

Pterodactyl: 6-DOF Integration of Guidance and Control Algorithms in Genesis

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The NASA-funded Pterodactyl project seeks to advance the current state-of-the-art for entry vehicles by developing novel guidance and control technologies for Deployable Entry Vehicles. This paper builds upon the Pterodactyl architecture that employed eight individually articulating flaps with two options for guidance, bank angle modulation with the Fully Numerical Predictor Corrector Entry Guidance (FNPEG) technique and angle of attack and sideslip modulation with FNPEG uncoupled range control. These, with a linear quadratic regulator controller, have previously been presented in separate 3-DOF trajectory simulations, one for translational motion and another for rotational dynamics. This work will show results for integrated 6-DOF simulations, leveraging recent advancements in trajectory simulation tools, namely the Julia-based Genesis package. Results show similar performance for both schemes when compared to the previously presented 3-DOF results once the controllers were adequately tuned. Angle of attack and sideslip modulation necessitated a controller designed at high dynamic pressure conditions, and bank angle modulation necessitated a controller designed at lower dynamic pressure conditions. Notably, angle of attack and sideslip modulation could not achieve the parachute deploy point target Mach number of 2, when only tuning the controller gains, thus future work will be needed to tune guidance specific parameters to achieve acceptable range targeting and guidance command tracking.

Nomenclature

ADEPT	=	Adaptive Deployable Entry and Placement Technology
DEV	=	Deployable Entry Vehicle
DOF	=	Degree(s) of Freedom

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FNPEG	=	Fully Numerical Predictor-corrected Entry Guidance
FNPEG URC	=	Fully Numerical Predictor-corrected Entry Guidance Uncoupled Range Control
GNC	=	Guidance Navigation and Control
HIAD	=	Hypersonic Inflatable Aerodynamic Decelerator
LQR	=	Linear Quadratic Regulator
PBV	=	Pterodactyl Baseline Vehicle
A	=	state matrix
B	=	control input matrix
K	=	feedback gain matrix
M	=	Mach number
Q	=	state diagonal weighting matrix
R	=	control input diagonal weighting matrix
S	=	vehicle aerodynamic reference area
C_s	=	aerodynamic side force acceleration
c	=	proportional gain tuning and scaling parameter for sideslip angle
e	=	normalized specific mechanical energy
e_i	=	integral error state of term i
m	=	vehicle mass
p	=	roll rate
q	=	pitch rate
q_∞	=	freestream dynamic pressure
$\bar{q}$	=	sensed dynamic pressure
r	=	yaw rate
r_{dist}	=	planetocentric radial distance
u	=	control input vector
V_∞	=	freestream velocity
x	=	state vector
α	=	angle of attack (alpha)
β	=	sideslip angle (beta)
δ	=	flap deflection angle
Δ	=	deviation
ψ	=	planetocentric azimuth of the planet-relative velocity
ρ_∞	=	freestream density
σ	=	bank angle
ξ	=	lateral control logic desired damping ratio
σ	=	lateral control logic desired frequency
Superscripts		
T	=	transpose
$\cdot$	=	first derivative
$*$	=	linearization point
Subscripts		
1–8	=	flap number
c	=	commanded value

I. Introduction

AS the scope of planetary exploration continues to expand, achieving bold science objectives will require precision landing site targeting and novel heatshield technologies. To address these needs, NASA has invested in

Deployable Entry Vehicle (DEV) technologies, such as the Adaptable, Deployable, Entry Placement Technology (ADEPT) [1] and hypersonic inflatable aerodynamic decelerator (HIAD) technology [2]. The NASA Pterodactyl project seeks to investigate novel guidance and control technologies for said Deployable Entry Vehicles. Previous work investigated three candidate control architectures including a flap control system, mass movement control system, and a reaction control system, where the flap control system was identified as the most promising as it allocated more payload volume and provided increased maneuverability [3]. Original guidance and control algorithms were developed to advance the capabilities of the flap control system. Yaw-to-bank employs a cascading control architecture with an outer loop modulating yaw angle to track bank angle commands from Fully Numerical Predictor-corrected Entry Guidance (FNPEG) and an inner loop which modulates the flap deflection angles to track the yaw angle commands from the outer loop and maintain a specified trim angle of attack [5]. Alpha-beta employs a linear quadratic regulator (LQR) controller, which executes angle of attack and sideslip angle commands provided by the FNPEG Uncoupled Range Control (FNPEG URC) algorithm [4].

Previously published work on the alpha-beta control and yaw-to-bank control methods utilized separate three degree-of-freedom (3-DOF) trajectory simulations, one for translational motion and another for rotational dynamics. The goal of this work is to integrate these guidance and control algorithms into a full six degree-of-freedom (6-DOF) trajectory simulation. In this paper, the methodology for implementation of a fully integrated 6-DOF simulation for both control methods is discussed. Additionally, a brief overview of the mission, vehicle configuration, aerodynamic database integration, and the Guidance and Control (G&C) system designs is provided. This is followed by a discussion of trends noted in each architecture when fully integrated into the 6-DOF trajectory simulation.

II. Methodology

This work seeks to build upon the foundational control and guidance algorithms, developed by the Pterodactyl Guidance and Control team, for an ADEPT vehicle with eight deployable flaps [4-6]. The original algorithms were developed and implemented using separate 3-DOF simulation platforms, one for the translational dynamics and another for rotational dynamics. The G&C methodologies that were developed are as follows: 1) simultaneous angle of attack and sideslip control (“alpha-beta”) and 2) yaw modulation to achieve bank control (“yaw-to-bank”).

The primary objective of this work is to combine these guidance and control systems in a 6-DOF trajectory simulation, Genesis [8], and verify performance against the results from the 3-DOF implementations in past work. Successful implementation of the 6-DOF implementation required a phased approach, which is outlined in Figure 1.

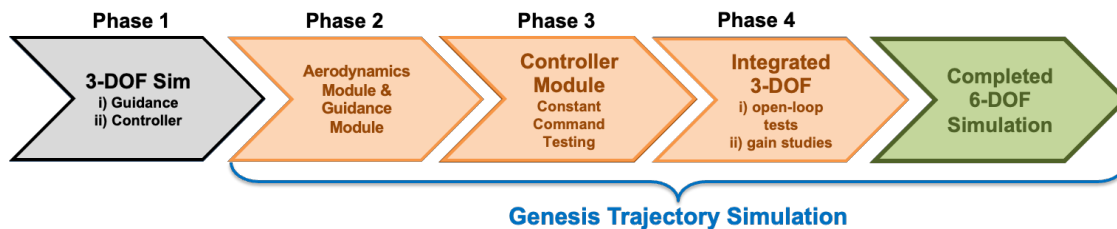


Figure 1: Phased implementation for fully coupled 6-DOF simulation

The first step is to reproduce the 3-DOF case study mission profile to ensure consistency between the aerodynamic databases and vehicle configurations implemented in the 6-DOF simulation. Phase 2 focused on implementation of the aerodynamics databases which were complex due to the varied flap deflections [7]. This phase also included running both guidance algorithms in 3-DOF mode. Phase 3 encompassed replicating the LQR based control algorithm, which was coded in Python, in the Genesis trajectory simulation and then testing the implementation using constant commands. Phase 4 consisted of integrating the guidance and control algorithms followed by checkouts to confirm successful implementation. This included running open-loop and then closed-loop to identify appropriate gains.

The Pterodactyl G&C algorithms are then integrated into the Julia-based Genesis 6-DOF trajectory simulation [8]. Using the 6-DOF translational and rotational equations of motion, and a 100 Hz Runge-Kutta 4 integration scheme, the G&C algorithms are implemented in the simulation using a `FlightSoftwareRateGroup` at a prescribed rate. The prescribed rate that was implemented for all simulations shown here was 500 Hz for both control and guidance. The pre-defined aerodynamic database, with dependence on Mach number (M), angle of attack (α), sideslip angle (β), and each deflection angle (δ_i), alters the forces and moments acting on the vehicle at each time step according to the

controlled-to flap deflection configuration and current state parameters. It is key to ensure that controller inputs are in the expected units and frame as those for which the controller was derived.

A. Lunar Return Mission

The lunar return mission case study was employed to build on existing framework and maintain relevancy for current spaceflight endeavors [5]. The flap control system steers the vehicle to a desired target location in the Utah Test and Training Range (UTTR). At an entry interface of 122 km, the entry velocity is 11 km/s, where the vehicle then decelerates to terminal descent conditions of Mach 2 as described in Figure 2. This target Mach number was selected because i) confidence level of aerodynamic simulation below Mach 2 was low and ii) the design of a descent system was out of the Pterodactyl development scope. This case does carry high Earth entry speeds and thus stresses the integrated flap system to maintain guidance commands. Both alpha-beta and yaw-to-bank architectures employ this case study and utilize the same target conditions.

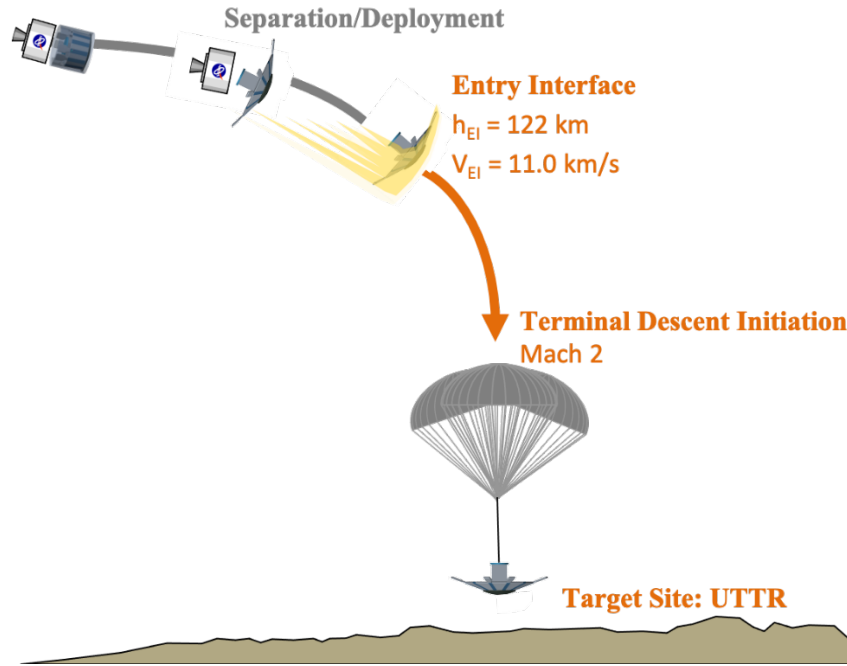


Figure 2: Lunar Sample Return, Earth Entry ConOps

B. PBV-II, PBV-IIa, and Aerodynamic Control Surface Architecture

The Pterodactyl Baseline Vehicle (PBV) was used to match the original development's configuration [5]. Specifically, PBV-II, shown in Figure 3, is the vehicle configuration used in the full 6-DOF simulations. The PBV-II nomenclature implies a symmetric configuration of the ADEPT vehicle with independently actuated flaps located at the radial edges of eight of the ribs. For the alpha-beta control method, PBV-II has no longitudinal center of gravity offset, while PBV-IIa requires a longitudinal center of gravity offset that enables a trim angle of attack (α_{trim}) for the yaw-to-bank control method. Note that the outer mold line is shared by both configurations and is represented by Figure 3. The mass and moment of inertia properties of PBV-II and PBV-IIa are listed in Table 1. The flap capabilities and bounding conditions are the same as the previous study: eight individually actuated flaps with an operating range of $+20^\circ$ into the flow and -45° out of the flow with a shared initial condition of -35° . For the angle of attack and sideslip control architecture, the lateral flaps (3-6) are intended to modulate the sideslip angle, whereas the longitudinal flaps (1-2, 7-8) alter the angle of attack angle.

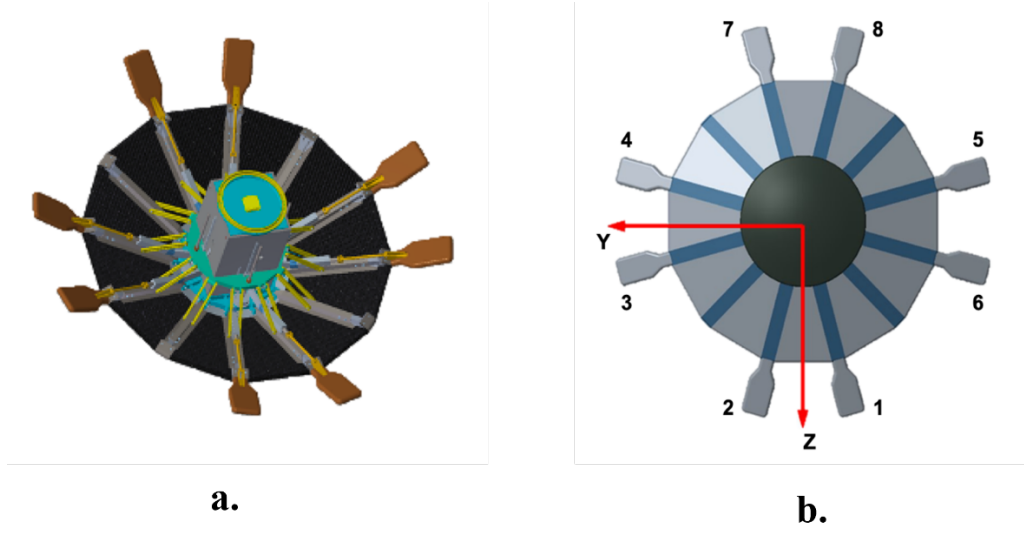


Figure 3: (a.) PBV-II Aft View, (b.) PBV-II Forebody View

Table 1: Vehicle Properties of PBV-II and PBV-IIa

Parameter	Units	PBV-II	PBV-IIa
Mass	kg	703.3	702.4
I_{xx}	kg-m ²	651.2	693.7
I_{yy}	kg-m ²	513.4	572.2
I_{zz}	kg-m ²	512.9	512.0
$I_{xy} = I_{yz}$	kg-m ²	0	0
$I_{xz} = I_{zx}$	kg-m ²	0	-35.23
CG measured from nose	[m, m, m]	[-0.458, 0, 0]	[-0.469, 0, -0.079]

C. Aerodynamic Database Generation

To use the 6-DOF Julia software, Genesis, an appropriately formatted aerodynamic database storing information of Pterodactyl's force and moment coefficients of the aeroshell and control surface deflected geometries, is needed. This takes the format of a dedicated Julia module, `PteroAero`. Cart3D was used to generate the aerodynamics database for a run matrix of flap deflection angles, body angle of attack, body sideslip, and Mach number as shown in Table 2 [7]. Note that both guidance and control algorithms have internal functions to produce analytical approximations of these databases and rely on correct implementation of the aerodynamics database in Genesis. It is out of the scope of this work to discuss those internal functions, but descriptions can be found in references [5] and [6].

In order to implement this in Genesis, the source database was symmetrized and categorized into a CSV file, and linear interpolators were built, which interpolate along the independent variables to calculate the aerodynamic data for each of the flaps and for the body (9 total). To query the aerodynamics of a specific vehicle configuration, the body angles, Mach number, and flap deflection angles are input, and the aerodynamic coefficients for each of the flaps and body are extracted from the interpolators. These coefficients are summed (leveraging superposition) to generate a total aerodynamic coefficient for the queried configuration.

Table 2: Cart3D Aerodynamic database simulation matrix

Angle of attack (α) [deg]	Sideslip (β) [deg]	Mach	Flap Deflection [deg]
-20, -15, -10, -5, 0	0, 5, 10, 15, 20	2, 5, 10, 15, 20, 31, 40	-45, -20, 0, 10, 20, 30

D. Guidance System Design

The guidance system is defined in detail in Johnson, et. al. [6], but a short overview is given here. The FNPEG URC guidance algorithm is used for angle of attack and sideslip control and the FNPEG algorithm is used for yaw-to-bank as in previous work [5]. FNPEG URC generates angle of attack and sideslip angle commands to alter the vehicle's lift and drag vectors assuming a fixed bank angle. FNPEG generates bank angle commands to roll the vehicle's total lift vector assuming a fixed angle of attack profile. Recall that the vehicle configuration for yaw-to-bank, PBV-IIa, possesses a longitudinal center of gravity offset, inducing a non-zero trim angle of attack (α_{trim}) and a corresponding lift vector. Both employ the Gauss-Newton method within the predictor-corrector logic to search for the best command angle magnitude versus energy profile to achieve a minimal miss distance [6]. This energy profile is represented by e , the normalized specific mechanical energy, which is expressed as

$$e = \frac{1}{r_{dist}} - \frac{V^2}{2}$$

where r_{dist} is the planetocentric radial distance to the vehicle and V is the planet-relative velocity. The alpha-magnitude profile for FNPEG URC is defined as

$$|\alpha(e)| = \alpha_0 + \frac{e - e_0}{e_f - e_0} (\alpha_f - \alpha_0)$$

This alpha-magnitude profile, $|\alpha(e)|$, is parameterized by a linear function of the normalized specific mechanical energy, e . FNPEG URC's, like FNPEG's, numerical method solves a least-squares problem with a single univariate function to find the α_0 needed to minimize the error function defined as

$$f(\alpha_0) = \frac{1}{2} [S_{togo}(e_f)]^2$$

where S_{togo} defines the great-circle range to the target site. The calculated α_0 and e_0 are used to predict the resultant trajectory within each prediction-correction cycle, and if the calculated α_0 does not meet the terminal constraint on the error of the range to target, then the Gauss-Newton scheme corrects the trajectory by updating α_0 until the error of the range to target is within limits. A corresponding procedure is defined for FNPEG guidance with σ instead of α .

While bank angle or angle of attack are used primarily to manage downrange error, the crossrange can be managed using bank angle reversals or sideslip. For FNPEG, the sign of the commanded bank angle can be changed using two different methods i) deadband-based lateral logic or ii) predictive lateral logic based on desired number of reversals [9]. FNPEG URC instead manages crossrange error by using an azimuth-based proportional-derivative (PD) control law defined by:

$$C_{s,cmd} = \Gamma [K_\psi (\psi_{cmd} - \psi) + K_{\dot{\psi}} (\dot{\psi}_{cmd} - \dot{\psi})]$$

where K_ψ is the proportional gain on azimuth error, $K_{\dot{\psi}}$ is the proportional gain on azimuth rate error, and Γ is the conversion factor from the side force acceleration to C_s . The conversion factor is defined by

$$\Gamma = \frac{m}{(1/2 \bar{q} S)}$$

where $\bar{q}$ is the sensed dynamic pressure and S is the aerodynamic reference area of the vehicle. The gains are defined by

$$K_\psi = \left| \frac{C_{s,max\beta}/\Gamma}{c_{max\beta}} \right|$$

$$K_{\dot{\psi}} = 2\xi\omega = 2\xi \sqrt{\frac{K_\psi}{m}}$$

where $C_{s,\max\beta}$ is the maximum side force coefficient achievable dependent on the user-input for the vehicle configuration, $c_{\max\beta}$ is a user-input gain to scale with the maximum expected side force, m is the estimated vehicle mass, ξ is the desired damping ratio, and ω is the desired augmented frequency. Using the aforementioned expressions, the commanded sideslip angle is determined by

$$\beta_{cmd} = \frac{C_{s,cmd} - z_{C_{s,\max\beta}}}{Y_{C_{s,\max\beta}}}$$

As detailed above, both FNPEG URC and FNPEG necessitate a user-defined control angle at a target energy to determine an angle profile linear with respect to energy for down range control. However, crossrange control for FNPEG and FNPEG URC have different lateral control logic. It has been observed that both FNPEG URC and FNPEG have reliable convergence rates [6].

E. FNPEG and FNPEG URC: 3-DOF Results

The 3-DOF FNPEG alpha-beta guidance results are found in Figure 4, and the yaw-to-bank guidance results are found in Figure 5. These will provide the baseline for comparison of the 6-DOF simulations results for each controller method.

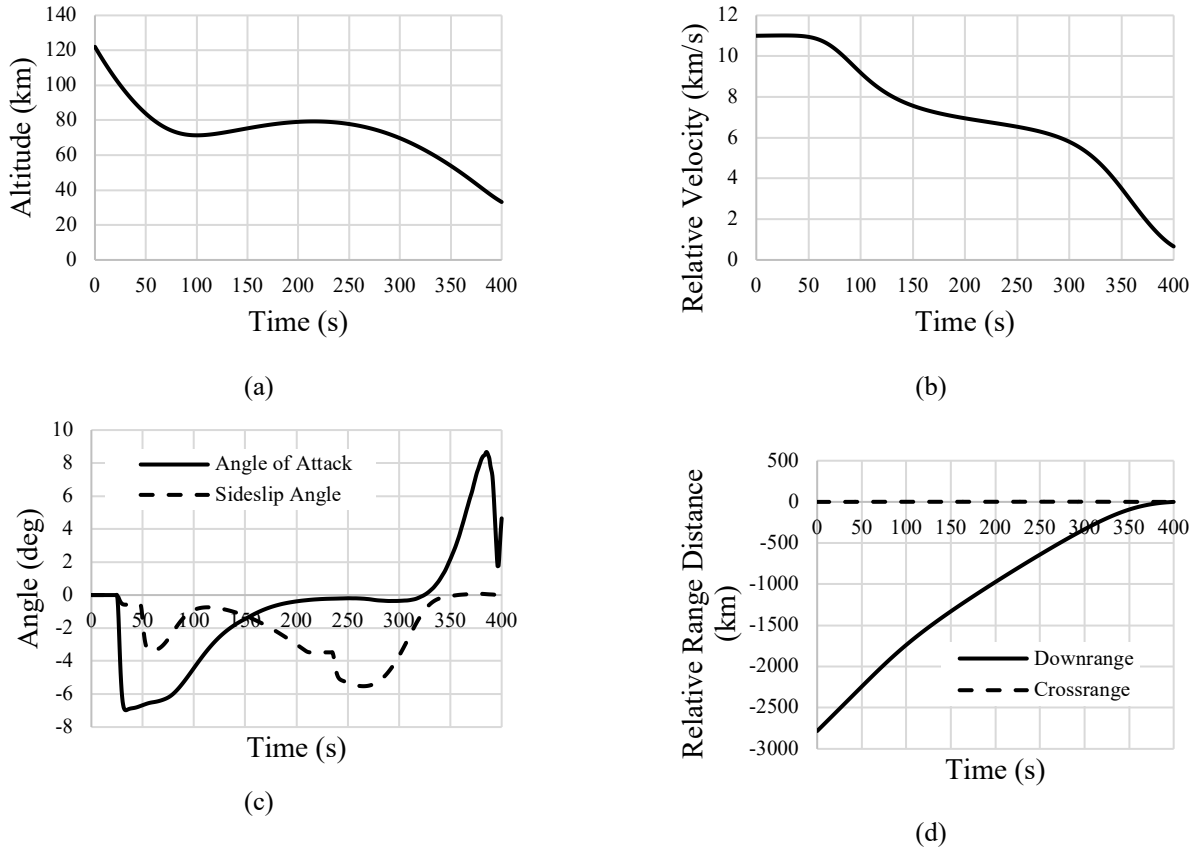


Figure 4: FNPEG URC alpha-beta 3-DOF Results [5]

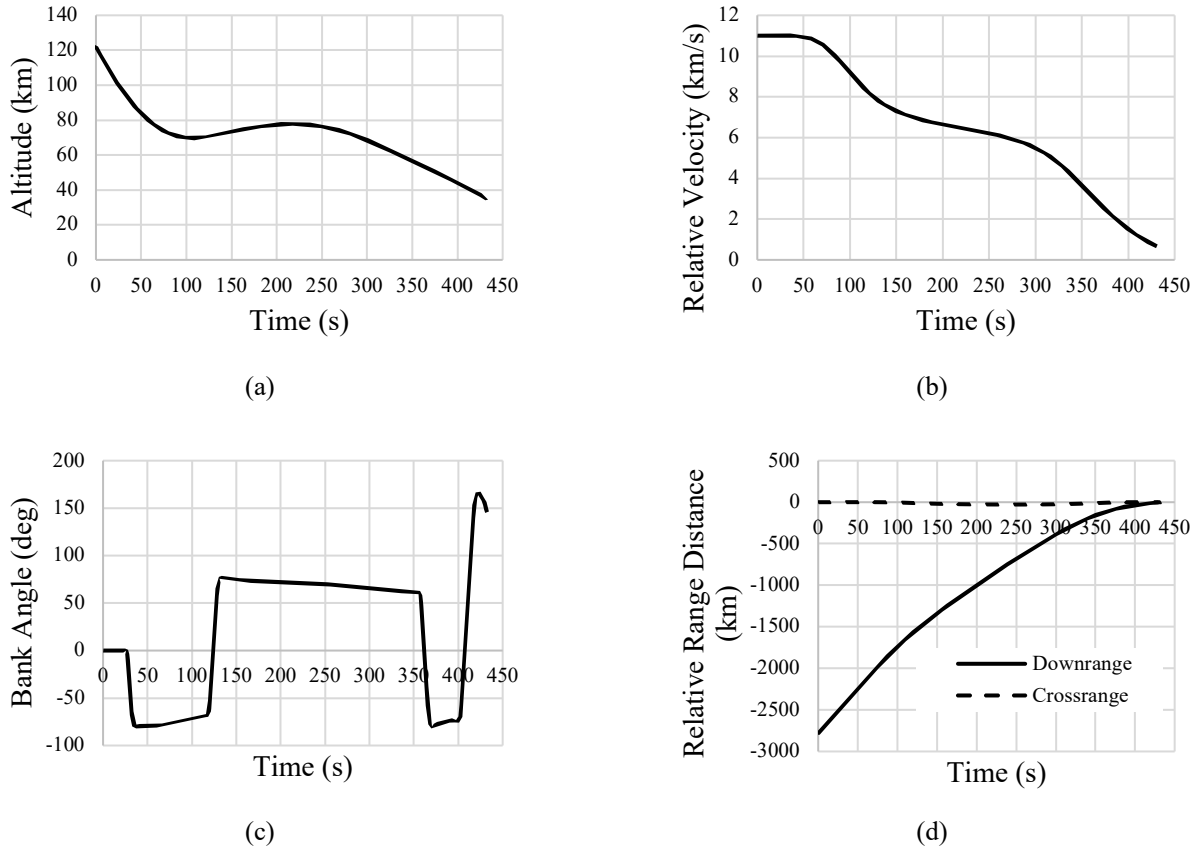


Figure 5: FNPEG yaw-to-bank 3-DOF Results [5]

F. Control System Design

The Pterodactyl team set out to design controllers that would determine the required deflections for each flap to achieve the appropriate guidance commands for each type of vehicle control method, alpha-beta or bank. This results in two different control designs. First, the control design for the alpha-beta method followed a traditional feedback control system as shown in Figure 6.

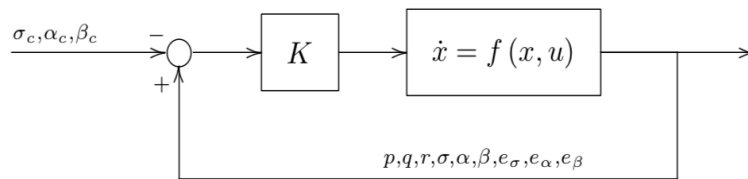


Figure 6: Control diagram for alpha-beta controller [4]

Second, among the advances of the Pterodactyl project, a patented control design for yaw-to-bank control was developed and is illustrated in Figure 7.

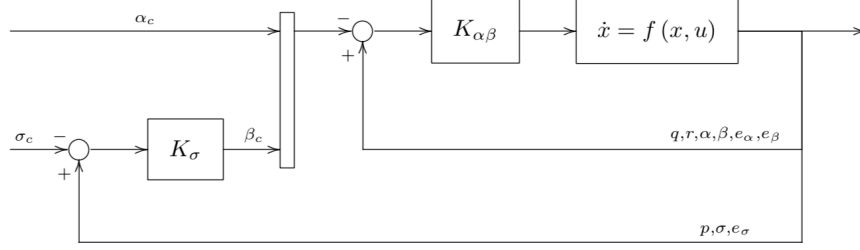


Figure 7: Control diagram for yaw-to-bank controller [10]

The above controllers require a process to calculate the gain matrix K for the alpha-beta control method and the gain matrices $K_{\alpha\beta}$ and K_{σ} for the yaw-to-bank control method. In Okolo, et. al. [4] and Margolis, et. al. [5] a linear quadratic regulator (LQR) is developed to determine appropriate gain matrices. The vehicle attitude state vector x , is defined as

$$x = [p \ q \ r \ \sigma \ \alpha \ \beta \ e_{\sigma} \ e_{\alpha} \ e_{\beta}]^T$$

where p , q , and r are the angular velocities of the vehicle with respect to the planetodetic North-East-Down reference frame expressed in body-fixed x , y , and z axes, σ is bank angle, α is angle of attack, β is sideslip angle, and e_{σ} , e_{α} , and e_{β} are the augmented integral error state variables for σ , α , and β , respectively. The control input vector, u , is expressed as

$$u = [\delta_1 \ \delta_2 \ \dots \ \delta_7 \ \delta_8]^T$$

where each δ_i is the deflection of the i th flap. The augmented vehicle attitude state defined above is largely de-coupled from the translational state. The equations of motion are linearized about x^* and u^* at a specified flight condition, to form the linear system

$$\Delta \dot{x} = A \Delta x + B \Delta u$$

where Δx and Δu are the deviations from the linearization point x^* and u^* with the state matrix, A , and the input matrix, B , defined by

$$A = \left. \frac{\partial f}{\partial x} \right|_{x^* u^*}$$

$$B = \left. \frac{\partial f}{\partial u} \right|_{x^* u^*}$$

where $f(x, u)$ is the vector-valued function of the derivatives for each state variable concatenated together. The linearization point assumes steady-state conditions, symmetric nominal control surface deflections, and trim angle of attack from a Newton-Raphson solver. To start, the control system was designed around flight conditions at the altitude that activated guidance and control as provided by the guidance simulation. The control law is then given by

$$u = u^* - K(x - x_c)$$

where x_c is the commanded state, and K , the feedback gain matrix, is computed to minimize the quadratic cost function

$$J = \int_0^{\infty} \Delta x^T(\tau) Q \Delta x(\tau) + \Delta u^T(\tau) R \Delta u(\tau) d\tau$$

and is calculated using either the Algebraic Riccati Equation or Linear Matrix Inequality depending on the case. The matrices Q and R are diagonal weighting matrices for the state tracking performance and control effort costs, respectively. The feedback gain matrix K is tuned to improve tracking and performance by updating the flight

conditions for the linearized point, namely freestream dynamic pressure, q_∞ , via fluid freestream density, ρ_∞ , and freestream vehicle velocity, V_∞ , as well as the values in the weighting matrices.

A Python code base by Margolis et. al. was used to output controller gains by adjusting variables that populate the LQR matrices, such as the flight conditions the LQR gains are designed about and the Q and R weighting matrices [5]. New gains, for both alpha-beta (K_{mat}) and yaw-to-bank (K_{ab} and K_{bank}), were tuned for use in the integrated 6-DOF simulations. The input parameters from previous studies were initially used for traceability and consistency [5].

G. Alpha-Beta and Yaw-to-Bank Controller Results: 3-DOF Rotational Dynamics

The 3-DOF alpha-beta controller results are found in Figure 8 and the yaw-to-bank controller results are found in Figure 9. These will provide the baseline for comparison of the 6-DOF simulations results for each controller method.

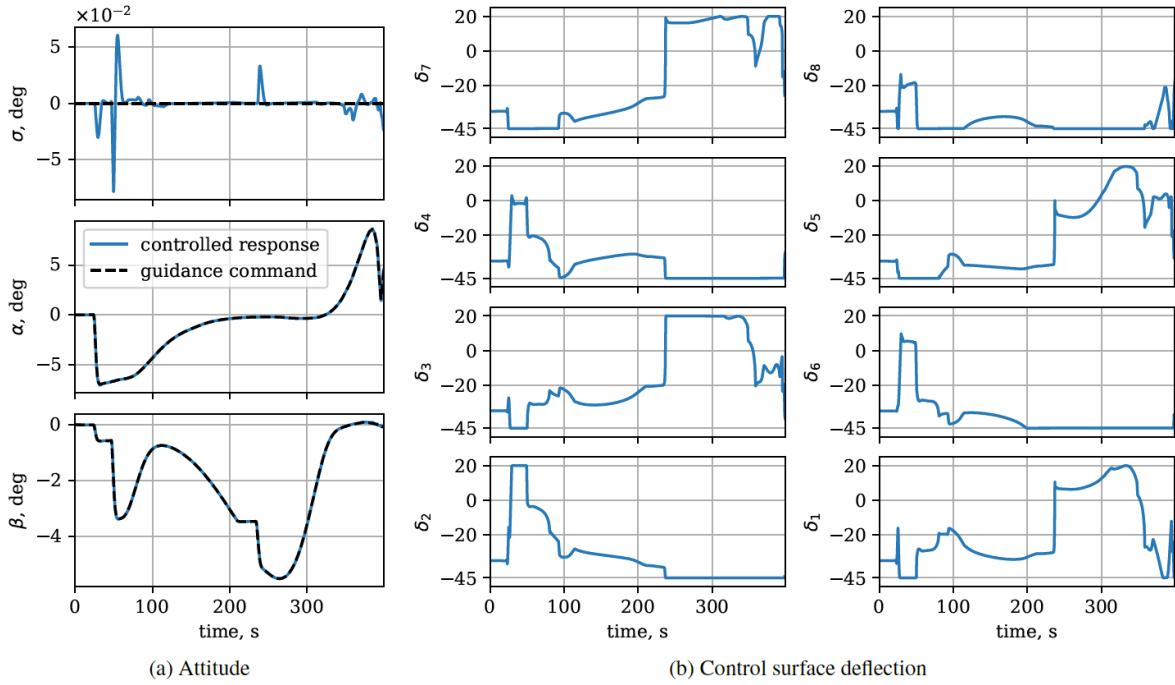


Figure 8: 3-DOF Simulation results for angle of attack and sideslip

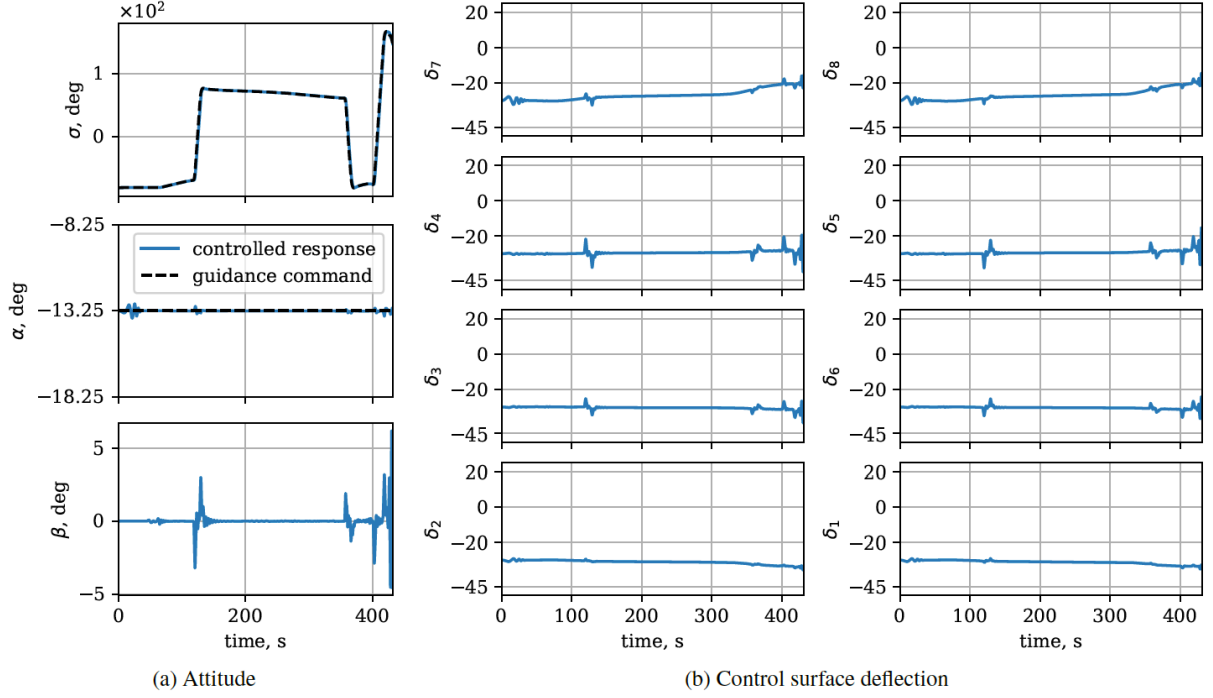


Figure 9: 3-DOF Simulation results for bank angle tracking

III. Results

A. Implementation of Integrated 6-DOF Simulation with Angle of Attack and Sideslip Control (Alpha-Beta) and FNPEG URC Guidance

The successful implementation of the alpha-beta 6-DOF simulation involved (1.) the verification and integration of the aerodynamics module, or *PteroAero*, that outputs aerodynamic force and moment coefficients of the vehicle into the trajectory simulation, (2.) the verification and integration of the controller module, or *PteroController*, which ingests the state of the vehicle at a point in time, and utilizes a pre-defined gain matrix, or *Kmat*, to stabilize the vehicle (referenced in Section III.C as *K*), and lastly (3.) testing the tracking of the guidance and commanded outputs of the angle of attack (α) and sideslip angle (β) after complete integration. Note, this work leveraged the existing FNPEG and FNPEG URC Julia packages for guidance. In each of these verification scenarios, the full 6-DOF dynamics were integrated with initial conditions as described in Section III.A, vehicle parameters as provided in Table 1, and simulated for a full trajectory, which terminates at Mach 2, to assess the integrated simulation. The verification process for the yaw-to-bank architecture was similar and is described in further detail in III.B.

1. Open Loop Case

Prior to the integration of guidance or control, the aerodynamics module was implemented and validated by running the 6-DOF simulation with no controller or guidance active, and by manually setting all eight flap deflections of the vehicle to 0° . The response in Figure 10 shows that the angle of attack and side slip angle holds at 0° throughout the full trajectory in the simulation, with small oscillations noted in angle of attack. These small oscillations were likely caused by a kinematic coupling that was not present in either of the 3-DOF simulations, illustrating the need to perform the evaluation of the coupled system in a full 6-DOF environment. It was deemed that integration of the vehicle aerodynamics into the 6-DOF environment was performed successfully and controller implementation could commence.

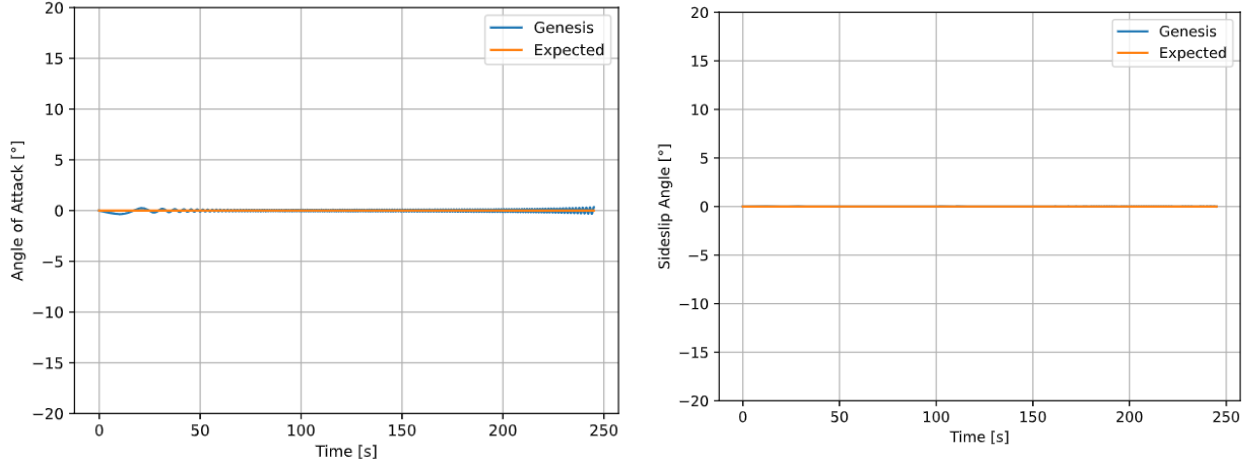


Figure 10: Angle of Attack and Side Slip Angle Responses in Open Loop Case

2. Controller Tuning for Alpha-Beta

Once the aerodatabase was established and deemed accurate, the integration and verification of the controller took place. The controller is in the form of a Julia based module, *PteroController*, which consists of the original controller algorithm translated to Julia. To verify the implementation of the alpha-beta controller, it was tested in isolation, turning the guidance off, and using manual hold values for the commanded angle of attack and sideslip angle. The hold commands tested were from within the control envelope included in Figure 6 of [5]. The controller is tuned by adjusting the gain matrix, or K_{mat} . The K_{mat} is generated using cost parameters and a specific condition of the trajectory, namely dynamic pressure controlled by velocity and density. Iterations with different K_{mat} s were designed to achieve better tracking, along with gain scheduling to target performance near surface impact. After testing multiple iterations of K_{mat} , the best simulation performance resulted from a K_{mat} that was designed with a high dynamic pressure of 14.6 kPa, and a doubled alpha cost parameter from the uncoupled 3-DOF controller cost (alpha cost = 182.4). This iteration of K_{mat} and cost matrix were used in the Guidance On, Control On case. The responses using this K_{mat} showed that the controller was able to hold at the *commanded* values of both the angle of attack (α_c) and sideslip angle (β_c) through an abbreviated time of the simulation (100 sec).

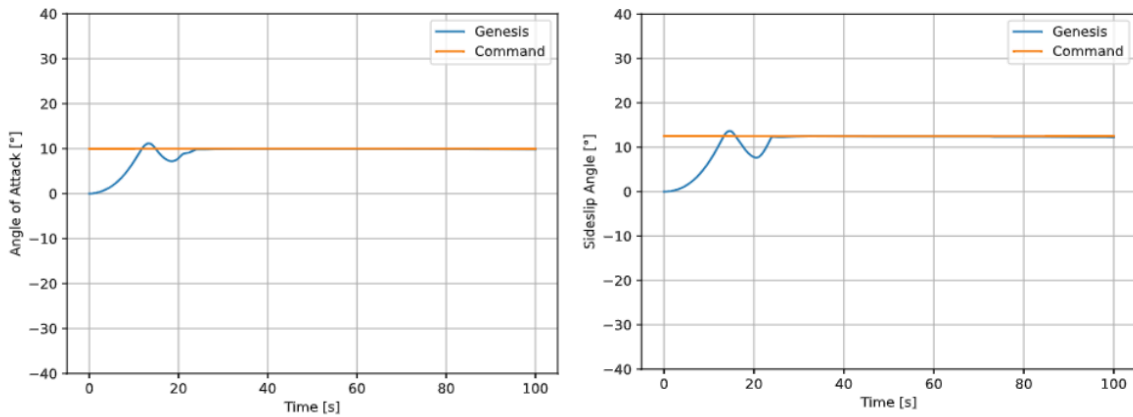


Figure 11: Angle of Attack and Sideslip Angle Response in Hold Angle Case, where $\alpha_c = 10^\circ$ and $\beta_c = 12.5^\circ$

3. Guidance On, Control On

To determine the performance of the integrated 6-DOF guidance and control for alpha-beta control, both guidance and control were turned on and active in the case study simulation as a respective *FlightSoftwareRateGroup*

in Genesis. The response in Figure 12 shows that the guided and commanded values for angle of attack and sideslip angle were nearly aligned and tracking throughout the majority of the simulation but began oscillating in the last 20 seconds indicating loss of control. At the end of this run, the final Mach number of the vehicle was about 2.1, which was the target value of Mach for descent. The final crossrange and downrange distance for this run were 16.6 m and 7.6 m, respectively. In comparison with the 3-DOF alpha-beta simulation results depicted in Figure 8, Figure 12 shows similar profiles for angle of attack and sideslip respectively, which indicates favorable performance until the aforementioned oscillations (starting at 384 seconds). Additional metrics of this simulation are shown in Figure 13 and Figure 14.



Figure 12: Wind Angles and Flap Deflection Responses for Baseline Target Values (Target Final: Mach 2.1)

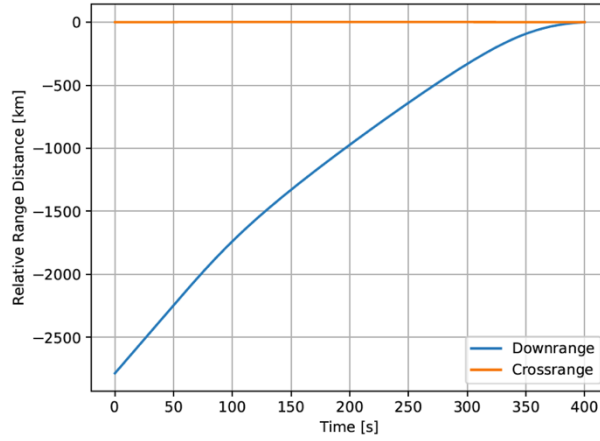


Figure 13: Range Distance for Baseline Target Values (Target Final: Mach 2)

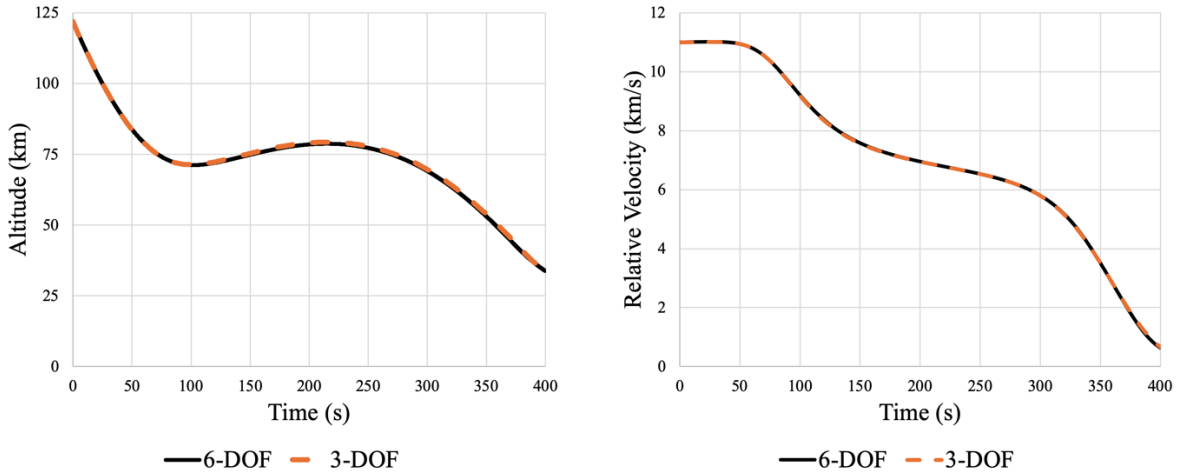


Figure 14: Altitude and Velocity for Baseline Target Values (Target Final: Mach 2)

Despite several attempts to tune the controller, degradation of tracking performance in the last 20 seconds of the simulation remained. This led the team to look at potential integration issues of both guidance and control that needed to be addressed. In an effort to achieve excellent tracking throughout an entire trajectory in a simulation, the guidance inputs initialized in the 6-DOF code were reviewed. A simulation was run using the best iteration of the K_{mat} in the controller as mentioned in the previous section, and the target velocity was increased from 686 m/s to 1483 m/s (essentially changing e in the guidance target), while keeping the same UTTR target location. The new target velocity was determined by extracting the vehicle velocity from 380 seconds (before tracking degradation) in the case shown in Figure 12 and Figure 14. The responses shown in Figure 15 are a 6-DOF simulation run with the higher target velocity with additional metrics provided in Figure 16 and Figure 17. Both angle of attack and side slip demonstrate very close tracking to the guidance commands, but a noticeable $\pm 1^\circ$ deviation in the bank angle is noted as compared to the results for Mach 2 terminal state. The close tracking between the commanded guidance values and the simulated response values indicates that the integration of the alpha-beta LQR controller and corresponding FNPEG URC guidance into Genesis was successfully completed.

The crossrange and downrange miss distance for this run were 5.1 m and 870 m, respectively, at a final Mach of about 4.4. The targeting performance for final downrange miss distance has noted degradation as compared to the

baseline guidance target of Mach 2.1 for the same target position (16.6 m and 7.6 m crossrange and downrange, respectively).

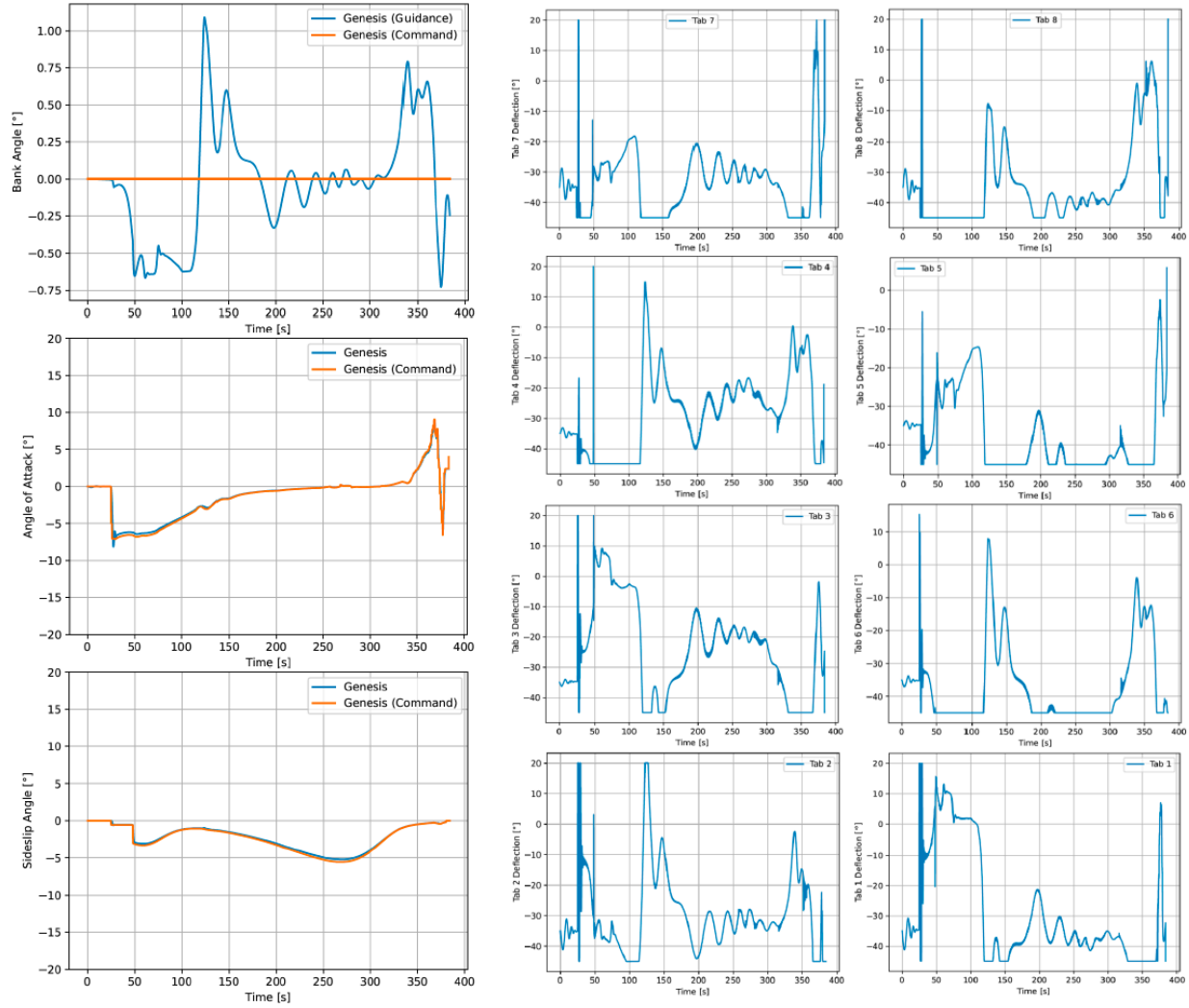


Figure 15: Wind Angles and Flap Deflection Responses for Changed Target Values (Target Final: Mach 4.4)

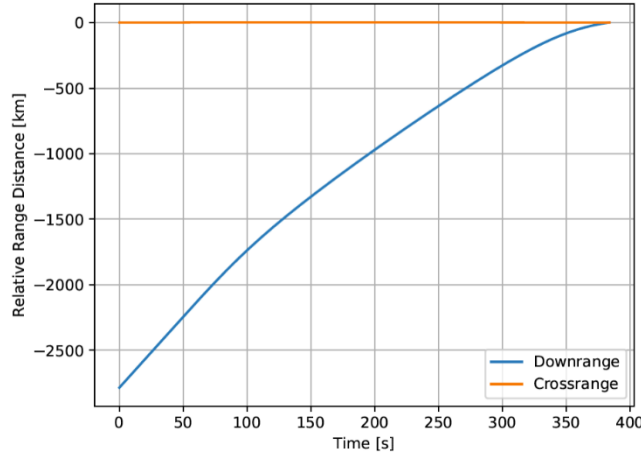


Figure 16: Range Distance for Changed Target Values (Target Final: Mach 4.4)

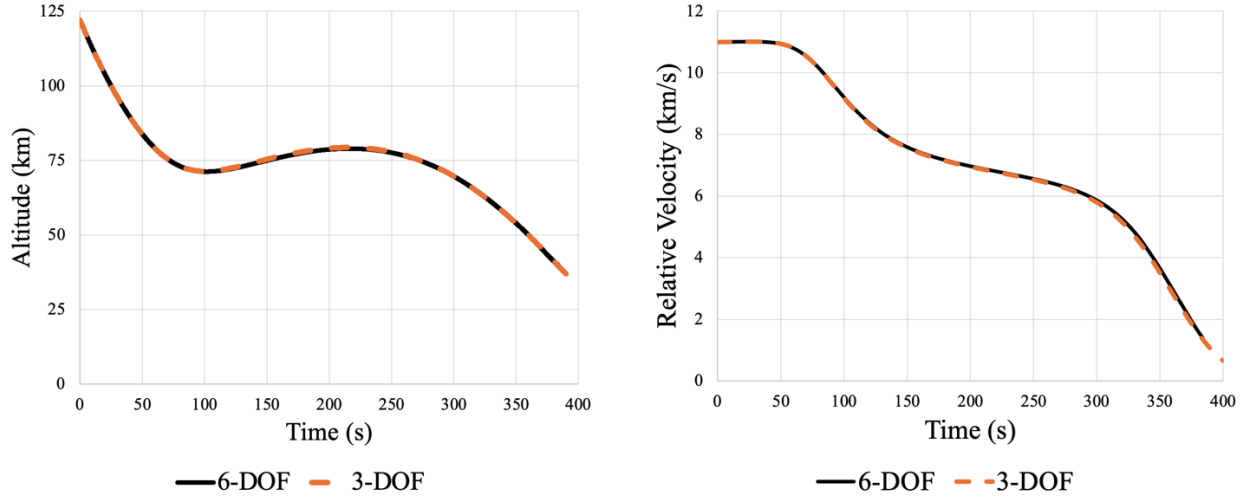


Figure 17: Altitude and Velocity for Changed Target Values (Target Final: Mach 4.4)

It may be noted that for both simulations, with baseline guidance target conditions and with the updated target velocity, saturation of the flaps is observed at varying points throughout the trajectory (Figure 12 and Figure 15). This behavior is known to be undesirable and necessitates further study to alleviate.

B. Implementation of Integrated 6-DOF Simulation with Yaw-To-Bank Control and FNPEG Guidance

The process of implementing the yaw-to-bank LQR controller into Genesis is similar to that of the alpha-beta LQR controller process described above. In each of the verification scenarios, the full 6-DOF dynamics were integrated, starting at the initial conditions described in Section III.A, using vehicle parameters for PBV-IIa in Table 1, and simulated for a full trajectory to assess the integrated simulation. The key differences between the two implementations are the Pterodactyl vehicle model, the gain matrices used in the controller (for yaw-to-bank, these are K_{ab} and K_{bank}), and the guidance output, which is now bank angle. Lessons learned through the implementation of the alpha-beta implementation are incorporated in the yaw-to-bank counterpart.

The yaw-to-bank control system was implemented after observations of roll increase that comes from an out of bounds sideslip angle due to the dihedral effect. For yaw-to-bank, the inner loop and outer loop LQR controllers have independent Q and R matrices which allow tuning of each control loop's behavior. It was assumed that the linearization point for both loops would be the same.

1. Open Loop and Controller Tuning

Similar methodology to the alpha-beta implementation (as described in III.A) was employed for the yaw-to-bank architecture. This process includes confirming the aerodatabase, mass properties, and simulation inputs with open loop cases then hold angle cases were used to test simulation response to controller inputs. The hold angle cases were successful and, for brevity, are not included. The yaw-to-bank controller employs novel mechanisms to alter the bank angle command via bank angle limits. Changes to the implementation of this limiter, at values of $\leq 1^\circ$, manifested a bank angle response that is highly dynamic and oscillatory as shown in Figure 18, indicating appropriate tuning to this limiter must be made.

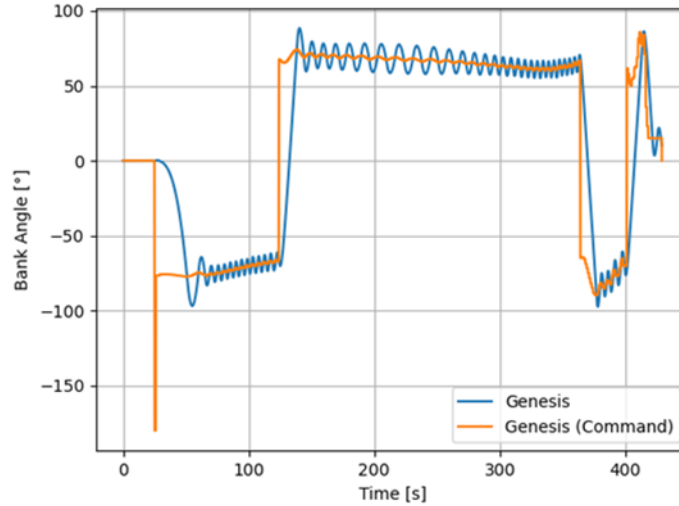


Figure 18: Bank Angle Response for Yaw-to-Bank with Non-Baseline Bank Angle Limit Case (Guidance on, Control on)

2. Guidance On, Control On

As mentioned previously, one of the major parameters that goes into designing gains is dynamic pressure. Increased dynamic pressure is generally expected to produce greater stability in the response throughout the trajectory as was observed for alpha-beta. In the case for yaw-to-bank, low dynamic pressure alone with a low bank limit was very slow and provided no tracking before eventual skip-out. However, when the bank limit is modified to larger values, e.g. bank limiter $\geq 10^\circ$ and combined with a low dynamic pressure of 100 Pa, it was empirically found that this combination creates favorable tracking, as shown in Figure 19, Figure 20, and Figure 21. Note that no adjustments to the costs were made to get the tracking needed. The crossrange miss distance is -36 meters and the downrange miss distance is 91 meters.

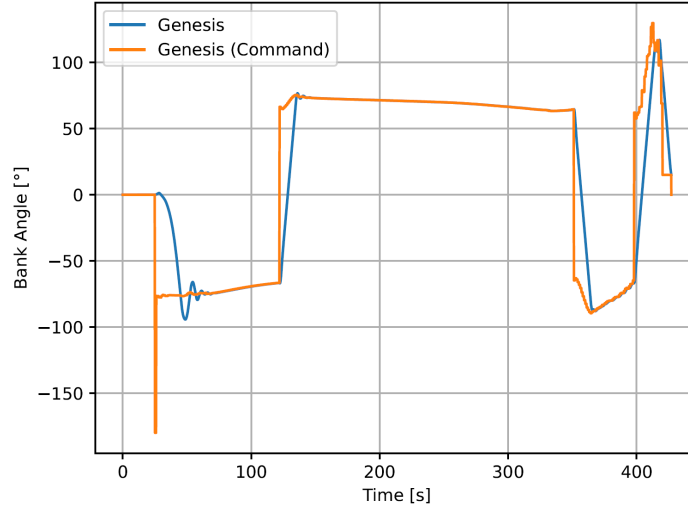


Figure 19: Bank Angle Response for Yaw-to-Bank with Controller Derived at 100 Pa Dynamic Pressure Case

This system depends on yaw to achieve a desired bank angle, so there are changes in the sideslip angle to achieve a roll moment through the dihedral effect that gives the desired bank angle command. At the beginning of entry, the slew rate for bank is slow as this is a low dynamic pressure regime with little force or moment actuation to impact vehicle dynamics from the flaps. In other words, the flaps are not experiencing significant dynamic pressure and therefore are not able to generate a noticeable or rapid vehicle response to achieve tracking at the beginning. As dynamic pressure increases and a bank reversal is commanded, the vehicle can achieve that bank command as the flaps can now impact force and moments. The vehicle flaps do not saturate as frequently in the yaw-to-bank architecture as compared to the alpha-beta architecture (Figure 12 vs. Figure 21). In comparison to the 3-DOF yaw-to-bank simulation results depicted in Figure 9, Figure 19 shows the bank angle commands have a similar profile and that the 6-DOF simulation is able to achieve this. However, Figure 20 shows a greater magnitude of sideslip angle excursions, $\sim 15^\circ$ compared to $\sim 5^\circ$ shown in Figure 9, possibly due to additional degrees of freedom in 6-DOF.

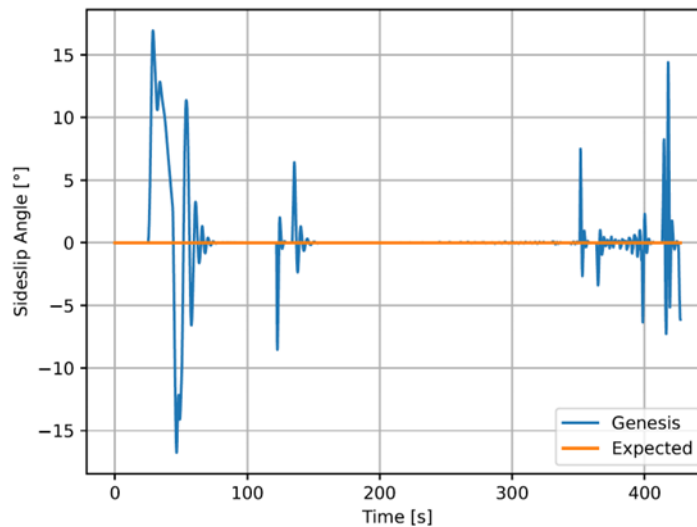


Figure 20: Sideslip Angle Response for Yaw-to-Bank 100 Pa Dynamic Pressure Case

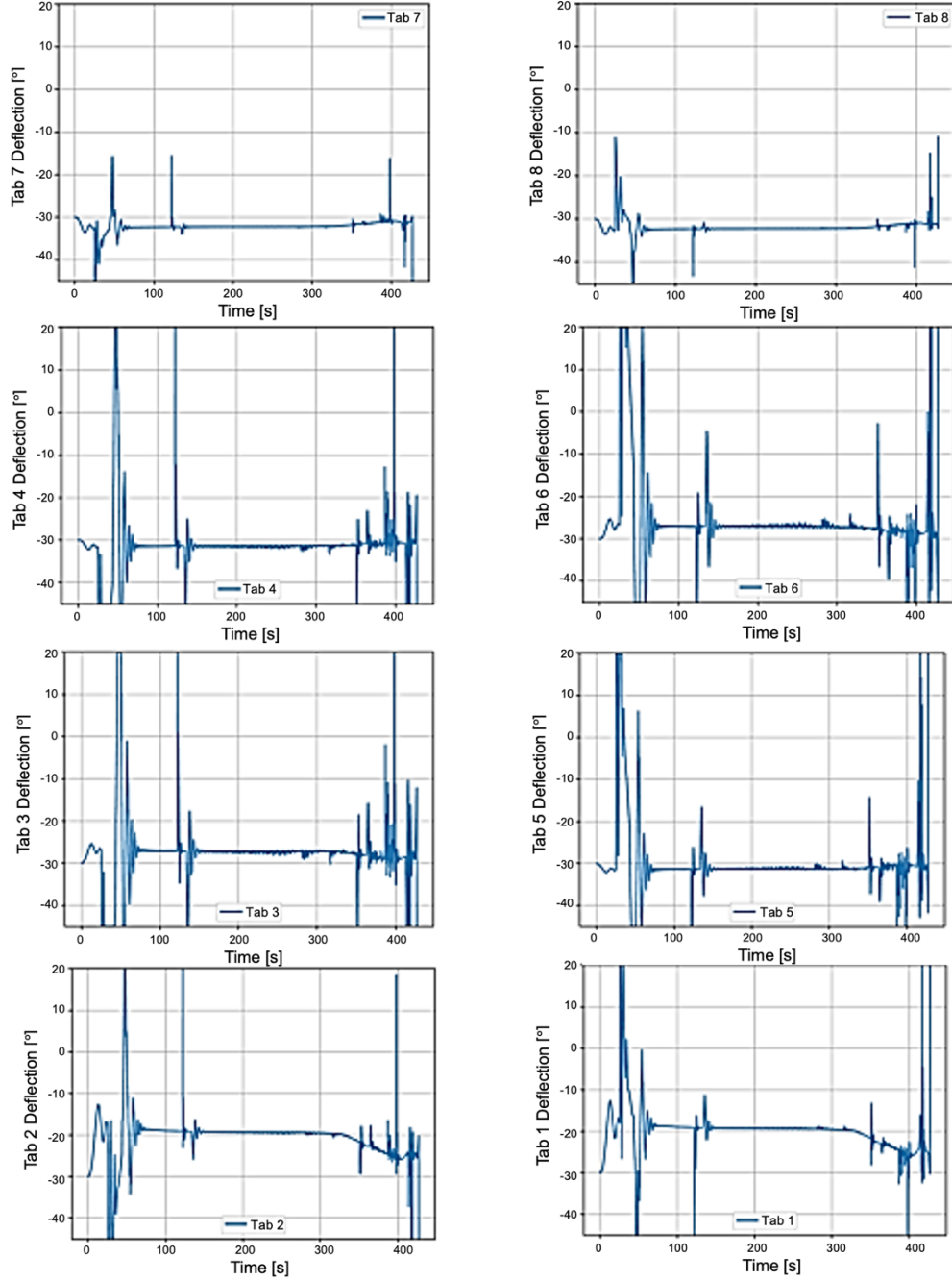


Figure 21: Tab Deflection Response for Yaw-to-Bank with 100 Pa Dynamic Pressure Case

IV. Discussion

Both alpha-beta and yaw-to-bank control architectures achieved qualitatively good tracking and performance and met the 3 km miss distance requirement as discussed above. It was found that the yaw-to-bank control architecture offers better targeting with fewer instances where the vehicle had to respond to rapid control inputs. The aerodynamic database is dependent on angle of attack and sideslip angle and since the yaw-to-bank controller holds angle of attack constant and minimally alters the sideslip angle, the aerodynamic forces change less throughout the simulation and during larger control events as compared to the alpha-beta controller. This makes the yaw-to-bank controller less sensitive to differing flight regimes (dynamic pressure, Mach) and offers greater controllability with shorter saturated

flap deflection instances. There are questions concerning the tracking performance for both simulations that can be investigated in future works which are respectively detailed in this section. An additional point of investigation is the effect of the prescribed rate for the controller `FlightSoftwareRateGroup`. As mentioned under Section G., the prescribed rate employed was 500 Hz. Further sensitivity tests need to be conducted to understand the effect on tracking and simulation performance by decreasing or increasing this rate. An area of development that can be assigned for future work is the development of a code base or module that calculates the gain matrix within Genesis. This will eliminate the process of calculating the gain matrices from the original Python code base, a-priori, and inserting them back into the integrated Genesis simulations. Overall, the stability and sensitivity of the integrated alpha-beta and yaw-to-bank controllers in Genesis require further dedicated investigations and development.

A. Angle of Attack and Sideslip (Alpha-Beta)

To achieve acceptable tracking performance and final position values that align with the intended target, the 6-DOF simulation required tuning the controller and adjusting the default gain matrix, `Kmat`. In comparison to the established 3-DOF simulation, the 6-DOF required a `Kmat` designed with a higher dynamic pressure and higher alpha cost. This may be due to the increase of degrees of freedom in the flight simulation requiring more of a “push” to achieve accurate tracking. In other words, higher degrees of freedom require greater control authority which can be translated to higher gain values from increased dynamic pressure and alpha cost within the controller set `Kmat`.

The “best” performance of tracking with the baseline, or original, guidance target conditions was achieved using a gain matrix designed with a higher dynamic pressure and increased alpha cost. The loss of tracking of the alpha-beta controller near the end of the trajectory, around 380 seconds, shown in Figure 12 and Figure 22, is conjectured to be a result of one or a combination the following:

1. Aerodynamics of the vehicle for Mach < 5
2. Aspects of the mission are driving the vehicle out of its control envelope
3. Guidance parameters in 3-DOF mode no longer valid in 6-DOF
4. The application of a linear controller to a non-linear system.

To expand on hypothesis (1.), Mach 5 was found to have non-monotonic aerodynamics as compared to larger Mach numbers, possibly because the CFD from which the aerodynamics were derived, Cart3D, is typically used for hypersonic regime applications (inviscid assumption). Because of this, forward work necessitates investigation of higher fidelity aerodynamic modeling at these lower Mach numbers (below Mach 5) to disentangle aerodynamic modeling impacts from controller and guidance capabilities. Relevant to hypothesis (2.), the control envelope in Figure 6 of [5] shows the commanded states as achievable, although a more thorough 6-DOF control envelope study needs to be conducted. For (3.), the target Mach was modified after establishing the best iterated `Kmat` in the controller, and as shown Figure 15, excellent tracking was noted throughout the simulation, and the final crossrange miss distance was only 2.6 meters. This result shows that future work on tuning the guidance parameters will be needed to ensure a terminal point Mach ≤ 2 because higher Mach number targets imply larger parachute systems, posing packaging and mass challenges. Changes may include modifying the target location for a given entry interface location, modifying the final angle of attack to preserve more lift capability, or modifying the side slip gains in the lateral channel. As for the final hypothesis (4.), the loss of tracking could be due to the current controller not translating well with the system. It is further considered that the problem may lie in the contradictory notion of trying to solve a non-linear problem with a linear solution. It is noted that concurrent with the loss of tracking in Figure 22 (near 380 seconds), there is an associated build-up of bank angle, highlighting the integrated, entangled parameters of interest and response in this problem. All of the above necessitate further investigation and dedicated study in future work.

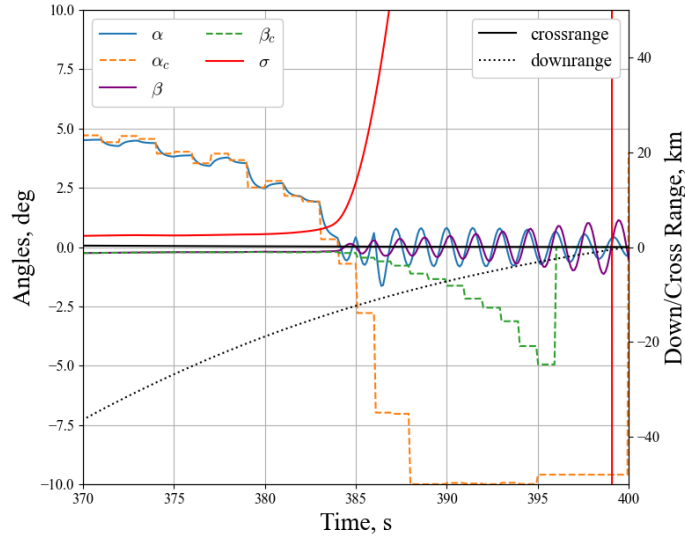


Figure 22: Relevant Parameter Zoom in of Alpha-Beta with Tracking Loss (Target Final Energy: Mach 2.1)

B. Robustness (Yaw-To-Bank)

The yaw-to-bank control architecture performance, shown in Figure 19, while not exhibiting perfect tracking and noted delayed slew rates in the first bank reversal (conceivably due to the low dynamic pressure), exhibited reasonable range targeting performance at 99 m total miss distance. The delayed slew rate causes a spike in the bank profile at the beginning of the trajectory. The reason for this is that the guidance algorithm expects bank rate and acceleration limits of $15^\circ/\text{s}$ and $5^\circ/\text{s}^2$, respectively, but the controller is much slower. The spike in the bank profile can be resolved by reducing the bank rate and acceleration limits to match the controller performance. Also, note that the bank angle shoots up at the end of the trajectory, indicating that the final bank for the energy profile can be tuned. The final bank angle target, in the bank energy profile, was set to 60° in both the 3-DOF and 6-DOF simulations. This value of final bank was selected to preserve some lift margin for dispersions towards the end of the trajectory. The bank profile spike towards the end of the trajectory indicates that there was a large margin of lift preserved that had to be guided out to not overshoot the target. Therefore, the final bank in the energy profile can be reduced to improve tracking in this region. This change will not affect the ability to maintain good control down to Mach 2 and will likely result in maintaining acceptable control to subsonic Mach numbers, easing packaging challenges of potential parachute descent systems. Finally, while the times at which the sideslip angle spiked were expected, at low dynamic pressure or at bank reversal points, the magnitude of the spike was not desirable due to control surface edge and aft body heating concerns. The authors believe that these heating concerns are manageable, but a Monte Carlo study should be performed to find the maximum spike in sideslip. Trends associated with controller changes such as cost parameters and state inputs were inconsistent and non-linear making this architecture an ideal candidate for a dedicated Monte Carlo study in its controller design. This could probe robustness and be used to determine the shape of the optimal design space considering all input variables, such as gain set costs and linearized state inputs.

V. Conclusions

The objectives of this work, to integrate two different guidance and control algorithms in a 6-DOF trajectory simulation, were successfully completed for a deployable vehicle with eight individually articulating flaps. Angle of attack and sideslip control (alpha-beta) showed good tracking until the end of the trajectory around 380 seconds. Results indicate that a controller derived at a high dynamic pressure and with an increased alpha cost condition gives the best performance in terms of tracking. However, when the vehicle Mach crosses 5 oscillations and tracking degradation are noted down to Mach 2. Gain scheduling in the angle of attack and sideslip controller was investigated in a variety of schemes with no obvious benefit in performance or tracking noted. Previous work in Margolis [5] with uncoupled 3-DOF simulations also did not employ gain scheduling, and the best performing controller in that case was derived at low dynamic pressure conditions. A controller derived at a high dynamic pressure condition

conceivably employs greater control authority and generates more rapid individual responses from the flaps. From this, it may be inferred that additional control authority is necessary when the simulation incorporates additional degrees-of-freedom. Possible reasons include cross-coupling of terms to excite rotation modes not obvious in 3-DOF, energy transfer between degrees-of-freedom, and an overall more excited system. Future work would consist of investigating the event behind this loss of tracking more extensively.

Yaw-to-bank controller showed that the best performance was under a gain set designed for lower dynamic pressure. This aligns with what was done with previous work done in a 3-DOF yaw-to-bank simulation with a controller implemented. Results from this 6-DOF study also showed that greater magnitudes for sideslip angles are needed in order to achieve the desired commanded bank angle. The controller performs best in regions where the dynamic pressure is larger. At the beginning of the trajectory, the dynamic pressure is too low for the flaps to respond well. While both alpha-beta and yaw-to-bank achieved a miss distance within requirements and acceptable tracking performance, additional effort is necessary to determine the control loss of alpha-beta and characterize robustness of yaw-to-bank and investigate its applicability to other case studies.

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