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A Controller for Tracking Steep Glide Slopes for an Unmanned Gyroplane

Wei Wu[1*]

[1] *SCE, Carrier, UTC, USA.*

Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

This paper presents a glide slope tracking controller for an autonomous gyroplane during the final approach. This controller tracks the glide slope by adjusting the airspeed command and the collective based on the altitude error. To track steep glide slope angles, while maintaining a minimal airspeed for lateral and directional control, a feedforward airspeed command is computed based on the wind estimation. The controller performance was tested for several vehicle configurations and under various wind conditions using nonlinear simulation.

Keywords: Gyroplane; unmanned aerial vehicle; steep glide slope; approach controller.

1 INTRODUCTION

The autogyro or gyroplane was developed by Juan de la Cierva in the 1920's and '30's. In 1923, the gyroplane was flown successfully for the first time and was ahead of the first successful helicopter flights by about 15 years [1].

*Corresponding author: E-mail: wu_esi@yahoo.com

Autogyro pioneers encountered and solved many technical problems associated with rotating wings [2,3,4] paving the way for the helicopter development in the 1940's. The research and development of autogyro stopped after WWII as the helicopter became popular and wildly accepted for military and commercial applications. While, the autogyro has become a popular hobby aircraft for amateur pilots [5]. Recently, more researches on the gyroplane began to take place, i.e. the aerodynamics of an autogyro in [6], the flight dynamics research on the autogyro in [7,8], controller designs in [9,10] There are also commercial interests in the gyroplane. Two companies, Carter Aviation Technologies and Groen Brothers Aviation, have resurrected the idea of autogyro and began to develop its capabilities using modern technologies [1].

The gyroplane considered here is a UAV (unmanned aerial vehicle) equipped with an autopilot used for cargo delivery and extraction. It has a single rotor with three blades. The gyroplane rotor is fully controllable with three controls: the collective pitch, the roll cyclic pitch, and the pitch cyclic pitch. The rudder control surface is used for the directional control. An engine and a push propeller unit provides the thrust for forward flight. For reasons such as landing in mountainous areas, landing on a short runway, the gyroplane requires a steep glide slope during landing. During the landing, the engine is put on idle. For this gyroplane, an autopilot is being designed, including all controllers for take-off, navigation, and landing.

The longitudinal glide slope tracking controller, also referred to as the approach altitude controller, presented in this paper aims to track the steepest glide slopes possible, especially when there is no wind or very little wind, at the same time maintaining airspeed above a minimal airspeed for lateral/directional control purposes. When there is a strong head wind, near vertical landing is achievable.

This paper is organized as follows. In Section 2, we will present the controller components and the control logic for the glide slope controller. In Section 3, the nonlinear simulation model is described and simulation results are presented. Conclusions are given in Section 4.

2 CONTROLLER DESIGN

The goal of this controller is to track the steepest glide slope angles possible when there is no wind or mild wind. This controller uses the airspeed controller and the collective pitch as actuators to achieve the altitude control during the glide slope tracking. It also schedules a reference TAS(true airspeed) command based on the wind estimation. A Delta TAS command is generated by a PID controller, and a Delta collective command is generated by another PID controller. The two PID controllers and the gains are designed for the best tracking performance. The P, I&D gains in both controllers are scheduled using the ground speed to achieve robust tracking performance under all wind conditions.

The gain scheduling rule basically results in using the collective channel when there is no wind, the airspeed channel when there is a fair amount of wind, and both of them when the wind is in between. The reference TAS command is scheduled each control cycle using the wind estimates to give a lowest possible airspeed range for tracking the steepest glide slopes and, at the same time, guaranteeing the minimal IAS(indicated airspeed) required for lateral and directional controls. The minimal IAS with a measurement error acceptable for flight control is usually $15m/s$ for a Pitot tube.

The total airspeed command to the airspeed inner loop is the sum of the reference TAS command and the Delta TAS command. To meet the minimal IAS command, the total TAS command is limited such that it is greater than or equal to the TAS which corresponds to the minimal IAS. The total collective command is the reference command plus the Delta collective command. In this controller, the reference collective command is set to zero. When the collective is controlled by the glide slope controller, the rotor speed should stay in the prescribed range. If the rotor speed limits are violated when the glide slope controller is in control of the collective, a rotor RPM controller takes over the collective control to bring the rotor speed back within the range.

2.1 Reference TAS Command Scheduling

The following assumptions are adopted.

1. No tail winds are considered.
2. Deliver maximum glide slope angles when there is no wind or light wind
3. Ground speed is approximately in the runway direction and runway direction is known.

The first assumptions assumes that the gyroplane lands into the wind. This controller works well under the headwind up to $20m/s$, the crosswind up to $10m/s$, and the tailwind up to $3m/s$ (although, it is not designed for it). According to the second assumption, the reference is set at the minimal airspeed, or very close to the minimal airspeed when there is no wind or light wind, which renders the slowest ground speeds under the airspeed restriction.

Let u_{min} be the minimal TAS corresponding to the prescribed minimal IAS. Δu_{max} be the limit for the Delta airspeed command. U_{gnd_min}, the minimal ground speed. U_{AS_off} is the speed if exceeded by the ground speed, delta TAS channel is turned off(all PID gains become zero). $\epsilon_{AS}(U_{gnd})$ is the gain scheduling factor for the Delta TAS channel, which is a function of the ground speed, U_{gnd}. Consider the wind component in the horizontal plane and let V_W the estimated wind speed. V_W is decomposed into the component along the ground course, V_{W_gnd}, and the component perpendicular to the ground course V_{W_cr} based on the wind course. Because the Pitot probe usually points forward of the gyroplane, so the TAS component in the forward direction is measured and controlled.

If $\sqrt{V_{W\_cr}^2 + (V_{W\_gnd} + U_{gnd\_min})^2} \geq u_{min}$, set the reference TAS command u_{ref} as

$$u_{ref} = \sqrt{V_{W\_cr}^2 + (V_{W\_gnd} + U_{gnd\_min})^2} + \Delta u_{max} \epsilon_{AS}(U_{gnd}) \quad (2.1)$$

otherwise

$$u_{ref} = u_{min} + \Delta u_{max} \epsilon_{AS}(U_{gnd}). \quad (2.2)$$

Because being able to vary the airspeed, thus varying the ground speed, enables the tracking of a range of glide slopes and steep glide slopes, the Delta airspeed channel needs to be engaged for the computed reference TAS command. The reference TAS command is limited by the speed, u_{AS_max},

$$u_{AS\_max} = \sqrt{V_{W\_cr}^2 + (V_{W\_gnd} + U_{gnd\_min} + U_{AS\_off})^2}. \quad (2.3)$$

if this speed is exceeded by the airspeed, the Delta airspeed channel is basically turned off. After computing u_{ref} using equation 1 or 2, if $u_{ref} > u_{AS\_max}$ and $u_{AS\_max} > u_{min}$, let

$$u_{ref} = u_{AS\_max}. \quad (2.4)$$

2.2 Gain Scheduling

There are two PID controllers, one for the airspeed channel and the other for the collective. Gains for each controller are scheduled according to the ground speed using a gain factor. The PID controllers determining the Delta commands are in the form

$$\Delta u = k_p(U_{gnd})e + k_i(U_{gnd}) \int e dt + k_d(U_{gnd})\dot{e} \quad (2.5)$$

where e is the altitude error, and Δu is the Delta command, i.e., Delta airspeed command or Delta collective command, $k_{p,i,d}$ is the proportional, integral, and derivative gain respectively. PID gains for both control channels are scheduled using a gain factor in the following form

$$k_{p,i,d}(U_{gnd}) = \epsilon(U_{gnd}) k_{p,i,d}^0 \quad (2.6)$$

where $k_{p,i,d}^0$ are the unscheduled, constant gains. The gain factor for the collective channel is

$$\epsilon_{col} = \begin{cases} 0 & \text{if } U_{gnd} \leq U_{AS\_on} \\ 1 & \text{if } U_{gnd} \geq U_{AS\_off} \\ \frac{U_{gnd} - U_{AS\_on}}{U_{AS\_off} - U_{AS\_on}} & \text{if } U_{AS\_on} < U_{gnd} < U_{AS\_off} \end{cases} \quad (2.7)$$

where U_{AS_on} is the speed that the collective channel is turned off(only the airspeed channel is on) if the ground speed is below it, and the gain factor for the airspeed channel is

$$\epsilon_{AS} = 1 - \epsilon_{col}. \tag{2.8}$$

Due the presence of the integrator in a PID controller, the controller output may not be zero even if all gains become zero and stay at zero after an instant of time. To avoid potential adverse interactions between the two control channels, a wash-out filter is implemented for each channel. The wash-out filter bring the controller output to zero according to a prescribed wash-out rate if a control channel is turned off for a period of time, i.e., the washout filter is activated if a channel is turned off at the current step and it was turned out at the previous step as well.

2.3 Inner Loop Controllers

The approach altitude controller uses the airspeed closed-loop as its effective plant. The airspeed closed-loop comprises the pitch closed-loop as the plant and a PID controller whose gains are scheduled using the dynamic pressure and the density as the scheduling parameters. The pitch closed-loop generates the longitudinal/pitch cyclic command via a PID controller with gains scheduled based on the dynamic pressure and the density.

The lateral controller during approach is the cross track controller with the bank closed-loop as the plant. This controller uses a PID controller with unscheduled gains. the bank closed-loop with turn coordination generates the lateral/roll cyclic command using a PID controller whose gains are scheduled based on the dynamic pressure and the density. The gyroplane heading is not explicitly controlled during approach, the gyroplane points to the wind due to the weathercock effect.

3 SIMULATION STUDY

3.1 Nonlinear Model

The gyroplane model used for simulation is based on the helicopter modeling techniques in [11]. Rotor thrust and the (uniform) rotor induced velocity are calculated together iteratively using equations derived from the blade element theory and the momentum theory. The center spring equivalent model is adopted for modeling the blade flapping stiffness. The blade flapping motion is modeled by a first-order differential equation describing the regressing mode, ignoring the blade advancing mode, by assuming that the flapping mode frequencies are high, well separated from the gyroplane airframe motion mode frequencies. The nonlinear equations of motion takes the form

$$\dot{x} = f(x, u) \tag{3.1}$$

where the state vector, x, includes the body frame velocity components u, v, w, the body frame angular rate, p, q, r, Euler angles ϕ, θ, ψ, the rotor disc flap angles β_{1c}, β_{1s}, and the rotor rotational speed Ω, the control vector u contains the pitch cyclic δ_{lon}, the roll cyclic δ_{lat}, the collective δ_{col}, the rudder deflection δ_{rud}, and the engine throttle δ_T.

Some of the controller parameters are as follows. $U_{gnd\_min} = 3m/s$, the minimum IAS is $15m/s$, $\Delta u_{max} = 8m/s$, $U_{AS\_on} = 10m/s$, $U_{AS\_off} = 15m/s$, Delta collective is limited between ± 2 degree(to avoid exceeding the rotor RPM limits).

3.2 Simulation Results

The gyroplane has several design configurations depending on the payload conditions, including the no load condition, the extreme fore center of gravity(F.C.G.), the extreme aft center of gravity(A.C.G.), the one sided load condition, and the full load condition. In the simulation, a moderate level of turbulence is applied. We simulated the glide slope tracking under different steady state wind conditions, including the headwind from $0 - 25m/s$, the crosswind from $0 - 15m/s$, and the tailwind from $0 - 3m/s$. Next, we will present part of the simulation results.

Figure 1 shows the glide slope tracking performance for the no load configuration without steady state wind. The glide slope is 25 degree. The IAS reference is at the minimum IAS because there is no wind. The control inputs are shown in Fig. 2. Because the ground speed is high, so the Delta airspeed channel is off most of the time, and the Delta collective responds to the tracking error. Fig. 3 shows the flight trajectory of the gyroplane landing from 2000 meter altitude. Another interesting experiment is to look at the tracking performance if we lower the minimal IAS. If the airspeed instrument can measure low pressure accurately or the lateral/directional control is adequate at low airspeeds, we may lower the minimal airspeed. It leads to tracking of steeper glide slope angles. Figure 4 shows the vehicle performance when the glide slope is 35 degree and the minimal IAS is $6m/s$. The glide slope angle is 10 degree larger compared to that when the minimal IAS is $15m/s$, and the cross track is still satisfactory. The steepest glide slope angles that the gyroplane can track successfully are different for different configurations. For ACG configuration and without steady state wind, the tracking performance and control outputs for the 16 degree glide slope are shown in Figure 5 and Figure 6 respectively.

For the same gyroplane configuration, assume 20m/s headwind. In this situation, we can command very steep glide slopes. Figure 7 shows the tracking of a 70 degree glide slope. Note that there is an artificial large tracking error at the beginning of the glide slope. This error is actually caused by the bumpy altitude command during the transition from a constant altitude to the steep glide slope. The altitude response is actually smooth. Figure 8 shows the control outputs. The gyroplane flies at low ground speed, so the Delta airspeed channel is active and the Delta collective channel is turned off based on the gain scheduling law. Consider a worse case that there is a $10m/s$ cross wind without headwind. The glide slope tracking performance for the 25 degree glide slope is shown in Figure 9. It appears that the tracking performance is degraded in the adverse wind condition, compared to the no wind case in Figure 1. In this case, both control channels are active according to the gain scheduling law, see Figure 10. Note that due to the strong cross wind, both control channels experienced extended periods of saturation which led to the less desirable control performance.

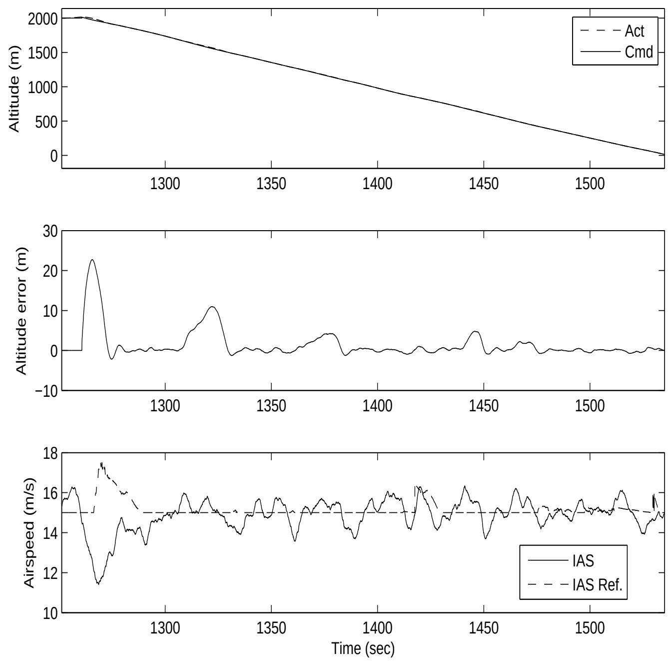

Figure 1: 25 degree glide slope tracking w/o wind.

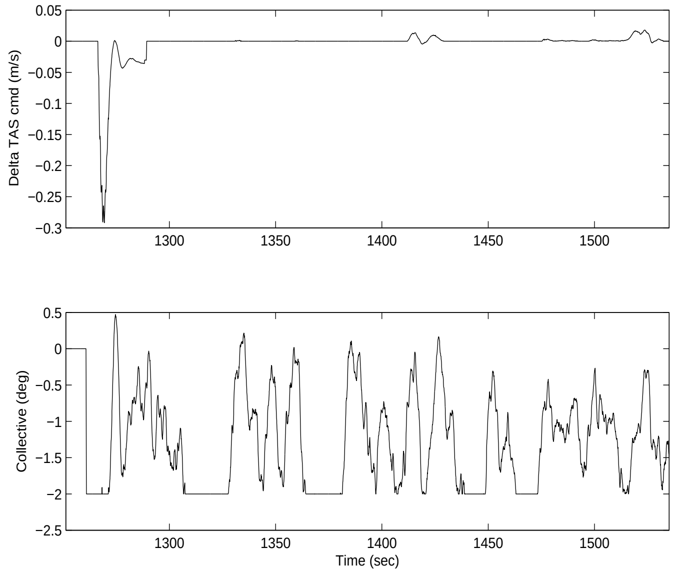

Figure 2: 25 degree glide slope controller outputs w/o wind.

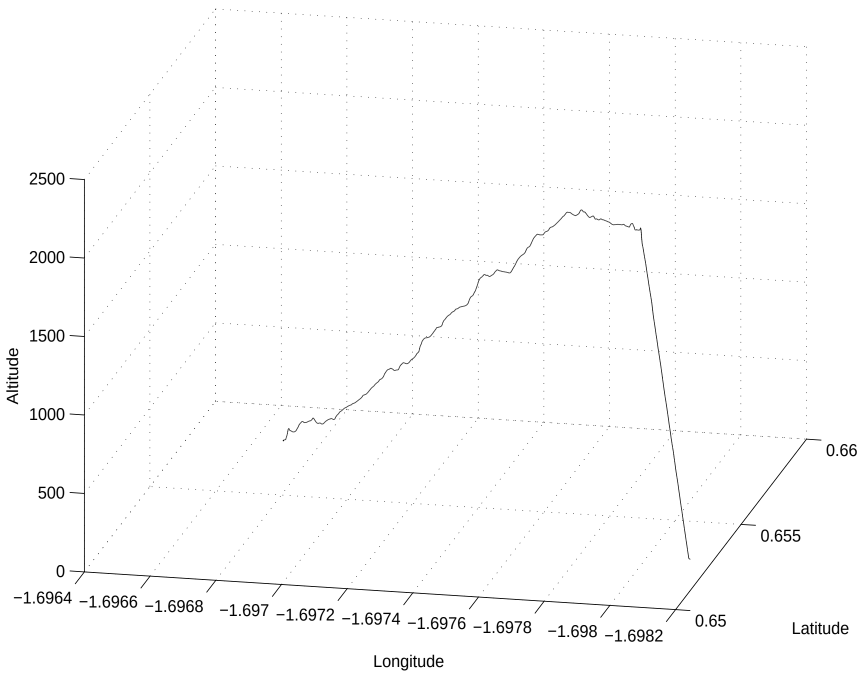

Figure 3: Flight path for 25 deg glide slope w/o wind.

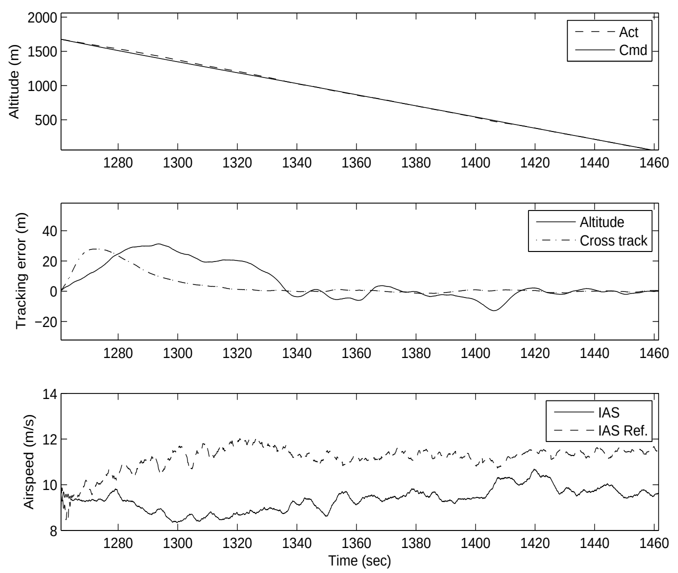

Figure 4: 35 deg glide slope w/o wind and IAS=6m/s.

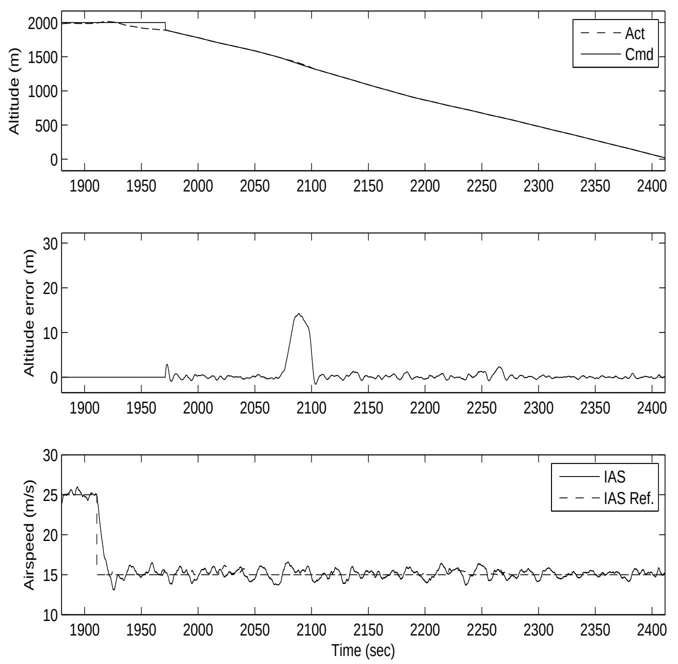

Figure 5: 16 degree glide slope tracking for ACG and no wind.

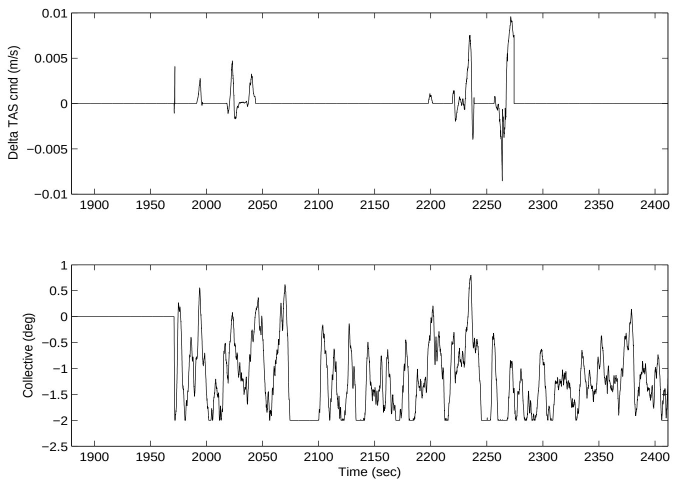

Figure 6: 16 degree glide slope controller outputs for ACG and no wind.

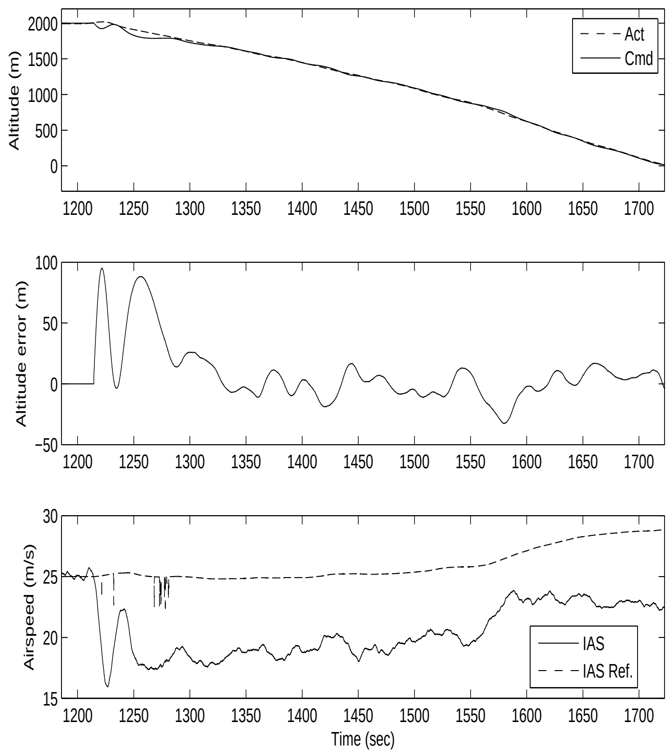

Figure 7: 70 degree glide slope tracking under 20m/s headwind.

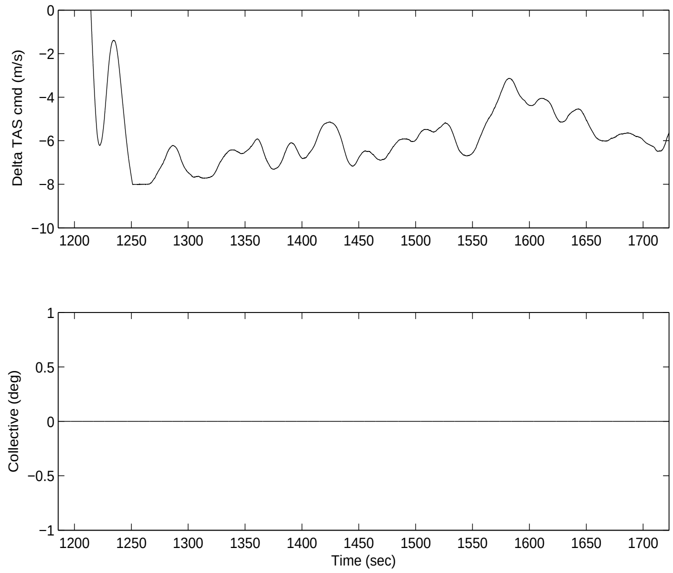

Figure 8: 70 degree glide slope controller outputs under 20m/s wind.

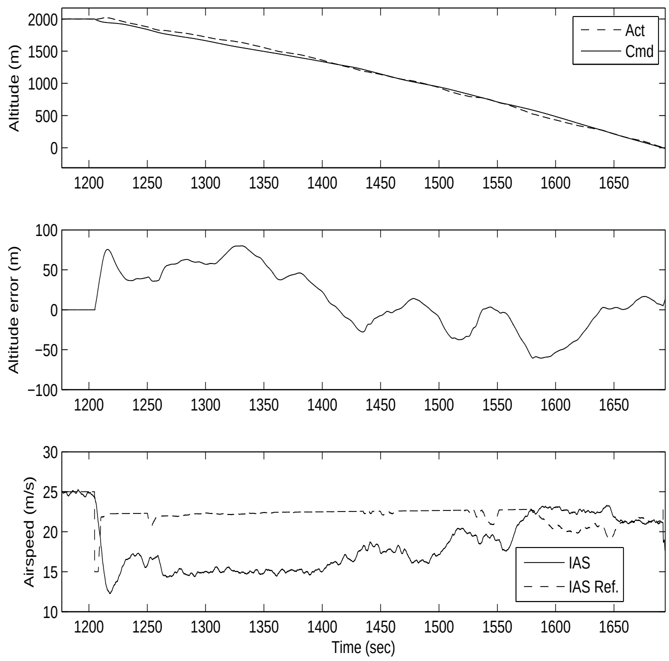

Figure 9: 25 degree glide slope tracking under 10m/s cross wind.

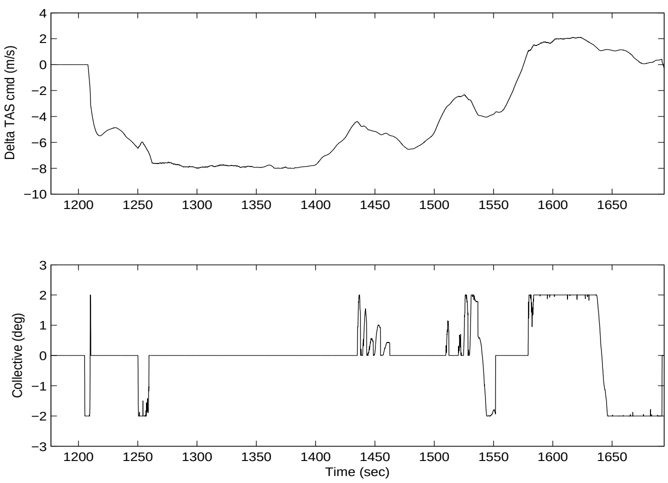

Figure 10: 25 degree glide slope controller outputs under 10m/s cross wind.

4 CONCLUSIONS

A glide slope controller design, as part of a cargo delivery and retrieve unmanned gyroplane autopilot, is presented. It is required to land the gyroplane at steep glide slope angles under various wind conditions. This controller computes a reference airspeed using the wind estimates such that a low airspeed reference is generated when this is no wind to achieve steep glide slope tracking. This reference airspeed is greater than or equal to the minimum airspeed which is required for lateral and directional control purposes. The glide slope controller use both the airspeed and the collective channel to generate a Delta airspeed command and a Delta collective command, and its PID gains are scheduled based on the ground speed. The blending of the two channels basically results in that the airspeed channel is active when the ground speed is low, and the collective is active when the ground speed is high. The performance of this controller was tested using a nonlinear model including the rotor flapping dynamics and the rotor speed model. Simulations under various headwind, cross wind and tailwind conditions were conducted for different vehicle configurations. Good results were obtained without wind and under headwind. When there is strong cross wind, the tracking performance is degraded due to control inputs saturation.

Competing Interests

The author declares that no competing interests exist.

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