes the definition and measuring method of UAV time-delay are fundamentally different. At present a unified recognition has not still been formed in concept of UAV time-delay. The time-delay of data link is still considered to be equivalent to UAV time-delay, but there are not the same. Another reason is that magnitude of UAV time-delay is larger than manned aircraft because of data link, which causes that traditional flying qualities evaluation criteria of manned aircraft are not applicable for UAV time-delay evaluation. Therefore, how to evaluate UAV time-delay and how to define relation between time-delay and flying qualities are to be solved in order to alleviate operator's workload and to improve handling qualities in UAV flight test. In this paper, study both in theoretical analysis and flight testing is started to figure out these two questions mentioned above.

2. Definition of time-delay in UAV

2.1 Definition of Unmanned Aerial Aircraft Time-delay

The concept of UAV time-delay is related to the components of UAV and characteristics of flying qualities, so the first question is to define the composition of UAV time-delay and to analyze the relationship between time-delay and flying qualities, which is helpful for analysis of UAV flying qualities.

2.1.1 Composition of UAV Time-delay

Time-delay of unmanned aircraft system consists of many items, not only the latency from input of manipulator system to response of control surface, but also latency of data link, digital processing in computers, and so on. Comparing with latency of aircraft response, magnitude of data link time-delay is greater. Figure 1 is the composition diagram of time-delay in UAV. The total time delay is the sum of uplink latency, down link latency and processing in Ground Control Station (GCS) and UAV latency.

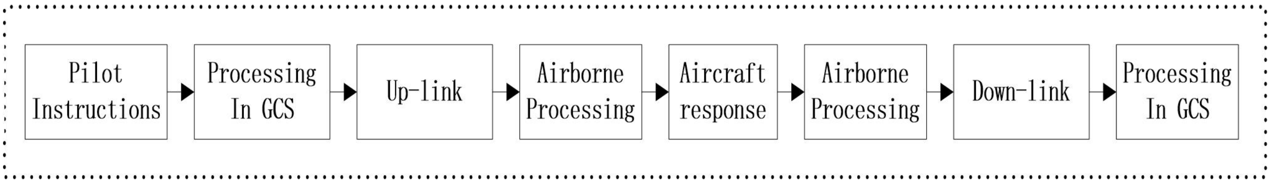

Figure 1 – Composition diagram of time-delay

2.1.2 Definition of Unmanned Aerial Aircraft Time-delay

Like definition of manned aircraft time-delay, time-delay of RPV reflects the relation in time-difference between input of order sent by pilot from GCS and display in screen of GCS down link from aircraft. For the remote control, this expression reflexes pilot's feeling of latency in aircraft motion after manipulation, which has approximation for large time-delay RPV control as well as less accurate. It is difficult to measure equivalent time-delay and the main method for measurement is depends on equivalent matching algorithm to calculating latency. For the RPV with large magnitude of time-delay, adaptive condition happens easily. Hence, a pre-knowledge hypothesis is proposed for time-delay of data link.

Taking longitudinal movement of manned aircraft as an example, pilot got feedback of pitch angular acceleration firstly during manipulation, but it is difficult to measure acceleration in flight testing. However, as the integral of angular acceleration, angular velocity refers to variation of angular acceleration directly, and angular speed is easy to measure and has high accuracy. Therefore, that is why using angular speed as main parameter to evaluate time-delay.

For remote piloted vehicle, pilot in GCS could not get feedback on change of angular speed, but get information about attitude instead. Hence, it is suggested to choose attitude as main evaluation indicator for time-delay. Meanwhile, from perspective of measurement and calculation, the most part of latency is led by data link, so it is not to emphasize precision of latency in aircraft. Considering all points mentioned above, the definition of time-delay in RPV is proposed as follows. The time-delay in RPV refers to time span from sending input of manipulating order by remote pilot in GCS to display of status of system in GCS via down linking after response of aircraft to input.

The composition of UAV includes the vehicle, GCS and data-link, which cause extra time-delay, so the study of UAV time-delay must clear and definite the composition of UAV. The time-delay of UAV is shown respectively in Figure 1. For UAV time-delay, the command instructions are going through so many links, such as processing in GCS, up-link transmission, onboard processing, aircraft response, airborne processing, down-link transmission, processing in GCS, and information got by remote pilot.

From Figure 1, it can be seen that：

- Comparing with manned aircraft, Time-delay of UAV contains transmission and processing of data-link.
- Time-delay measurement can be seen as one closed-loop for UAV, so time-delay evaluation criteria should reflect the closed-loop characteristics of aircraft.

In addition, the data link can be seen as a main contributor of UAV time-delay, including line-of-sight and beyond sight. Table 1 showed the components of UAV data link time-delay. It can be seen that the minimum of time-delay in line-of sight data link is 120ms. For satellite communication, the minimum of time-delay is 600 ms approximately. The data link of time-delay comprises signal transmitting, sending, encryption, decoding, signal synchronization, computation and so on. From the view of the order of magnitude, time-delay of data-link magnitude is nearly equal or larger than the time-delay of UAV. However, the time-delay during operation for pilot in ground control station includes data-link, control system and aircraft time-delay, the combination of which is larger than time-delay of aircraft response.

Table 1 – Statistics of time-delay for UAV

Phase	Line-of-sight (LOS)		Satellite	
	Min(ms)	Max(ms)	Min(ms)	Max(ms)
sending	40.0	300.0	80.0	300.0
Signal transmission	0.2	3.3	239.0	281.0
Signal encryption	0.0	4.0	0	4.0
Signal compression	0.0	375.0	0	375.0
Error corrrection	0.0	1.5	0.0	1.5
Signal synchronizaiton	8.0	32.0	8.0	32.0
calculation	10.0	30.0	10.0	30.0
Up-link	58.2	370.8	337.0	648.5
Down-link	58.2	745.8	337.0	1023.5
Loop delay	116.4	1116.6	674.0	1672.0

2.2 The relationship between time-delay and flying qualities for UAV

2.2.1 Time-delay of UAV under different control mode

Currently, the modes of control for UAV are generally divided into three categories according to degree of human interaction. The first kind of control mode is remote control mode which is the most fundamental flight control mode and provides a directly link between GCS and aircraft. Second one is semi-autonomous control mode. And the last one is autonomous control mode which represents the direction of UAV development and needs high level of artificial intelligence. There are different flying qualities requirements for different control modes, so is requirements of time-delay.

Autonomous (semi-autonomous) control mode: fully autonomy refers to no human intervention and all actions are performed by UAS itself, while pilot just act as a supervisor. Pilot does not give real-time and continuous operation, which do not form a real time closed-loop control. So there is controversy about whether time-delay in autonomous control mode belongs to the field of flying qualities or not. But the scale of time-delay has direct impact on completion of task, and especially discrete instructions are send to manipulate the aircraft. Hence, it is suggested that time-delay evaluation in autonomous and semi-autonomous control mode should be confined to qualitative evaluation.

Remote control mode: this mode is similar to manned aircraft control. Remote control pilot operates the system and uploads control instructions, and then the vehicle responds normally and transfers state to GCS, all of which are completed in closed-loop operation by remote pilot. Generally, remote control mode is designed as emergency mode, which is used to ensure UAV flight safety and recovery when the main control mode disables or appears large deviation. According to contrastive analysis, time-delay evaluation could represent the characteristics of UAV flying qualities. Hence, the research focuses on time-delay under remote control mode in this paper as well as the relationship between time-delay and flying qualities.

2.2.2 Time-delay meaning under remote control mode

It can be seen that time-delay of remote control UAV reflects the time relationship between pilot in GCS sending commands and flight status down-link to GCS. For task under remote control mode, the definition of time-delay reflects that pilot feels the delay of aircraft response after operation, and accuracy of time-delay measurement is poor. For remote control UAV with larger magnitude of time-delay, mismatch of equivalent system occurs easily. Hence, a priori assumption should be proposed for data-link time-delay.

Taking longitudinal maneuver of manned aircraft as an example, during operation, the direct feedback to pilot is the change of pitch acceleration, due to difficult to measure acceleration during flight test. And angular velocity, which is the result of angular acceleration integral, could reflect the change of angular acceleration. Angular velocity is easy to measure and has high accuracy, so it is practical to choose angular velocity to evaluate time-delay. That is why to choose angular velocity as evaluation index for UAV time-delay.

For remote piloted UAV, pilot could not feel the change of angular acceleration directly, but the change of aircraft attitude. Therefore, it is recommended that attitude could be used as the main index for time-delay evaluation. Meanwhile, from the perspective of measurement and computation, the most of time-delay is caused by data link. There is no need to emphasize the accuracy of time-delay for the aircraft itself. In conclusion, the definition of UAV time-delay could be defined as follows. The time-delay is refers to time span from sending operation instructions by remote pilot in GCS to display of status of UAV in GCS via down linking after response of aircraft to instructions. According to the definition and meaning of time-delay, it is suggested to choose step maneuvers in three directions, longitudinal, lateral and directional step.

3. UAV time-delay evaluation criteria

The flying qualities generally include objective and subjective evaluation criteria. Objective evaluation criteria have specific quantitative index while subjective evaluation criteria are based on the qualitative assessment of pilot. It is known that flying qualities evaluation criteria are qualitative requirements originally. In the beginning of development of flying qualities, the initial requirement is that an everyman could implement accurate control in a reasonable length of time when structure and operation of aircraft are simple enough. For UAV, there is less flight test data and qualitative evaluation for analysis currently and there is no definitive quantitative evaluation criteria for some certain flight test subjects. Hence, combining quantitative index with qualitative assessment is the main way for UAV flying qualities evaluation. In this section, time-delay evaluation criteria are proposed on the basis of subjective and objective evaluation comprehensive evaluation.

3.1 Objective evaluation criterion

In order to determine the evaluation indicator of time-delay quantification, a ground closed-loop test was design using UAV and simulator. UAV pilot rectify a deviation of landing in ground simulation environment, which is rate control mode. Also, in ground closed-loop test system, the range of time-delay is 310-610 ms, which can be set according to the situation. During flight, the range of time-delay located between 450 ms and 500 ms. Table 2 showed the evaluation of UAV pilot in ground test.

From the evaluation of UAV pilots, it can be concluded that when time-delay exceeds over 400ms, the workload of UAV pilots would increase. Hence, during landing phase, 400ms is unacceptable for operation. Currently, the value of time-delay is considered as the same in longitudinal, lateral and directional directions due to tests.

Additionally, different mission has different requirement on time-delay. For example, payload operation may cause the magnitude of time-delay going beyond the value shown above in remote control mode. Besides, when response type changes, the workload caused by time-delay may change accordingly, and then flying qualities scale rating will be affected. In this paper, the time-delay of different response in remote control mode was analyzed and the evaluation criteria were suggested.

Table 2 – Comments about closed-loop test from pilots

No.	Time-delay(ms)	Closed-loop operation
1	290	Task can be finished
2	352	Task can be finished, but need more mental stress
3	406	Hard to finish precise landing under large Disturbance, more probability for oscillation
4	452	Disturbance causing Coupling oscillation, difficult finish to landing
5	508	Coupling oscillation, pilot cannot finish normal landing
6	581	Hard to finish precise heading
7	635	More difficult to finish landing (6 times unsuccessful landing)

3.2 Subjective evaluation criterion

Subjective evaluation use structure and form of Cooper-Harper rating scale in manned-aircraft as a reference, which include mission performance, UAV safety and security, workload and so on qualitative evaluation. Among these elements, safety refers to stability and controllability of UAV mission performance considers the ability to accomplish task under disturbance. Figure 2 shows modified UAV qualitative Cooper-Harper rating scale evaluation. Taking three elements of flying qualities in account, the modified Cooper-Harper rating scale are divided into three levels: safety, mission performance and satisfaction requirement.

3.2.1 Safety Requirements

First level is safety requirement, the purpose of which is to judge whether the UAV is safe. Safety is the basic requirement. If safety requirement is not meet stability requirement, then scale rating of flying qualities is 10. If UAV is stable and complete mission successfully, the next step is to evaluate if the mission performance is meet the requirement.

3.2.2 Mission Performance Evaluation

If UAV cannot accomplish the task, the mission performance cannot meet requirement, drawback should be considered. There are three conditions about drawback. Firstly, there is big flaw, and under certain disturbance UAV is controllable. Furthermore, under some disturbance, UAV can execute instructions. Moreover, without disturbance, control instructions can be followed by UAV.

3.2.3 Satisfaction Evaluation

If task performance meets related requirements, satisfaction assessment should be rated, which is divided into satisfaction and dissatisfaction. According to Cooper-Harper rating scale theory, there are three levels for dissatisfaction. The first level is very objectionable but tolerable deficiency, so the system has adequate performance without certain disturbance circumstance. The second is moderately objectionable deficiency, and the system has adequate performance under certain disturbance. The third one is minor but annoying deficiency, and the system has desired performance without disturbance.

For satisfaction, there are also three levels. Firstly, there is minor deficiency and the system has desired performance in certain disturbance conditions. Secondly, there is small deficiency, so the system has desired performance under certain boundary or disturbance conditions. Thirdly, there is no deficiency, so the system has desired performance in whole flight envelope.

4. Flight Test Demonstration and Application

4.1 Flight test task design

In order to demonstrate the time-delay evaluation criteria applied on the landing phase, flight test task is designed and on reconnaissance UAV is selected as the test drone, which has two control modes, autonomous and remote control. And during landing phase, rate control was used under remote control mode.

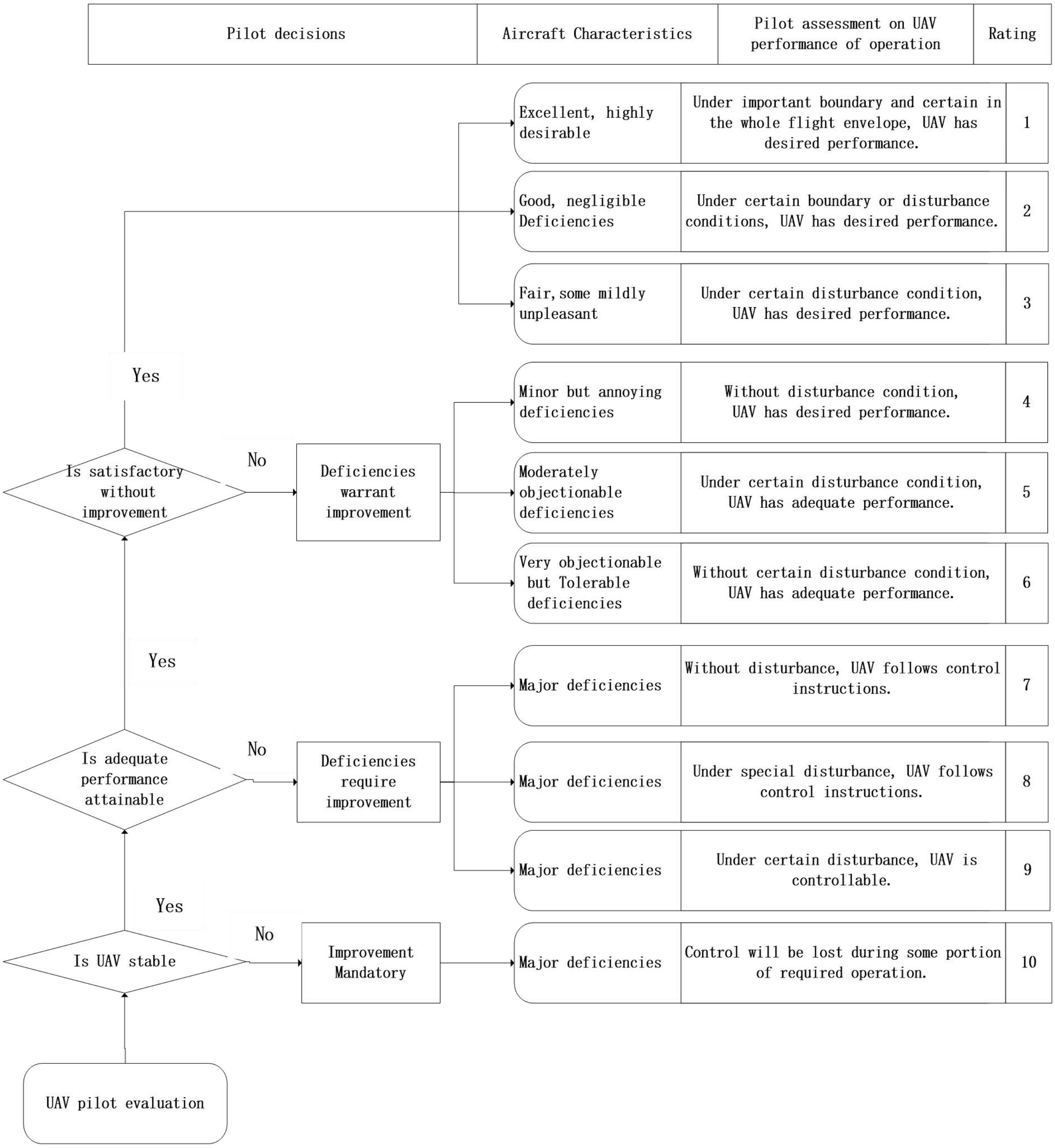

Figure 2 – Modified Cooper-Harper rating scale for UAV

4.1.1 Open-loop task: impulse and step operation in remote control mode

Considering mission requirements, remote control mode is usually used in line-of-sight during landing operation. So impulse and step maneuvers would be carried out in line-of-sight and landing configuration in open loop task.

4.1.2 Closed-loop: pilot control drone landing under remote control mode

In UAV flight test, pilot and aircraft are separated due to no pilot on board. Therefore UAV pilot could not feel aircraft state and working conditions of aircraft and sub-systems as their counterpart, manned aircraft pilot. When malfunction occurs, UAV pilot could not perceive, handle or mitigate unsafe flight condition immediately and effectively. Especially in landing during flight test, timely detection and treatment are the key point if there is exceptional situation, all of which are more dependent on careful test design, safety analysis and emergency disposal. Once design defect was found in control law, emergency reserve plan, and test plan and so on, risk is high due to limited disposal capability for UAV itself and pilot.

Hence, manual remote control mode and go-around before touchdown was proposed in flight test design, which could reduce the risk. And this test method could be called manual simulated landing. During landing, UAV remote pilot control the vehicle to align heading, descend and so on. During descending, step maneuvers in three directions are completed to examine time-delay. In order to avoid and reduce risk, go-around was executed before landing.

4.2 Flight test Results analysis

Through a lot of open-loop tests, time-delay is measured for on certain type of UAV. Table 3 shows time-delay in longitudinal direction, which indicated time-delay for this type of UAV in longitudinal direction is about 400 ms approximately. Evaluations of UAV pilots indicate that under line-of-sight the magnitude of time-delay is small, and maneuver in open-loop test is easy to complete but operation like rectifying a deviation during landing is hard to execute.

Table 3 – Statistics of longitudinal time-delay for UAV

No.	Time-delay(ms)	No.	Time-delay(ms)
1	405	11	375
2	390	12	405
3	392	13	408
4	440	14	395
5	445	15	420
6	406	16	315
7	404	17	450
8	407	18	455
9	356	19	472
10	359	20	503

Figure 3 illustrates the curve of landing and go-around. UAV enters the glide path form height of 400 m. In 400 m flight height, altitude holding are carried out, UAV pilot operate slowly and gently. Heading direction and attitude is kept stable, and the pitch angular is 5°. After 100 sec, UAV glide. When 150 sec, speed, altitude and attitude changed, UAV pilot couldn’t ensure gliding stably. The operation is frequently in longitudinal and lateral direction.

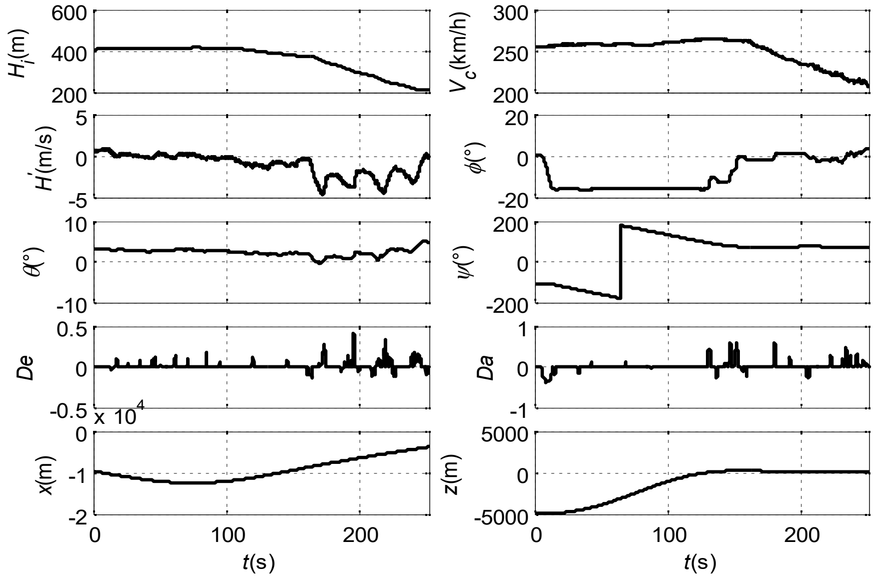

Figure 3 – Simulated approach and go around in remote piloted control mode

After flight test, comments from pilot show that during the whole process of flight test, UAV pilots evaluate high workload, difficult to keep attitude and heading, and could not land effectively and safely. Pilot use modified Cooper-Harper rating scale for UAV above to rate for every task. The time-delay statistics is shown in Table 4. The scale rating of flying qualities focus on 5-6 rates, which shows that UAV pilots must pay more workload, attention and compensation to finish mission in remote control mode. Consequently, accidents or incidents are occurred easily. The result of time-delay and evaluation are matching.

Table 4 – Pilot rating based on modified Cooper-Harper rate

Pilot	Longitudinal control	Lateral control
1	5	4
2	6	6
3	5	4

Additionally, malfunction under auto-control-mode happened, pilot take over the control of UAV using remote control mode. It is difficult for pilot to land UAV in remote control mode. From analysis, large magnitude of time-delay and data link interruption would cause many incidents during landing, which cause great loss.

5. Conclusion

As development of UAV, time-delay in operation has been becoming one significant problem in UAV operation. From perspective of flying qualities, the definition, the measurement method and evaluation criterion of time-delay for UAV were proposed according to the experience about manned-aircraft time-delay, which were verified in ground simulation and flight test. Results indicate that scope of time-delay is found and suggestions are given, which is helpful for study of UAV flying qualities regulation formulation and UAS design in future.

In addition, establishing a more perfect UAV flying qualities evaluation criterion is an effective way to guide UAV design and flight test. Meantime, flight test is the most direct and effective way for research of UAV flying qualities. In future, comprehensive flying qualities will be established to demonstrate the performance of UAV.

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