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PREDICTIVE LATERAL LOGIC FOR NUMERICAL ENTRY GUIDANCE ALGORITHMS

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Recent entry guidance algorithm development[1][2][3] has tended to focus on numerical integration of trajectories onboard in order to evaluate candidate bank profiles. Such methods enjoy benefits such as flexibility to varying mission profiles and improved robustness to large dispersions. A common element across many of these modern entry guidance algorithms is a reliance upon the concept of Apollo-heritage lateral error (or azimuth error) deadbands in which the number of bank reversals to be performed is non-deterministic. This paper presents a closed-loop bank reversal method that operates with a fixed number of bank reversals defined prior to flight. However, this number of bank reversals can be modified at any point, including in flight, based on contingencies such as fuel leaks where propellant usage must be minimized.

INTRODUCTION

Recent entry guidance algorithm research[1][2][3] has yielded several algorithms that numerically integrate the equations of motion for a gliding entry vehicle to some terminal state. Based on some error signal defined by the deviation of the predicted terminal state from some desired terminal state, the bank angle profile is updated so as to minimize the terminal errors. This process is repeated until satisfactorily small terminal errors are achieved. Once this error tolerance is met, the guidance algorithm produces a bank angle command to be effected by the spacecraft's attitude control system.

Moving away from an analytical predictor-corrector methodology to a numerical predictor-corrector (NPC) methodology forces a large quantum increase in software complexity. However, many modern NPC algorithms only utilize their NPC for the longitudinal targeting channel (downrange). In several instances, the bank reversal logic is based upon a simple error deadband scheme[4][5],[6] which draws heritage from earlier vehicles like Apollo, the Space Shuttle, and the Mars Science Laboratory *Curiosity* entry vehicle. In this simple concept, the vehicle will reverse the sign of its bank angle when its lateral angle error (or azimuth error) relative to the target exceeds some deadband. Typically, the lateral error deadband is defined as some function of velocity, and is frequently modeled as a first-order or second-order polynomial.

$$Lat_{DB} = c_0 + c_1 V^2 \tag{1}$$

Such an approach requires the designer to specify c_0 and c_1 to obtain satisfactory performance. This set of coefficients determines how large of lateral excursions are tolerable based on the current velocity. As the vehicle proceeds through its trajectory, its lateral error will ping-pong back and forth

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within the deadband, bouncing from one side of the constraint to the other. As a result, the number of bank reversals performed is stochastic. From Monte Carlo analysis, a designer can attempt to find a set of deadband coefficients which produce suitable behavior, but there will be no direct control over the number of bank reversals performed.

This uncertainty forces spacecraft designers to budget for the worst-case propellant consumption during entry, which leads to increased propellant usage, creating the need for larger propellant tanks (increased spacecraft dry mass). Given the desire to minimize spacecraft dry mass to maximize payload, it would be desirable to be able to constrain the number of bank reversals to a fixed number so that propellant consumption caused by bank reversals can be constrained throughout entry flight.

ALGORITHM DEVELOPMENT

Assuming that a numerical predictor-corrector algorithm is available, then the terminal state of the trajectory for the converged bank profile can be determined. It is assumed that the converged bank profile contains no changes in bank angle sign.

Once the longitudinal channel (downrange targeting) has converged, the terminal state corresponding to that converged bank angle profile is available. If the vehicle were to also determine the bank profile with the opposite sign that also minimizes the terminal downrange error, the "opposite terminal state" would be available. From a given terminal state, the terminal crossrange error can be readily computed. Let the terminal crossrange error from the current converged bank angle profile be defined as χ^+, and let the opposite terminal crossrange error from the opposite bank profile be defined as χ^-. See Figure 1 for a graphical illustration.

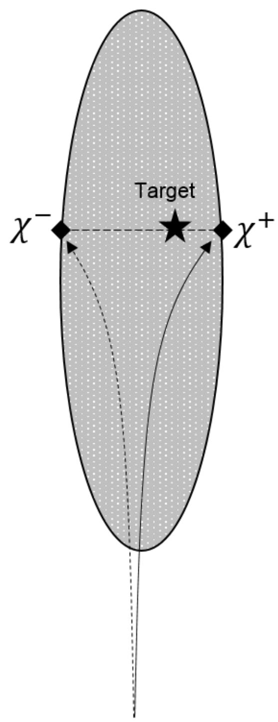

Figure 1. Illustration of notional vehicle capability footprint with terminal crossrange errors for the current bank angle and opposite signed bank angle profile.

As the vehicle flies its current bank angle profile, it depletes energy through drag. As a result, the vehicle's crossrange capability in the opposite direction reduces over time as the vehicle proceeds down its current path and simultaneously depletes energy. Consequently, the opposite terminal crossrange error will shrink over time. During this interval, the current terminal crossrange error is unchanged. See Figure 2.

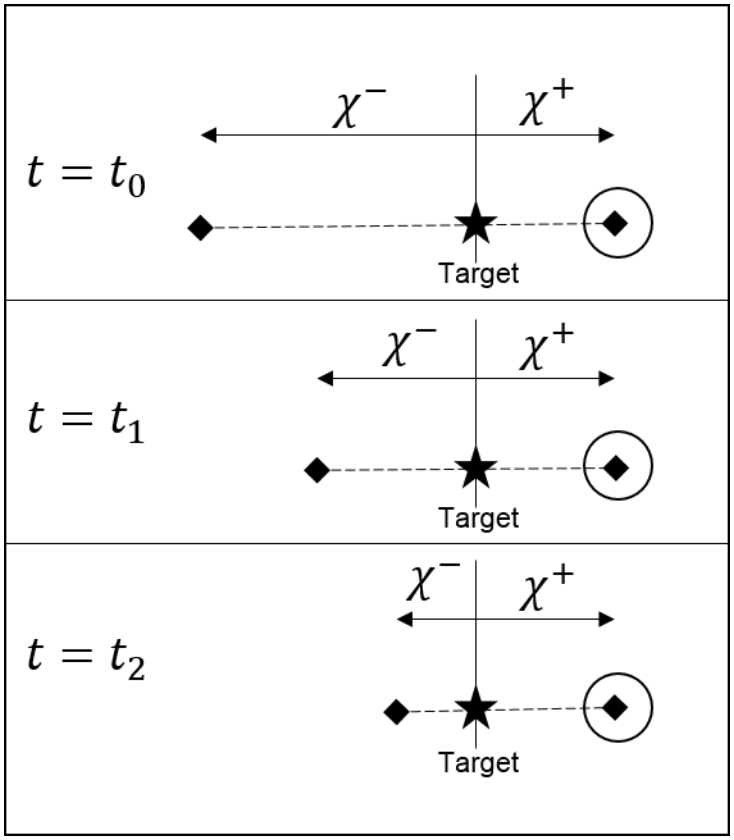

Figure 2. The vehicle has a positive bank angle, and the predicted terminal crossrange error is denoted as χ^+. The opposite terminal state has a crossrange error denoted as χ^-. As the vehicle depletes energy while flying toward the right side of the footprint, the opposite crossrange capability shrinks over time.

If we proceed down the current path for too long, the vehicle will lose its ability to achieve the target. This condition occurs when the opposite terminal crossrange error is exactly 0.

To prevent this from occuring, the algorithm should execute a bank reversal once the opposite terminal crossrange error becomes significantly smaller (in magnitude) than the current terminal crossrange error. In other words, once the ratio of $|\frac{\chi^+}{\chi^-}|$ becomes too large, then a bank reversal should occur.

At this point, the question is what constitutes "too large" of a ratio to trigger a bank reversal? A trajectory designer may have an intuitive feel that the ratio should not exceed some number K, say $K = 4$ for example. This implies that a bank reversal will only occur when the magnitude of the current terminal crossrange error is 4 times larger than the magnitude of the opposite terminal crossrange error.

If a bank reversal occurs when the current terminal crossrange error is $\chi^+ = +100km$ with a $K = 4$, this implies that the opposite terminal crossrange error is $|\chi^-| \leq 25$km. For now, assume that the bank reversal is instantaneous, or that the trajectory prediction using the opposite bank profile accurately modeled a finite bank reversal maneuver from its current bank angle. In either case, upon executing a bank reversal, the new "current" terminal crossrange error becomes $\chi_i^+ = \chi_{i-1}^- = 25$km. With a fixed value of $K = 4$, the next bank reversal will occur when $|\chi^-| \leq \frac{\chi^+}{K}$ or when $|\chi^-| \leq 6.25$ km $\leq 25/4$. At that point, the "current" and "opposite" terminal crossranges switch again, and the cycle repeats until entry guidance terminates.

The reader may notice that the vehicle's terminal crossrange is geometrically reduced at each bank reversal by the constant factor of $1/K$. For a given number of bank reversals n, some value of K, and some terminal crossrange error at some initial condition χ_0, the terminal crossrange error after n bank reversals may be expressed as:

$$|\chi_f| = \frac{|\chi_0|}{K^n} \tag{2}$$

If the final terminal crossrange error is specified (must be larger than zero), then the equation can be re-arranged to solve for either K or for n.

$$K = \left|\frac{\chi_0}{\chi_f}\right|^{1/n} \tag{3}$$

$$n = \frac{\log\left|\frac{\chi_0}{\chi_f}\right|}{\log K} \tag{4}$$

This simple formulation can be easily converted into a closed-loop bank reversal algorithm by simply replacing the initial χ_0 with the current $\chi(t)$, specifying the number of bank reversals remaining to be performed (n), and defining the terminal crossrange error tolerance χ_f. With these parameters defined, the formulation becomes:

$$K = \left|\frac{\chi(t)}{\chi_f}\right|^{1/n} \tag{5}$$

If $|\chi(t)/\chi^-| > K$, then a bank reversal is commanded, and n is decremented by one. This process repeats until $n = 0$.

COMMENTARY

Robustness and Lateral Parameter K

For robustness of the entry guidance, it is recommended that the value of K not exceed some upper limit. Recall that the terminal crossrange errors are determined via numerical trajectory predictions which are dependent upon assumptions about the vehicle's aerodynamic parameters and atmospheric properties. If the vehicle's modeling of the environment and vehicle performance deviates from the truth, then the predictions, including the terminal crossrange error, will be in error.

For large values of K, the vehicle will allow the guidance target to become quite close to the predicted crossrange capability. If this predicted capability is overpredicted by the vehicle, then the guidance system may not command a bank reversal prior to the target falling outside the true crossrange capability.

However, for small values of K, like $K = 2$, the guidance system works to keep the target well-centered within the cross-ranging capability of the vehicle. This benefit comes at the cost of performing more bank reversals and associated propellant consumption.

Existing work[7] demonstrated how terminal crossrange errors can be somewhat controlled by performing a carefully timed single bank reversal. Such an approach is functionally equivalent to setting K to be a very large number. Such an approach is theoretically possible, though it is not expected to perform well under large uncertainty or dispersions. Instead, by executing more than 1 bank reversal, the guidance algorithm is not staking its accuracy on a single critical bank maneuver.

The amount of crossrange capability consumed with each bank reversal is equal to $K/(K+1)$. For $K = 10$, this implies that the vehicle will fail if its crossrange prediction is overpredicted by $1 - 10/(10+1) = 9.09\%$. As a result, for early flights of new vehicles when uncertainty in vehicle properties (mass properties, aerodynamic performance) is elevated, it may be advisable to set K to a lower value such that less is staked upon accurate prediction of the crossrange capability. As a result, an early entry vehicle would perform more bank reversals for added robustness to prediction errors. As the entry vehicle matures and its performance is better understood over several test flights, crossrange capability may be predicted with less uncertainty, which would allow the vehicle to set K to a larger value, enabling future propellant reduction. This reduction in propellant loading may enable larger payload mass once the vehicle capability is better understood.

Autonomy

With a prudent choice of K and knowledge of the initial terminal crossrange error χ_0, the number of bank reversals for a "reasonable" K can be defined using Eq. 4. This number of bank reversals will need to be rounded upwards to the nearest integer value, and then used as the initial value of the bank reversal.

$$n_0 = \left\lceil \frac{log \left| \frac{\chi_0}{\chi_f} \right|}{log K_{Reasonable}} \right\rceil \tag{6}$$

Once this value of n_0 is obtained, then the entry guidance can proceed as before by computing K dynamically based on the values of $\chi(t)$, n, and χ_f.

The value of this is approach is that the vehicle can be even more autonomous to respond to off-nominal situations beyond the original designer's plans with need for ground intervention.

Edge Cases If $|\chi_0| < |\chi_f|$, then the logarithm of that ratio will be a negative number. To prevent this, one should ensure that the ratio is constrained such that the floor is zero. If that were unconstrained, the result would be a command for "negative" bank reversals (not physically realizable) that would serve to increase the maximum terminal crossrange error to the χ_f value.

PERFORMANCE & USAGE

This lateral logic scheme was developed in late 2010 and remained unpublished. Upon collaboration with Ping Lu to evaluate the Fully Numeric Predictive Entry Guidance (FNPEG) algorithm in 2015, the author suggested this approach to Dr. Lu to eliminate the tuning of a lateral corridor. Dr. Lu has incorporated this algorithm into his baseline FNPEG algorithm[8] and it has demonstrated excellent performance without requiring any tuning (consistent with the design philosophy of FNPEG).

This algorithm is designed to be easy to implement within existing numerical predictor-corrector entry guidance algorithms, and it is largely agnostic of the longitudinal channel. Its most basic requirements are that the longitudinal channel accounts for the effects of the signed bank angle in its numerical prediction and that no bank reversals are modeled within longitudinal. In other words, for an entry guidance algorithm with a fully decoupled longitudinal and lateral channel, this bank reversal algorithm should be considered as a viable candidate.

SUMMARY

The algorithm described in this paper enables the spacecraft designer to deterministically fix the number of bank reversals that will be performed by the entry guidance system. Additionally, the algorithm is sufficiently flexible to allow a change in the number of bank reversals to be performed, enabling operational restrictions on propellant consumption in the face of contingency scenarios. This algorithm also enables greater control over the propellant consumption, which reduces uncertainty in propellant budgeting, enabling potential reductions in spacecraft mass.

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