EVALUATION OF THE GENERALIZED EXPLICIT GUIDANCE LAW APPLIED TO THE BALLISTIC TRAJECTORY EXTENDED RANGE MUNITION

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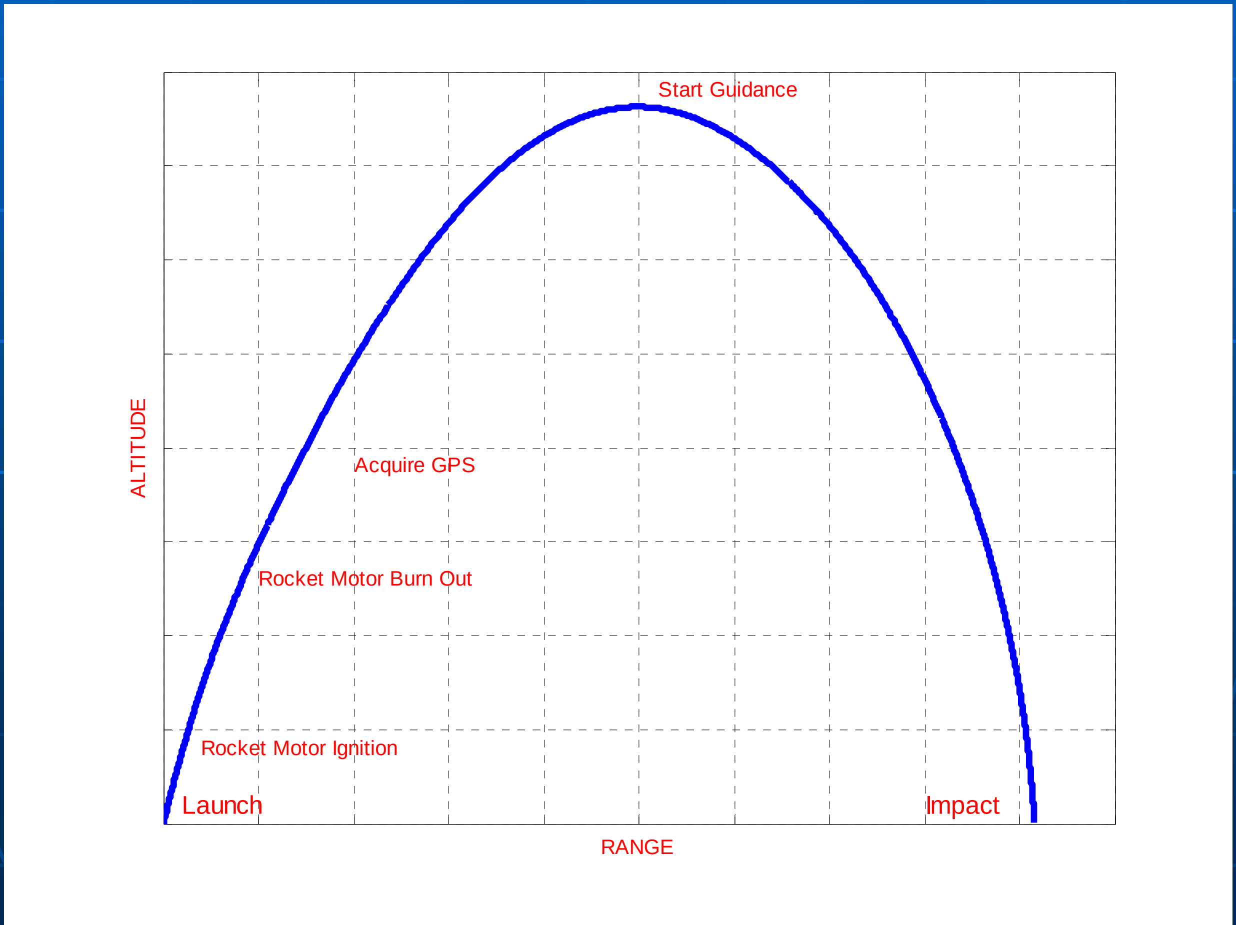
INTRODUCTION

- This paper evaluates the performance of an NSWCDL developed guidance law (GENEX) when applied to the Ballistic Trajectory Extended Range Munition (BTERM)
- BTERM is a 5" gun launched rocket assisted projectile that uses onboard guidance along with an integrated inertial navigation system (GPS/INS) to engage ground based stationary targets at various ranges
- BTERM is currently being developed and flight tested under a demonstration program for the U.S. Navy by Alliant Techsystems (ATK) to demonstrate alternative precision munition concepts that can meet or exceed the Naval Surface Fire Support (NSFS) requirements
- The BTERM system design is based closely on a similar projectile known as the Autonomous Naval Support Round (ANSR) [1,2]
- The ANSR system concept was originally proposed by NSWCDL as a low cost and low risk munition.

BTERM CONOPS

- The BTERM/ANSR concept uses a large rocket motor to achieve an extended range by following a near ballistic path with no “gliding”



BTERM CONOPS

- BTERM uses a single axis control system (autopilot) that consists of a pair of canards for lateral control and tail fins for stability
- The canards are deployed just prior to guidance activation which typically occurs at apogee; the fins are deployed right after gun exit
- The projectile rolls about its longitudinal axis throughout the flight at a rate of 20-30 Hz and uses roll commutation to translate guidance commands to canard deflection commands
- Successful flight tests conducted at the White Sands Missile Range (WSMR) in 2003 (and more recently at Yuma Proving Ground in 2006) have demonstrated that the Guidance, Navigation and Control (GNC) concepts used by the ANSR/BTERM projectiles are highly effective[3]

GUIDANCE BACKGROUND

- The main purpose of using a guidance law in general, is to ensure that an objective such as hitting the target or achieving an acceptable miss distance at intercept or impact is realized
- Traditional guidance laws such as Proportional Navigation (PN) and other laws based on line of sight guidance are generally adequate for achieving the requirement of minimal miss distance
- *Many missiles/projectiles (such as the BTERM) may have additional constraints at intercept or impact that traditional guidance laws are not designed to achieve*
- Examples of typical additional constraints
  - Control of projectile flight path angle (velocity vector) at impact
  - Control of projectile attitude angle at impact
  - Control of projectile speed at impact
  - Control of time of flight

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GENEX GUIDANCE LAW

- The GENEX guidance law was developed at NSWCDL for application to missiles, projectiles and unmanned vehicles. It is a generalization of an earlier guidance law known as Explicit Guidance[4] (E-Guidance)
- GENEX shapes the trajectory so that the specified terminal geometry (velocity vector or flight path) is achieved at impact while minimizing the miss distance
- Unlike the original E-guidance law, GENEX allows the designer to control the extent of the trajectory shaping through the use of a selectable parameter (n) that controls how “aggressively” the shaping is done

GENEX GUIDANCE LAW

- Mathematically, the cost function used for derivation of the GENEX law is :

$$J = \int_0^{T_0} \frac{u^2}{2T^n}$$

where T is the projectile time to go, u is the control effort (acceleration), and n is a user selectable quantity that specifies how much curvature (aggressiveness) is desired in the trajectory

- Including the time to go in the cost function in an inverse sense, allows for greater control to be placed on the acceleration usage as T approaches zero

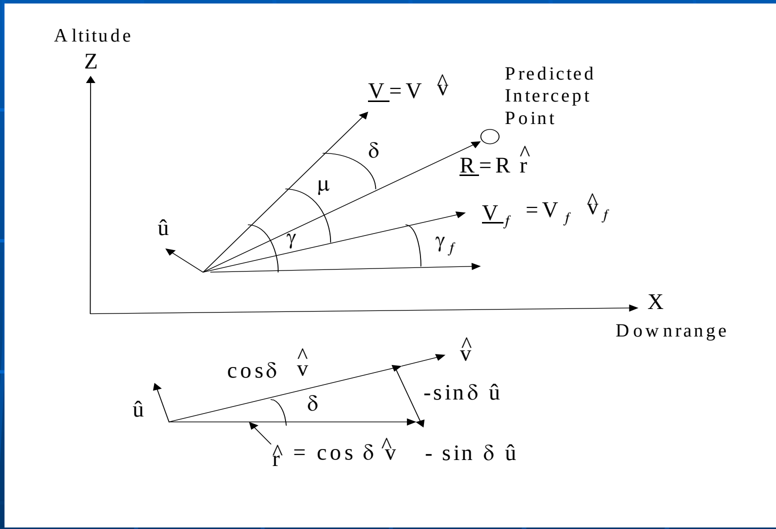
- The specification of the final velocity vector is done by including it as a constraint in the optimal control problem

GENEX GUIDANCE LAW

- Using optimal control theory, the acceleration command normal to the velocity can be shown to be[5] :

$$\underline{u}_{\perp} = \frac{V^2}{R}\left[K_1(\hat{r} - \hat{v}\cos\delta) + K_2(\hat{v}_f - \hat{v}\cos\mu)\right]$$

V *= Projectile velocity*
R*= Range to go*
δ = heading error
μ = velocity error
γ = flight path angle



- The gains K_1 and K_2 are given by

$$K_1 = (n+2)(n+3)$$
$$K_2 = -(n+1)(n+2)$$

Note: The first term is a PN like term that drives the miss distance to zero and the second term is the trajectory shaping term that enforces the specification on the final velocity vector orientation

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PERFORMANCE EVALUATION

- This evaluation is an engineering study of the feasibility of using the GENEX guidance law. Therefore, the results presented here are preliminary and not meant to be reflective of the actual BTERM (demonstration round) system performance

- For evaluation of the GENEX law, a high fidelity six degree of freedom model is used to examine BTERM trajectories from gun launch to impact

- The scenario chosen for evaluation is one where the Quadrant Elevation (QE) is 53 degrees and the target is at a range of 57 nautical miles downrange

- The main criterion used for evaluation is : Given the maneuverability limits of the airframe, how controllable is the impact flight path angle in a typical engagement scenario while keeping the miss distance small (< 30 meters)

- Performance Evaluation is done nominally (ideal conditions) as well as stochastically (inclusion of error sources for Monte Carlo runs)

PERFORMANCE EVALUATION

The system errors* considered are:

- QE error (+/- 0.9 deg)
- launch tip off errors (+/- 4.5 radian/sec)
- muzzle velocity variation (1%)
- GPS errors
- Rocket Motor (thrust variation 4.5%, ignition delay 3 seconds and burn time 1 second) errors
- atmospheric variations (winds, dynamic pressure)
- aerodynamic/mass properties errors
- guidance roll error (+/- 10 degrees)†

* 3 Sigma values specified

† Residual INS attitude error

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PERFORMANCE EVALUATION

- The goal of this preliminary guidance evaluation is to assess the range of controllability of the impact flight path angle (IFPA) when the range to target, QE, and the ignition delay of the rocket motor are specified

- A nominal QE of 53 degrees is selected which results in an IFPA of 54 degrees for a purely ballistic (unguided) flight

- The range of controllability using GENEX is then

IFPA1< 54< IFPA2

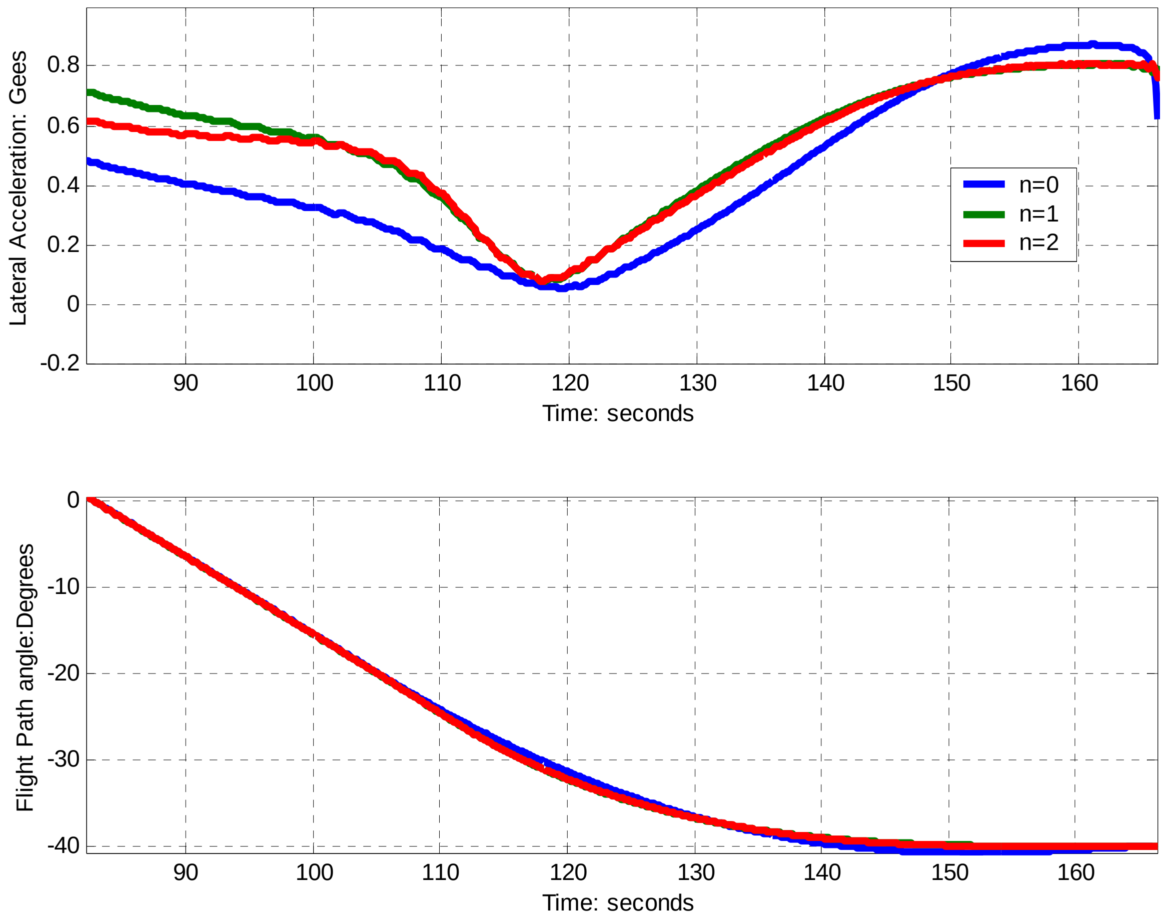
where IFPA1 is the lower limit at which the IFPA can be controlled and IFPA2 is the upper limit at which the IFPA can be controlled

For the scenario considered here it is found that,

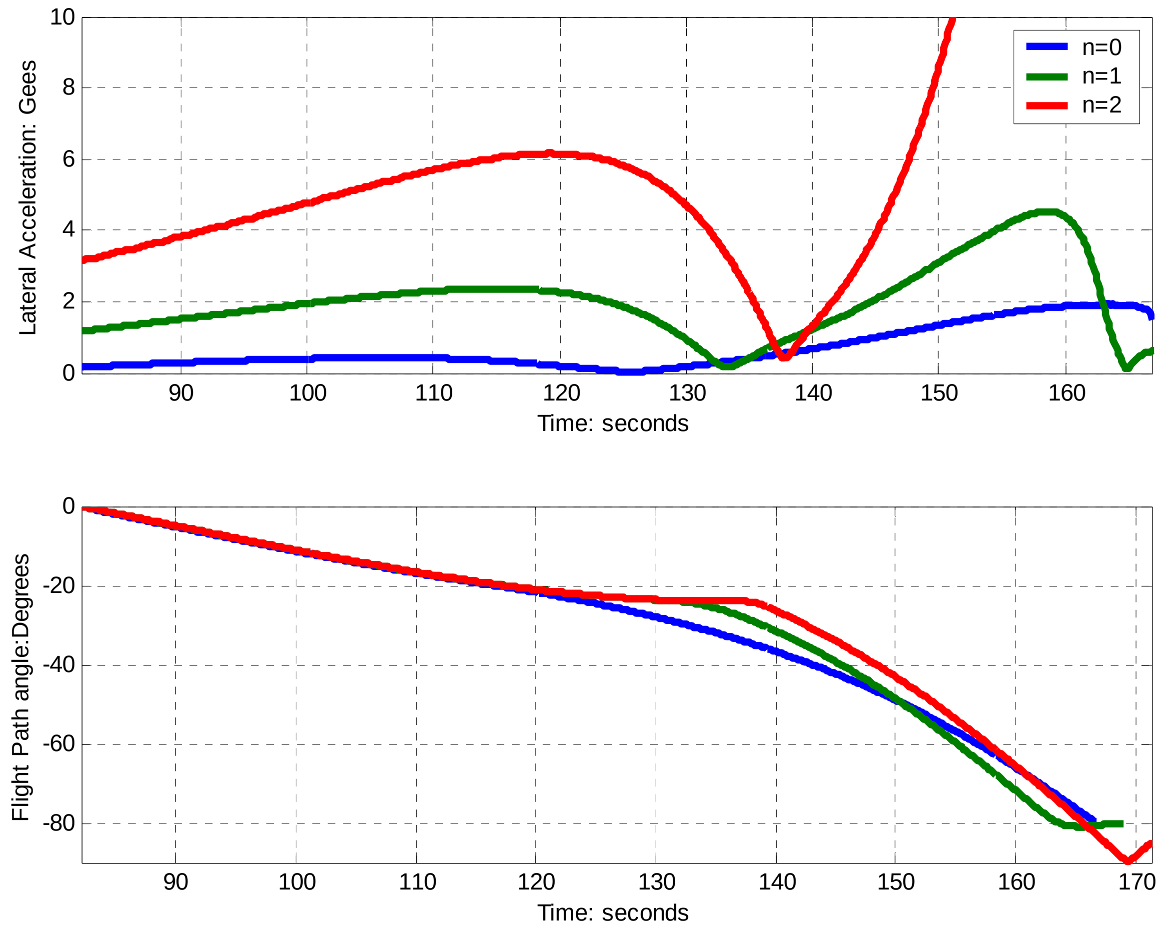
IFPA1 = 40 degrees

IFPA2 = 80 degrees

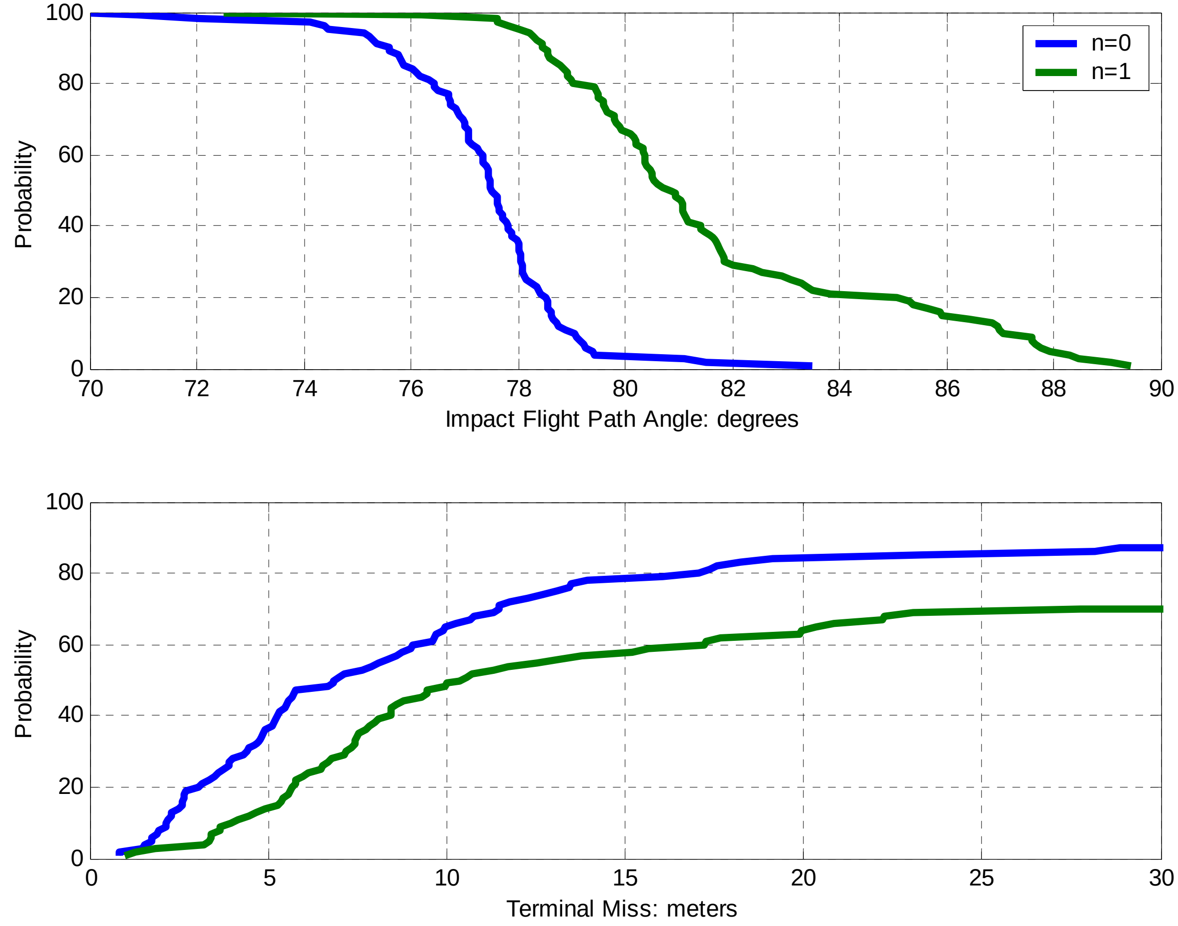
NOMINAL PERFORMANCE
(IFPA1 = 40 degrees)



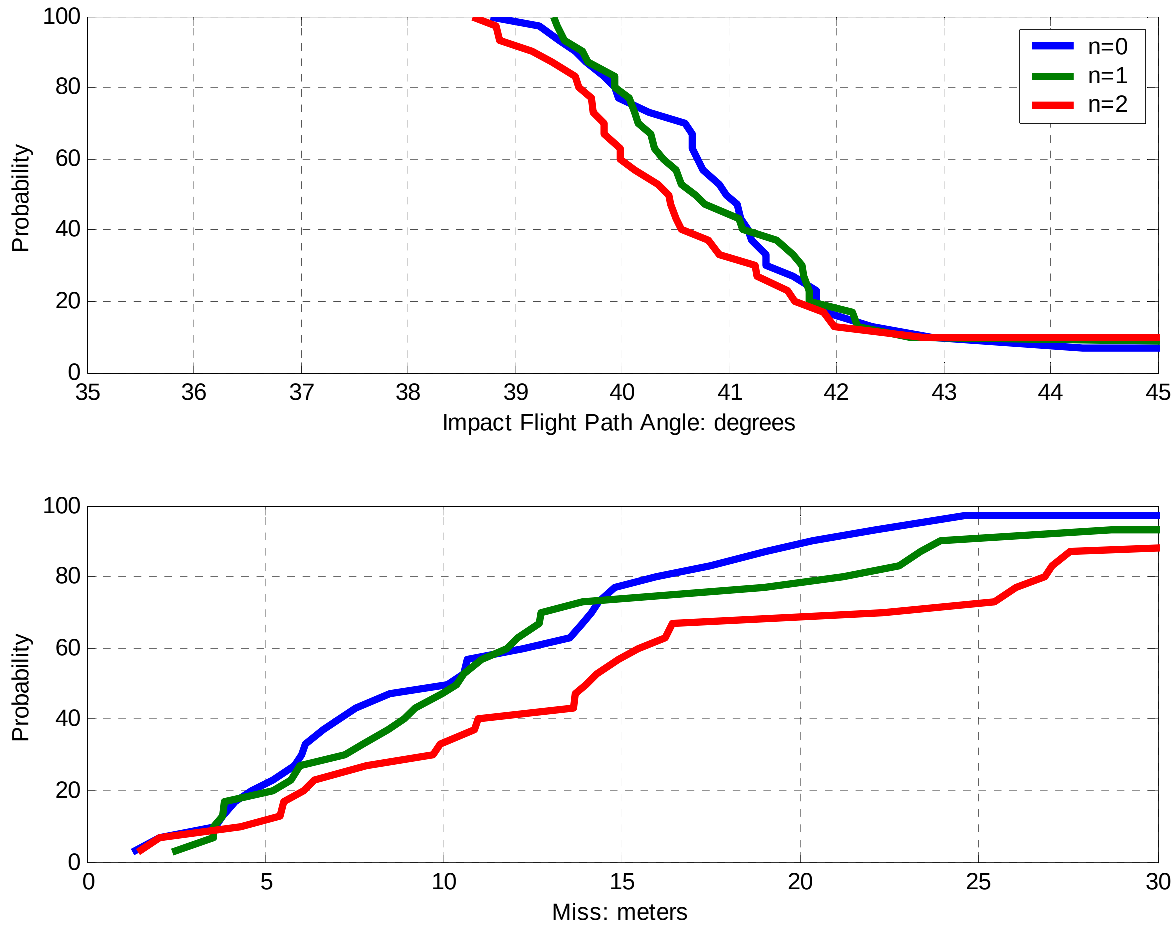
NOMINAL PERFORMANCE (IFPA2 = 80 degrees)



STOCHASTIC PERFORMANCE (IFPA2 = 80 degrees)



STOCHASTIC PERFORMANCE (IFPA1 = 40 degrees)



CONCLUSIONS

- The GENEX guidance law has been shown to be very effective in controlling the impact flight path angle and minimizing the terminal miss distance when applied to BTERM
- In general, for a given QE and ignition delay, the range of IFPA controllability is limited by the acceleration capability of the airframe, and the time to go
- The beneficial effects of increasing n (up to 2 in case of BTERM) are:
  - to make the trajectory of the projectile approach the specified IFPA quicker, and
  - to make a higher % of shots achieve the specified IFPA
- The disadvantages of increasing n are:
  - requiring a higher lateral acceleration demand during the guided flight
  - an increase in miss distance

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REFERENCES

1. *Fraysse, J. "ANSR System Definition", NAVSEA Dahlgren Power-point presentation, September 2001*

2. *Pamadi, K. B., Ohlmeyer, E.J., and Pepitone, T. R., "Assessment of a GPS Guided Spinning Projectile Using an Accelerometer-Only IMU", AIAA Guidance, Navigation, and Control Conference, AIAA-2004-4881, Providence, R.I.*

3. *Coskren, D., Easterly, T., Polutchko, R., "Low-Cost GPS/INS Guidance for Navy Munitions Launches", GPS World magazine, September 2005, page 23.*

4. *Cherry, G., "A General Explicit, Optimizing Guidance Law for Rocket-Propelled Spacecraft", AIAA paper 64-638, AIAA Astrodynamics, Guidance and Control Conference, August 1964*

5. *Ohlmeyer, E.J., "Control of Terminal Engagement Geometry Using Generalized Vector Explicit Guidance", Proceedings of the American Control Conference, Vol. 1, IEEE, pp. 396-401*

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