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STUDY ON THE DELAY OF UAV DATA-LINK BASED ON DARKROOM CALIBRATE-LINK METHOD

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ABSTRACT

The existing test method for properties of UAV data-link is usually the actual flight test or field "distance" test, which has long test cycle and difficulty for the extraction of test data. In view of this situation, we in this work adopted the data-link semi-physical simulation test platform based on darkroom calibrate-link method, establishing and analyzing the space natural decline model, atmospheric environment model, and aircraft attitude angle model that affecting the transmitting and receiving of signals. Meanwhile, the average delay from-terminal-to-terminal and the fluctuation of the average delay of the UAV under different MAC channel access protocols are discussed using the darkroom calibrate-link method. In order to improve the response characteristics of the UAV, time delay is compensated using optimal control methods, and the effectiveness of the compensation method is validated based on and the platform we built. The simulation results show that, the design of UAV data-link can be calculated by this theory, and the introduction of the optimal control method significantly improves the dynamic response characteristics of the UAV.

Keywords: *UAV Data-Link; Calibrate-Link Method; Compensation Method*

1. INTRODUCTION

Modern high-tech war possesses the nature of large-scale, complex battlefield environment and fewer casualties; UAV, with the advantages of small mass, mobility and environmental adaptability, reflects increasingly significance in actual combat. Typically, the information exchange between UAV and the outside world relies on the data-link; therefore, the application of the data-link largely determines the operational capacity of the UAV. According to the direction of data transmission, the UAV data-link can be divided into the uplink and downlink. Uplink mainly completes the sending and receiving of remote control command from ground station to the UAV; downlink mainly completes the telemetry data from UAV to ground station and the sending and receiving of infrared or television image [1].The performance of data-link directly affects the performance of the UAV. The existing test method for properties of UAV data-link is usually the actual flight test or field "distance" test. This test method with long test cycle (usually up to a few months), and difficulty for the extraction of test data, is very expensive.

During long-distance flight, a closed loop circuit is formed between the ground control station and the UAV by satellite relay. The transmission delay of UAV system is defined as the period of time from the input of an instruction to the generation of the corresponding output by the man-machine interface. In addition to the delay resulted from flight simulator (sampling delay, processing delay and data transmission delay), the delay of the UAV system also includes the delay caused by the inherent distance from the satellite, network nodes, and other equipment. The time delay is a necessity when information is transmitted through the data-link. The main cause of data-link communication delay contains communication message structure, communication speed, communication capacity, communication distance and multiple communication modes. In addition, there are hardware physical delay, such as sensor delay, operation delay and display delay. Terminal carriers of UAV data-link are generally in the state of relative fast motion, and its tracking, capturing, positioning and attacking objects aye time sensitive too; therefore, the effect of time delay on the combat effectiveness of the unmanned combat system is especially significant. In the frequency domain, delay is exhibited as the phase lag, which will worsen the system and even make the system unstable. There are many kinds of delay compensation methods for control systems, with the common characteristics of the guarantee of the stability of the system. For the UAV system, the operator observes the state of the air craft and the external scene through the human-machine interface in the ground control station; because of the system delay, the operator cannot grasp the real-time specific situation, but only obtain the image and status before the delay [2].Because of the delay system cannot generate real-time scene, the operator cannot realize real-time control on the UAV.

In view of this situation, in this paper we put forward the establishment of a data-link semi-physical simulation test platform, constituting the transceiver terminal of electromagnetic signals through a variety of simulators, and connected by the mathematical model into a closed loop. This platform can provide a simulation test environment for the UAV data-link, realize performance parameter (such as sensitivity, error rate) testing of telemetry and remote control systems, and can effectively shorten the development cycle and reduce test cost. In this paper, we examined the delay of UAV data-link based on this platform.

2. THEORETICAL MODEL OF THE DARKROOM CALIBRATE-LINK METHOD

2.1 Attenuation Model

Free-space is equivalent to rational space in vacuum state, where the propagation of the electromagnetic wave will not be obstructed nor be reflected. In actual cases, if the atmosphere is uniform medium, and both the relative dielectric constant and relative permeability are equal to 1, then the intensity of the ground reflection signal reaching the receiving antenna is negligible. However, as the propagation distance increasing, the energy will keep fading, which is due to the diffusion loss of the energy of the spherical wave during the propagation process [3].

The reception power of the receiving antenna is:

$$P_r(d)=\frac{P_tG_tG_r\lambda^2}{(4\pi)^2d^2} \tag{1}$$

Where, P_t is transmit power, P_r is receive power, G_t is the gain of the transmit antenna, G_r is the gain of the receive antenna, d is distance, λ is the signal wavelength. When $G_t=1$, $G_r=1$, free-space propagation fading PL can be calculated using the following formula:

$$PL=10\log\frac{P_t}{P_r}=10\log[\frac{(4\pi)^2d^2}{\lambda^2}] \tag{2}$$

Rainfall will bring signal attenuation to the performance of the radio system; meanwhile the scattering effect due to rainfall will cause inter-system interference. Under uniform rainfall conditions, the calculation of clouds and rain attenuation is relatively simple; but in most cases, rainfall is not uniform in time and space, and the unevenness of the cloud/rain medium shows the randomness, which brings great difficulty into the calculation [4].Therefore, we need to find a precise mathematical model to describe the non-uniformity of the cloud/rain medium, and achieve simulation on clouds and rain fading through establishing a convenient and practical empirical formula. The most typical model formula is the rain attenuation prediction model proposed by ITU-R, which has advantages of less input parameters, simple and easy to use, and wide application range. By formula (3), we can calculate the attenuation power P_s due to rainfall.

$$P_s=a_R\times L_E\times\theta \tag{3}$$

Where, a_R is the rain attenuation rate (dB/km), θ is the propagation path elevation angle (in radians), L_E is the effective distance (km) if the rain band.

During the transmission of wireless signal in the atmospheric environment, due to factors such as ground surface, terrain feature, the received signal is the synthesized wave of the direct wave and the reflectance wave of multi-channel, which will express the phenomenon of multipath attenuation. The main parameters describing the multipath propagation include the number of the transmission path, the attenuation amount along each transmission path, delay and the Doppler frequency shift. In order to truly reflect the influence of a certain geographic landscape on the performance of wireless communication system, we in this work mainly examine the signal from the viewpoint of transmission.

The Power and Time for direct signal reaching the receiving end is respectively:

$$Power=P_tG_tG_r(\frac{\lambda}{4\pi R})^2 \tag{4}$$

$$Time=\frac{R}{c} \tag{5}$$

Where, P_t is transmit power, G_t is the gain of the transmit antenna, G_r is the gain of the receive antenna, R is distance, λ is the signal wavelength, c is the speed of light. The Power and Time after the scattered i is:

$$Power_i=\frac{P_tG_tG_r\lambda^2 delt_i}{(4\pi R_{i1}R_{i2})^2} \quad (6)$$

$$Time_i=\frac{R_{i1}+R_{i2}}{c} \quad (7)$$

The relative attenuation Att_i and relative time delay $delay_i$ is

$$Att_i=Power\text{-}Power_i \quad (8)$$

$$delay_i=Time\text{-}Time_i \quad (9)$$

2.2 The Calibrate-Link Method

The control simulation of the monitoring station success rate is realized based on the theoretical receiving power and the test environment link fading simulation. Due to the inconsistency between the darkroom free space fading and the feeder fading under different simulation frequencies, the data-link should be calibrated according to test conditions before the test [5].The aim of the calibrate-link method is to reduce the effect of the environmental factors on the simulation test. The procedure of the calibrate-link method is as follows:

1)Calibrate the vector network: directly connect the transceiver of the vector network, set *s*21to be 0.

2) Measure the test link *s*21, i.e. the system loss *Ls*, and store the data.

3)Measure the total loss (-) or gain (+) of the receive path, denoted as *Lsr*.

4)Measure the total gain of the receive antenna, denoted as *Gr*.

5) Measure the total loss (-) or gain (+) of the transmit path, denoted as *Lst*: *Lst* =*Ls* − *Lsr*− *Gr*

2.3 The Establishment Of Simulation Model And Compensation Method

UAVs have a symmetry plane, and the gyroscopic torque effect of rotating members is ignored. For reference motion, the symmetry plane is in the vertical direction, and the movement plane is overlapped with the aircraft plane [6-8].Simplify the 6 DOF equations of a UAV using linear small perturbation, and discretize the vertical small perturbation equations:

$$\left.\begin{aligned} &X_{k+1}=\Phi X_k+\Gamma(b_m u_{k\text{-}m}+b_{m+1}u_{k\text{-}m+1}+\cdots+b_n u_{k\text{-}n}) \\ &b_m,b_{m+1},\cdots b_n\in\{0,1\},\sum_{i=m}^{n}b_i=1 \end{aligned}\right\}$$

(10)

The control amount reaching the plane at moment k cannot be completely determined, but the probability distribution of the time delay at moment k can be obtained, and the state variables are easily measurable. Therefore, apply full state feedback and optimal control theory on the system. Make the performance indicator

$$J=E\left\{X_N^TPX_N+\sum_{k=0}^{N-1}\left[X_k^TQX_k+u_k^TRu_k\right]\right\} \quad (11)$$

reach its minimum value, let:

$$\hat{X}=\left[X^T\ u_{k\text{-}n}\ u_{k\text{-}n+1}\cdots u_{k\text{-}m}\right]^T$$

$$\hat{\Phi}=\begin{bmatrix}\Phi & b_0 & b_1 & \cdots & b_{n\text{-}m\text{-}1}\\ 0&0&0&\cdots&0\\ 0&0&0&\cdots&0\\ 0&0&0&\cdots&0\end{bmatrix}$$

$$\hat{P}=\begin{bmatrix}P & \\ & 0_{n\text{-}m}\end{bmatrix},\ \hat{Q}=\begin{bmatrix}Q & \\ & 0_{n\text{-}m}\end{bmatrix}$$

Equations (10) and (11) can be rewritten as:

$$\hat{X}_{k+1}=\Phi\hat{X}_k+\Gamma u_k \quad (12)$$

$$J=E\left\{\hat{X}_N^T\hat{P}\hat{X}+\sum_{k=0}^{N-1}\left[\hat{X}_k^T\hat{Q}\hat{X}+u_k^TRu_k\right]\right\} \quad (13)$$

The optimal control law meeting indicators formula (11) can be obtained using dynamic programming method:

$$u_k=\text{-}[R+E(B_k^TS_{k+1}B_k)]^{\text{-}1}E(B_k^TS_{k+1}A_k)Z_k \quad (14)$$

Where

$$\begin{aligned} S_k=&E(A_k^TS_{k+1}A_k)+\hat{Q}-E(A_k^TS_{k+1}B_k)\times \\ &[R+E(B_k^TS_{k+1}B)]^{\text{-}1}E(B_k^TS_{k+1}A_k) \end{aligned} \quad (15)$$

$$S_n=\hat{P}_n \quad (16)$$

Set the expression of the four brackets in equation (15) is e_q, then its expectations is:

$$E(e_q)=\sum_{i=m}^{n}p_ie_{q|b_i=1} \quad (17)$$

When the high-altitude long-endurance relay UAV performs a task, the cruising speed can reach about 650 km/h, so we set the node move randomly in the speed of 180 m/s. When the combat UAVs performs tasks, its moving speed and direction is of the most changeable and is generally between 200-500 km/h, so here we set the network nodes corresponding to the combat UAV move randomly in the speed from 60 m/s to 120m/s. In practice, the data to be sent from the UAV to the controller is generally labeled as a number of packets, and these packets will be sent out one by one; in this context, the constant bit rate protocol is adopted by the application layer of each combat UAV and the ground control station. For the convenience of qualitative discussion on the simulation results, in the simulation process, set all the combat UAVs will send 200 packets (64 byte) to the control station, and the time interval between two packets to be sent is 10ms.

3. RESULTS AND ANALYSIS

After the setup of all the environmental parameters, the numbers of short-range and long-range combat UAVs are 2,3,5,6,8,10,20,30,40,50,60 and 2, 3, 6, 8,10,12,14,15,16,20,30,40,50,60 respectively. In order to reflect the variation characteristics of the performance of UAV data-link on the number of terminal nodes more accurately, keep the distance between the newly added nodes and the communication platform within 200 km.

3.1 Analysis On The Controllers Receiving Data Packets

Figure 1 shows the relationship of the success rate for the control station receiving the packets from short-range and long-range combat UAVs with the number of combat UAVs.

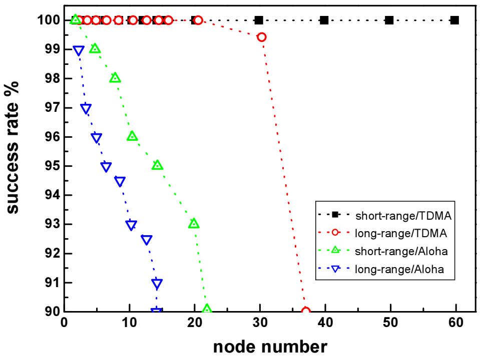

Figure 1 The Success Rate For The Control Station Receiving The Packets

It can be seen from Figure 4, when the TDMA access protocol is adopted for short-range combat UAVs, the success rate of the ground control station receiving data packets from UAV is independent from the size of the UAV network, and the success rate remains in 100%. When the TDMA access protocol is adopted for long-range combat UAVs, the success rate of the ground control station receiving data packets from UAV will decline slightly with the extending of the UAV network size. In actual combat, most of the signals the UAV transmits to the control station are image and video data; if the loss of these data is limited, it is usually can be restored through certain processing method. Here in this work we assume the data can be restored if the success rate is larger than 90%. From Figure 4 we can learn that, if the TDMA access protocol is adopted for long-range combat UAVs, the success rate is always larger than 90% when the number of nodes is less than 35. When adopt Aloha channel access protocol, both the packet loss rate of short-range and long-range combat UAVs will increase significantly with the increase of network nodes; when the number of short-range network nodes exceeds 20, the success rate will be smaller than 90%, and the success rate will be smaller than 90% when the number of long-range network nodes exceeds 15.

3.2 Analysis On The Average Delay From-Terminal-To-Terminal

Figure 2 shows the dependence of the average delay from-terminal-to-terminal of the application layer for short-range and long-range combat UAVs sending data to the control station on the changes of the network size.

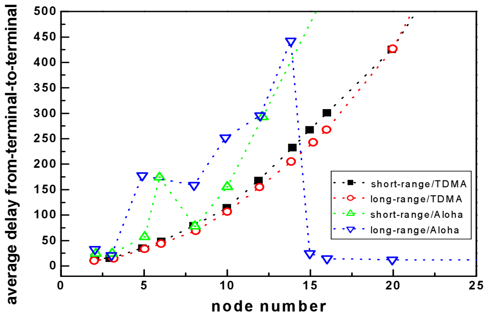

Figure 2 The Average Delay From-Terminal-To-Terminal

From the simulation results on the time delay we can learn that, when the success rate of the data receiving is larger than 90%, the average delay from-terminal-to-terminal will increase with the increase of the number of combat UAVs. When Aloha channel access protocol is adopted, the fluctuation of the delay is relatively larger; When TDMA channel access protocol is adopted, the scaling of the delay is close to a linear relationship.

3.3 Analysis On The Fluctuation Of The Average Delay

Figure 3 shows the dependence of the fluctuation of the average delay for short-range and long-range combat UAVs sending data to the control station on the changes of the network size.

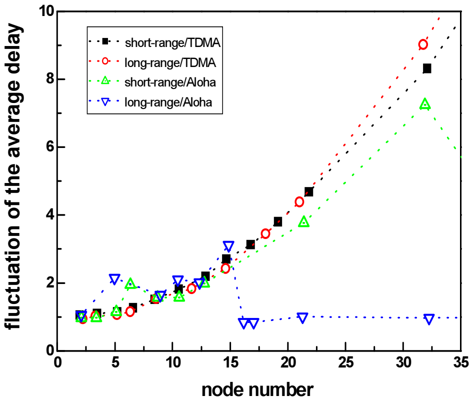

Figure 3the Fluctuation Of The Average Delay

From Figure 3we can learn that, when the success rate of the data receiving is larger than 90%, the fluctuation of the average delay of both short-range and long-range combat UAVs will increase with the increase of the number of combat UAVs.

3.4 The Delay Compensation

In order to verify the effectiveness of the method on the delay modeling and compensation method, we in this work examined the UAV platform: the clock cycle for the UAV system is 02 s, and the initial state is Ma= 0. 61 and h = 5 000 m. The simulation results are shown in Figure 4.

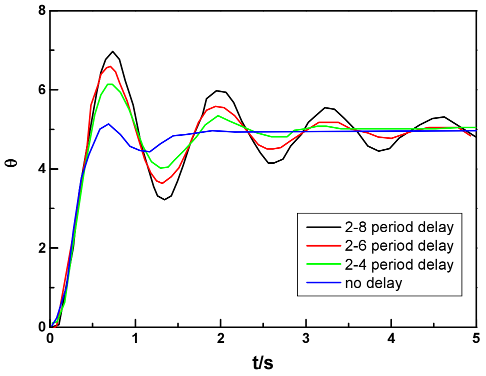

Figure 4 Uncompensated UAV Pitch Angle Response Curve

Figure 4 shows that the response characteristics of the UAV adding the effect of delay is obviously deteriorated, verifying the theoretical analysis on the impact of delay on the dynamic response characteristics of UAVs. And as the delay increasing, the dynamic characteristics of the UAV will consequently be deteriorated. It can be predicted that with the continuous increase of the delay, the UAV will become uncontrollable. Assuming the delay range of 0.02 ~ 0. 12 s (1 ~ 6 clock cycles), we discussed the response of the UAV in three conditions: consider the delay, the delay is compensated, and not consider the delay, and the result is shown in Figure 5 and 6.From the comparison of the attitude angle response of the UAV of the three conditions, we can learn that, with the introduction of the data-link delay modeling and optimal control theory, 1)the overshoot of the UAV pitch angle is reduced by 43%, and the time needed into a stable state is reduced by 1.3 s; 2)the overshoot of the UAV roll angle is reduced by 50%, and the time needed into a stable state is reduced by 1.1 s. Therefore, we can assert that the data-link delay model and optimal control theory adopted in this work is feasible and effective.

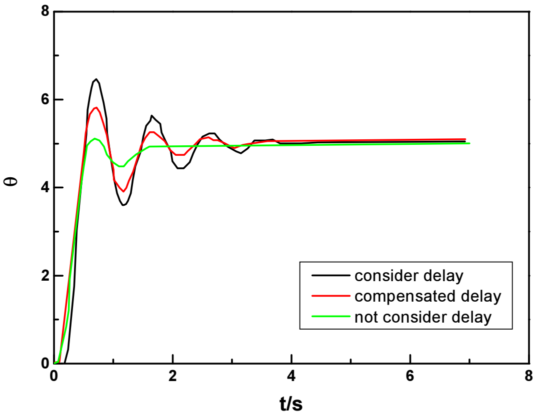

Figure 5 Response Curves When The Command Pitch Angle Is 5°

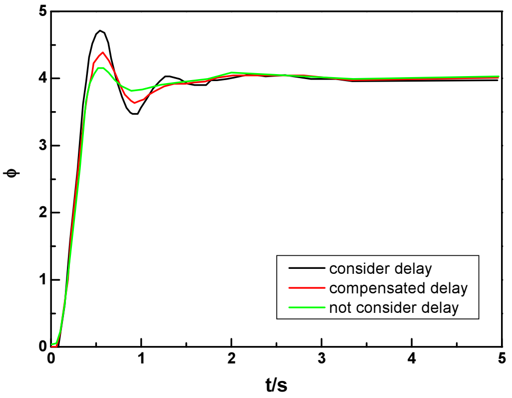

Figure6 Response Curves When The Command Roll Angle Is 4°

4 CONCLUSION

In this paper, the research shows that with the increasing of the delay, the dynamic response characteristics of the UAV is deteriorated, and when the time delay increases to a certain extent, the UAV will become difficult to control, thus it is desired to be designed to minimize the delay to ensure the performance of the UAV. After the compensation using the model established in this work, dynamic response characteristics of the UAV is significantly improved, indicating the data-link delay model and optimal control theory adopted in this work is feasible and effective. In this paper we also examined the time delay of the UAV data-link under the impact of factors such as node number, physical distance, subnet channel access protocol type etc. In-depth research and discussion on the algorithm of the proposed model is not performed, but it still has certain reference value for the simulation of UAV data-link.

5 ACKNOWLEDGEMENT

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