Effects of Packet Format and SBAS Measurement Rate on the Emergency Control of an UAV

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Abstract

The need for an embedded design considering both the telemetry and telecommand packet formats and the control system structure in the GCS controller of an UAV is presented in this work. In particular, an extreme situation (loss of INS information in the GCS) is used to evaluate the effect of different parameters relevant for UAV stability, and considering as SBAS data sampled at 1 s as well as data sampled at 10 s. The objective of the work is to evidence the packet structure and the SBAS sampling time effects, so the chosen control strategy is simple in order do not hide them. At the final of the paper, the behavior of an advanced control strategy is also shown.

1. Introduction

Although the main impulse of the UAVs (Unmanned Air Vehicles) is due to the development of Uninhabited Combat Air Vehicles (UCAV), other kinds of applications are growing, such as surveillance systems and telecommunication relays. This is the case of the NASA solar-electric stratospheric aircraft, known as Helios, which is the basis for a new infrastructure devoted to telecommunications.

The High Altitude Platforms (HAPs) [1,2] are a recent solution to solve the problem of increasing needs of telecommunication systems. HAPs are expected to be of major importance to telecommunications and navigation in the next future. These platforms, which work like pseudo-stationary satellites, offer some advantages in front of satellite or terrestrial platforms for some remote sensing and broadband communications such as direct contact without intermediate relays or signal delays, flexibility in placement, payload modification or maintenance. Moreover, the High Altitude Long Endurance (HALE) platforms are cost effective and no pollution alternatives (powered by solar panels) to satellite or terrestrial systems. Their comparative advantages in front of satellite or terrestrial systems are summarized in [3]. At present several projects are developed abroad [4], such as the HELINET project, achieved by a European Union team from Italy, UK, Spain, Switzerland, Slovenia and Hungary [5]. The mission of the HeliNet is to provide traffic monitoring, environmental surveillance and broadband applications.
The Ground Control Station (GCS) is the segment of the HAP that provides command and control of the vehicle and its payload. In normal situation, the task of the GCS is to send way-points to the on-board autopilots, and to supervise the correct execution of them. In emergency situations, such as loss of INS information, the UAVs require provision for fault detection and recovery. Failure of actual telemetry data from some in-flight altimeter, compass or IMU (accelerometers and gyros) must be detected, and automatically reconfigured the autopilots and the GCS control algorithms [6][7]. In most aerospace applications sensor/actuator failure detection is achieved by the use of redundant hardware and voting systems, ignoring the failed component. The use of the “analytical redundancy” is an alternative [8] in which the failure of some components is compensated by reconfiguring the control scheme. Different solutions based on advanced control strategies have been proposed, such as multi-model Kalman filtering, or multi-model LQG controllers [9]. In general, the adaptive control of failures is based on reconfigurable control strategies. These may be performed at level 1 (in-flight control) and at level 2 (GCS telemetry and telecommand). In the second case the control commands (set-points) are computed from higher levels (Hierarchical Supervisory Inference and Decision System) at longer time scale. Then the UAV controllers operate at different time scales (multirate control) [7].

In this paper an approach to the GCS emergency closed loop control of the HeliPlat scaled prototype [5] is presented. A simple feedback configuration (proportional control) is assessed in order to simulate the aircraft longitudinal stability in case if IMU failures, when only GPS or SBAS positioning data is available. SBAS includes all the augmented satellite positioning systems: WASS, EGNOS and MSAS. Typical GPS and SBAS equipment can provide position, velocity, time range and delta measurements at a minimum of once per second (the minimum operational standard is 1 Hz). However, sensors interfacing directly with certain autopilots may require a higher update rate, being typical a value of 10 Hz [8] [10] [11]. Apart from these two sampling periods, the proportional telecontrol algorithm in the GCS is also assessed at larger sampling periods, in order to evaluate the effects over the aircraft longitudinal stability of sampling period dilations due to unrecoverable frame errors in packet telemetry or telecommand.

The definitive controllers will be more complex than a simple proportional controller, incorporating more conditions of robustness and other supervisory techniques, such as fuzzy logic. However, a first approach based on proportional controllers will evidence the effects of the sampling period, without the masked conclusions that could produce advanced control strategies. At the end of this paper it is also presented a hyperstable adaptive control strategy for comparative purposes between the proportional controllers and a possible advanced strategy.

On the other hand, the telemetry and telecommand signals (CCSDS-based) use a narrowband centered around 2.5 GHz. These signals are employed to control as much aircraft guidance as payload behavior. Besides, some low-speed data from users may be transmitted in this band. In this paper, the performance of the telecommand protocol is evaluated from two points of view: 1) by sending the commands to the aircraft immediately after their computation from telemetry data, and 2), by sending them jointly with other payload commands and user data. The first option is safer from the aircraft stability point of view, whereas the second one is more efficient for high information rate.
2. Aircraft Longitudinal Model

For the objective of this paper a simple aircraft model is considered. The nonlinear equations of motion are linearized and decoupled into four equations in order to provide a derived analytical model for longitudinal motion, referred to the aircraft body axes. The aircraft is assumed in unaccelerated flight and in fixed atmosphere. It is considered to be disturbed only by deflection of the elevator, which causes a pitching moment, but we assume it does not cause rolling or yawing moments. Perturbations are bounded to be small around the model equilibrium point.

Using the HeliPlat [5] data, these equations become:

\[ \ddot{x} = A \dot{x} + B \ddot{u} \]

being:

\[ \ddot{x} = \begin{pmatrix} a \\ \theta \\ \alpha \\ u \end{pmatrix} \]

\[ a = \dot{\theta} \]

\[ \theta = \text{change in the angle between the horizontal and the OX axis.} \]

\[ \alpha = \text{change in the angle of attack (AOA).} \]

\[ u = \text{change in linear velocity (forward).} \]

\[ \ddot{u} = C_{m\delta_e} \delta_e \]

\[ C_{m\delta_e} = \text{elevator effectiveness.} \]

\[ \delta_e = \text{elevator deflection.} \]

\[ A = \begin{pmatrix} -0.2668 & 0 & -0.2612 & 0 \\ 1 & 0 & 0 & 0 \\ 0.9379 & 0 & -0.7682 & 0 \\ 0 & -0.1279 & 0.1587 & 0 \end{pmatrix}, \quad B = \begin{pmatrix} 0.146 \\ 0 \\ 0.0358 \\ 0 \end{pmatrix} \]

\[ \theta = C_1 \ddot{x} \]

\[ C_1 = \begin{pmatrix} 0 & 1 & 0 & 0 \end{pmatrix} \]

\[ u = C_2 \ddot{x} \]

\[ C_2 = \begin{pmatrix} 0 & 0 & 0 & 1 \end{pmatrix} \]
Combining these equations, the closed loop transfer function from $\theta$ to $\delta_e$ is obtained as:

$$G_\theta(s) = C_1(sI-A)^{-1} B = 0.146 \ C_{m\delta_e} \ \frac{s + 0.704}{s^3 + 1.035s + 0.45} = \frac{\theta}{\delta_e}$$

and between $u$ and $\delta_e$ is:

$$G_u(s) = C_2(sI-A)^{-1} B = 0.0057 \ C_{m\delta_e} \ \frac{s^2 + 0.8124s - 2.3144}{s^3 + 1.035s + 0.45} = \frac{u}{\delta_e}$$

The altitude $z$ may be approximated by:

$$\dot{z} = w - u \ \sin \theta,$$

being $w$ the linear velocity in the downward direction.

The following figure shows the root-locus of the discrete time transfer function from $\theta$ to $\delta_e$ (at $T=1$) when the aircraft is controlled by means of a proportional controller. Notice the stability of the aircraft (all the locus are inside the unity circle).

![Root Locus Graph]

*Figure 1.* Root locus of the transfer function from $\theta$ to $\delta_e$. (MATLAB).
However, if the controller includes a time delay of a sampling period (a single pole in the origin of the Z-plane), the aircraft model becomes unstable when the controller gain is increased, as shown in Figure 2.

![Figure 2. Root locus of the delayed transfer function from $\theta$ to $\dot{\delta}_w$. (MATLAB).](image)

### 3. Aircraft Telecontrol

In an emergency situation we suppose a minimum of operative subsystems for longitudinal stability: the elevator servo driver, with on-board $\theta$ feedback, and the GPS/GNSS/EGNOS instrumentation, which allows the telemetry of the aircraft altitude ($z$) to the GCS.

![Figure 3. Minimum telecontrol loop.](image)
There are in the literature different robust control strategies useful for aircraft control. However, in this first study, we select a simple proportional control ($K_t$) in order to evidence the effects of the sampling period (imposed by positioning instrumentation) and those of the telecommand frame structure. In the same way, Kalman filtering of received altitude ($z$) is not included in the study.

From the above equations, and using the proportional control in the GCS, the Matlab-Simulink model of the overall system is shown in Fig. 4. The servo transfer function of the figure corresponds to the elevator servo-driver.

![Figure 4. Matlab/Simulink model.](image)

The zero order hold (ZOH) in the GCS represents the discrete nature of the GCS control algorithm, and the hold time duration is fitted to the sampling period, imposed by the positioning system measurement rate (10 Hz or 1 Hz).

4. Simulation Results

The behavior of the aircraft is studied at different sampling periods and two strategies for packet telecontrol are assessed. The first one (Fig. 5a) consists on sending the telecommand orders immediately after they are computed, avoiding delays in the control action, whereas the second strategy (Fig. 5b) consist on holding the control orders until the rest of the information for payload telecontrol is available. At this time all the commands are transmitted in oneself data package. This second option implies an additional delay in the control law (the discrete-time transfer function shows an additional pole in the origin of the Z-plane).
Figure 5.  a) Fast telecommand mode.  b) Transmission in one packet data.
Legend: TM = telemetry, TC = aircraft telecontrol, PY = payload telecontrol.

The simulation results are presented in Figs. 6 to 9. In Fig. 6 different proportional gains (K_t) are compared. Notice the faster stabilization time when K_t is increased. However, for high values of K_t the system becomes unstable. The different final values are not a problem because they are easily resolvable if an integral action is included in the loop.

Figure 6. Effects of the controller gain K_t.

The Fig. 7 shows the simulation results for sampling periods of 1 s and 0.1 s. The system becomes unstable for the 1-second case.
In Fig. 8 the sampling period is held at the 0.1 second case, with $K_t=1$. This situation is only stable for minimum delay mode for packet telecommand (Fig. 5a). For the packet structure of Fig. 5b the system becomes unstable. This fact is an indicator of the convenience of the use of multirate digital controllers in forecast of emergency situations. However, as it is shown in Fig. 9, if the proportional value is decreased, all the positioning systems and packet telemetry options are acceptable, at the price of slower transient responses.
The previous simulation studies have been based on a very simple controller (only proportional action) in order to evidence the effects of the sampling period (T cycle) and those of the packet structure that conditions the elapsed time between the telemetry inputs to the controller and the telecommand outputs. Obviously, if the GCS control strategy is based on advanced controllers, the robustness in front of sampling period dilations is increased. Figure 10 shows the results when the controller is a parallel model reference adaptive system (MRAS), designed according to the Hiperstability Theory [12] and being the reference model M(s) a first order block, and with a proportional (Kp) plus integral (Ki) based control action in the feedback loop.
Figure 10. Adaptive controller (based on reference model and hyperstability-based designs).

In this case the aircraft shows increased robustness in front of the sampling period variations and used strategies for packet telemetry. Moreover, it can support the loss of
one telemetry packet \((Ts = 2 \cdot T_{cycle})\) if the reference model and the loop parameters are suitably reconfigured (Fig. 10b). The transient response of the reference model \(-M(s)\)- should be slowed and the values of \(K_p\) and \(K_i\) reduced if some telemetry packets are lost.

5. Conclusion

An approach for estimating the effects of the packet telecontrol format and the positioning measurements rate constraints has been presented. Starting from a longitudinal stability model of the UAV, proportional and adaptive control laws have been studied. In the proportional case, UAV stability is only guaranteed for low gains in the proportional action. This fact enlarges the transient response on the UAV. Besides, a proportional control law is not capable to support the loss of a telemetry packet without instabilities in the aircraft altitude. Moreover, it is necessary a packet structure where, after receiving the telemetry data, the ground controller computes the aircraft telecommand orders in a faster time scale than the payload orders, sending both orders into telecommand packets transmitted at different time instants. The adaptive control (considered for our purposes like an example of advanced controllers) allows all the packet telemetry modes considered in this paper, and even the loss of some telecommand packets by reconfiguring the reference model and the loop parameters.

These results are a first approach of the GCS controller strategy taking into account a particular emergency situation (failures in the INS). In the final controller design several control levels must be implemented, such as on-board primary and secondary controllers and GCS hierarchical control composed by primary loops (searching stability), secondary loops (searching precision) and tertiary loops (searching dynamics optimization and reconfigurability), both of them computed at different time scales and with a large set of control structures candidate for each loop. In this paper has been shown that, independently of the controller structure, telecommunication aspects must be embedded in the controller designs. Packet telemetry and telecontrol effects must be included in the discrete time model of the aircraft used to design these controllers in order to improve the robustness. And, on the other hand, advanced controllers that in the literature show spectral restrictions, as chattering, must be avoided taking into account the telemetry packets restrictions. Compared with other similar applications, such as satellite telecontrol, the UAV control is more restrictive from the stability point of view, because its faster dynamics and model complexity.

6. REFERENCES


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