NAVSEA WARFARE CENTERS DAHLGREN

NAVAL SURFACE WARFARE CENTER · DAHLGREN DIVISION

GUN & ELECTRIC WEAPON SYSTEMS DEPARTMENT (E)

Flight Modeling and Simulation Capabilities for Gun and Mortar Systems

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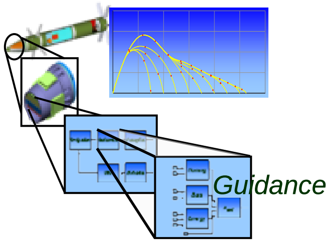
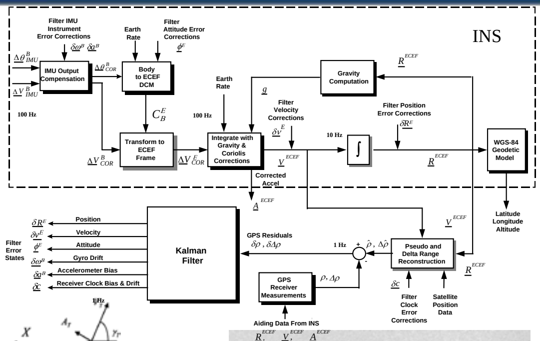
Outline

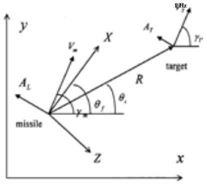
- NSWCDD Aerosciences
- Gun/Mortar Flight Modeling and Simulation (M&S) : Exterior Ballistics
- Examples of M&S/Flight Analyses
- Closing Remarks

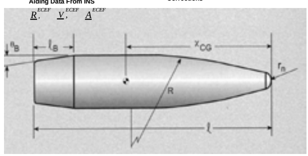
AeroSciences – What we do

Vision — Deep bench expert team in flight mechanics, aerodynamics, aerothermodynamics and guidance, navigation, and control (GNC) to lead the development and integration of effective missiles, projectiles and weapon systems









Lines of Business

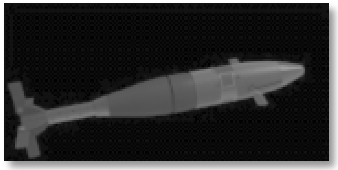
- Exterior Ballistics/ Range Safety/Ship Hazard Analysis
- Tactical Ballistic Missile Defense Weapon (TBMD) System Integration
- Anti Air Warfare(AAW) /Surface Warfare Weapon (SuW) System Integration
- Active Programs: Railgun/Hyper-Velocity Projectile (HVP), LCS Surface Ship Mission Module (SSMM), PC GRIFFIN
- Legacy/Recent Programs: STANDARD MISSILE family (SM2-6), Extended Range Guided Munition (ERGM), Ballistic Trajectory Extended Range Munition (BTERM), Precision Universal Mortar Attack (PUMA), Precision Extended Range Munition (PERM), and other Navy/Marine Corps programs

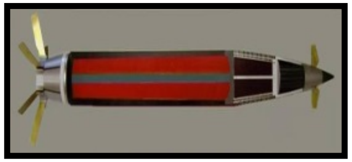
Competencies

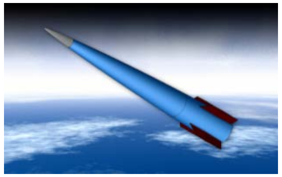
- Flight Mechanics & Dynamics
- Aerodynamics Characterization & Analysis
- Wind Tunnel Test Design and Analysis
- Performance Analysis
- Airframe design
- Guidance, Navigation, and Control Analysis & design
- Linear & Non-Linear State Estimation
- Requirements Definition and Analysis
- Aero-thermal Analysis

Gun/Mortar Focus Areas

- Land and Sea launched weapon platforms
- Guided/Unguided
- Ballistic and controlled flight
- Rocket assisted and free flight
- Endo and exoatmospheric flight regimes







Focus of Flight Modeling and Simulation

Aerodynamics

- AERO PREDICTION (AP), PRODAS, Wind Tunnel & Flight Testing
- 6-dof high fidelity nonlinear aerodynamic models
- Free flight ballistics modeling
- Aerodynamic modeling for canard, wing and tail deflections
- Collaboration with industry and government for CFD and wind tunnel testing
- Post flight aerodynamic reconstruction modeling

Guidance, Navigation, and Control

- Guidance algorithms for stationary and maneuvering air, sea and land targets, midcourse and terminal phases
- Autopilot (control) algorithms to support tail/wing/canard control; open and closed loop topologies;
- Navigation algorithms to support GPS/inertial navigation/ seeker (strapdown , gimballed etc.)

Footprint, Range Safety, Post Flight, and Endgame/System Performance

- 3-6 DOF Monte Carlo Analysis Capabilities
- Failure mode modeling (launch, in-flight, component, etc.)
- Guided and unguided dispersions
- Rocket motor modeling
- System and environment error models
- Error tree modeling

State Estimation

- State estimation algorithms to support GNC architectures and target tracking (e.g. small boat tracking)
- Linear state estimation algorithms: (examples: Kalman Filtering and alfa/beta filtering)
- Non linear state estimation algorithms Examples: Extended Kalman filtering (EKF), Unscented Kalman filtering (UKF), Particle filtering (PF)

Aerodynamics

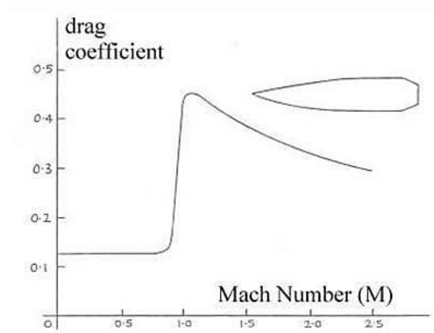
Projectile/Mortar Aerodynamics

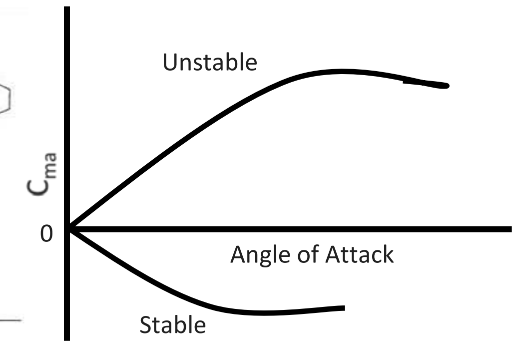
- Modeling of aerodynamic force and moment coefficients present unique challenges due to inherent nonlinear parameter dependencies and asymmetric air flow over bodies, interference effects arising from tail, canards and/or wings, etc.

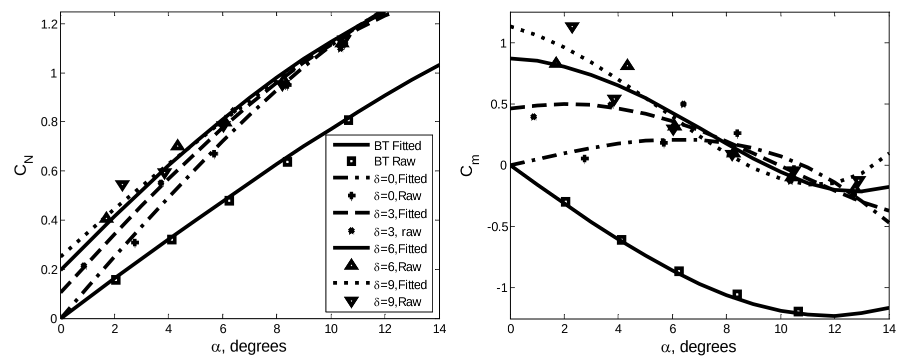
- Many gun/mortar projectiles are usually free rolling for the initial portion of flight, requiring an accurate modeling of aerodynamic coupling (yaw-roll resonance) which can be highly nonlinear and difficult to model

- In general, obtaining accurate aerodynamics is typically an iterative process that involves a combination of semi empirical prediction tool application (e.g. AP09/PRODAS), CFD analysis, wind tunnel, and some flight testing

Example aero coefficients







Example of Normal Force and Pitching moment Coefficients for a canard controlled projectile that are nonlinear with respect to angle of attack

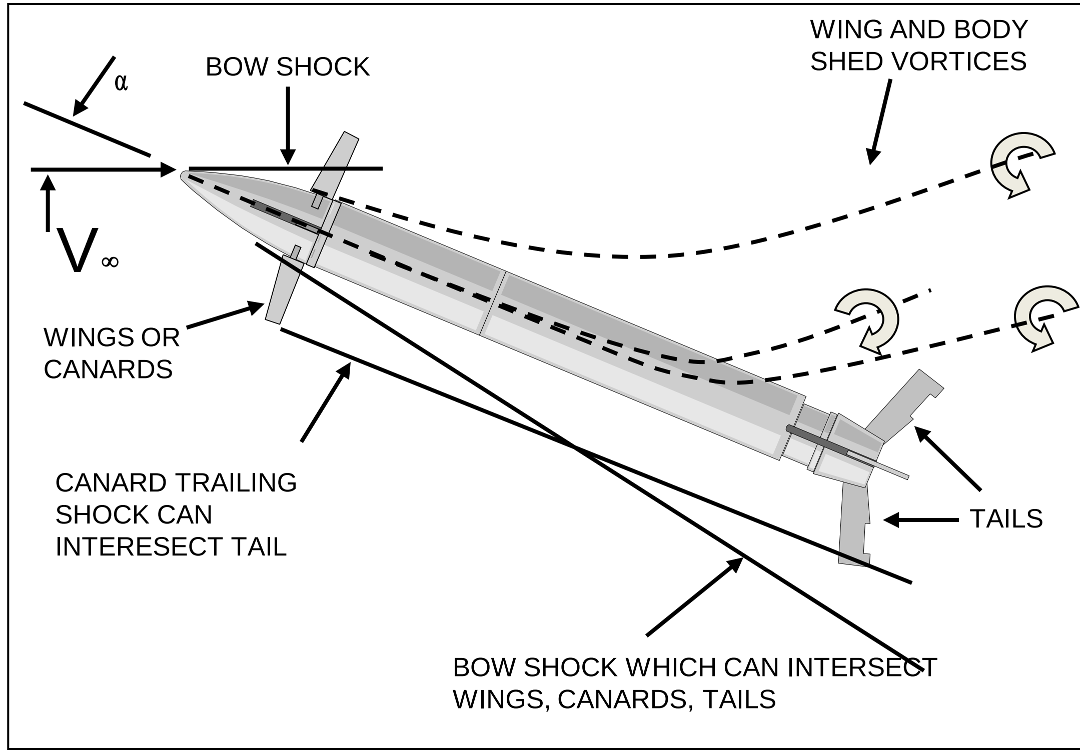
AEROPREDICTION

OBJECTIVE

PREDICT AERODYNAMICS COST EFFECTIVELY AND WITH REASONABLE ACCURACY OVER FLIGHT ENVELOPE OF INTEREST TO WEAPONS DESIGNERS

APPLICATION REQUIREMENT OF APC

- INPUTS TO 3-DOF/TRIM PERFORMANCE MODELS
- AERODYNAMIC DESIGN (PRELIMINARY)
- PRELIMINARY STRUCTURAL LOADINGS
- CONVECTIVE HEAT TRANSFER INPUTS

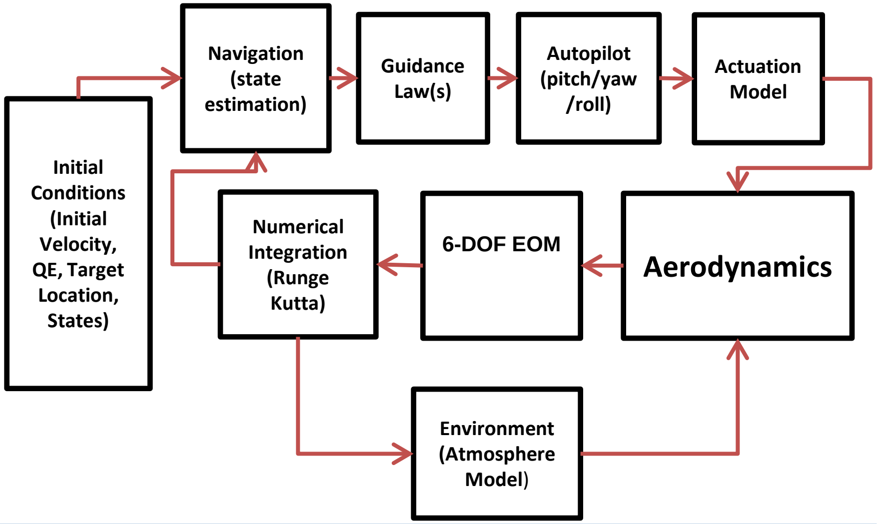


OVERALL FLIGHT REQUIREMENTS

MACH NUMBER:	0-15
ANGLE-OF-ATTACK:	0-90º
CONTROL DEFLECTION: ✂30°	
ROLL ORIENTATION:	0°, 45°
SETS OF FINS:	0, 1, 2 REQUIRED; 3 DESIRED
BODY GEOMETRY:	AXISYMMETRIC REQUIRED; NONAXISYMMETRIC TREATMENT DESIRED

Generic 6-DOF Architecture

- High fidelity 6DOF aero modeling requires interpretation and analysis of results from aero-prediction tools, CFD, wind tunnel and flight data
- Nonlinear dependencies can be captured in coefficients modeled using localized secant slopes that take into account changes with respect to angle of attack, roll orientation, control deflections and other flight parameters



6-DOF Equations of Motion (EOM)

(simplified for illustration)

$$F_x + mg_x = m(\dot{u} + qw - rv)$$

$$F_y + mg_y = m(\dot{v} + ru - pw)$$

$$F_z + mg_z = m(\dot{w} + pv - qu)$$

$$M_x = \dot{p}I_x$$

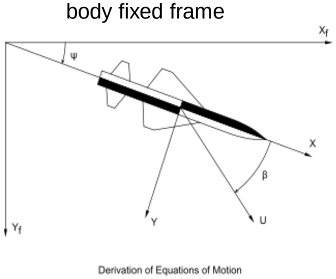
$$M_y = \dot{q}I_y + pr(I_x - I_z)$$

$$M_z = \dot{r}I_z + pq(I_y - I_x)$$

Euler Eq.s

$$\left\{\begin{aligned} \dot{\phi} &= p + \tan\theta(q\sin\phi + r\cos\phi) \\ \dot{\theta} &= q\cos\phi - r\sin\phi \\ \dot{\psi} &= \frac{q\sin\phi + r\cos\phi}{\cos\theta} \end{aligned}\right.$$

Flat Earth (f) inertial and body fixed frame



Aerodynamic Forces and Moment Expansion

Forces

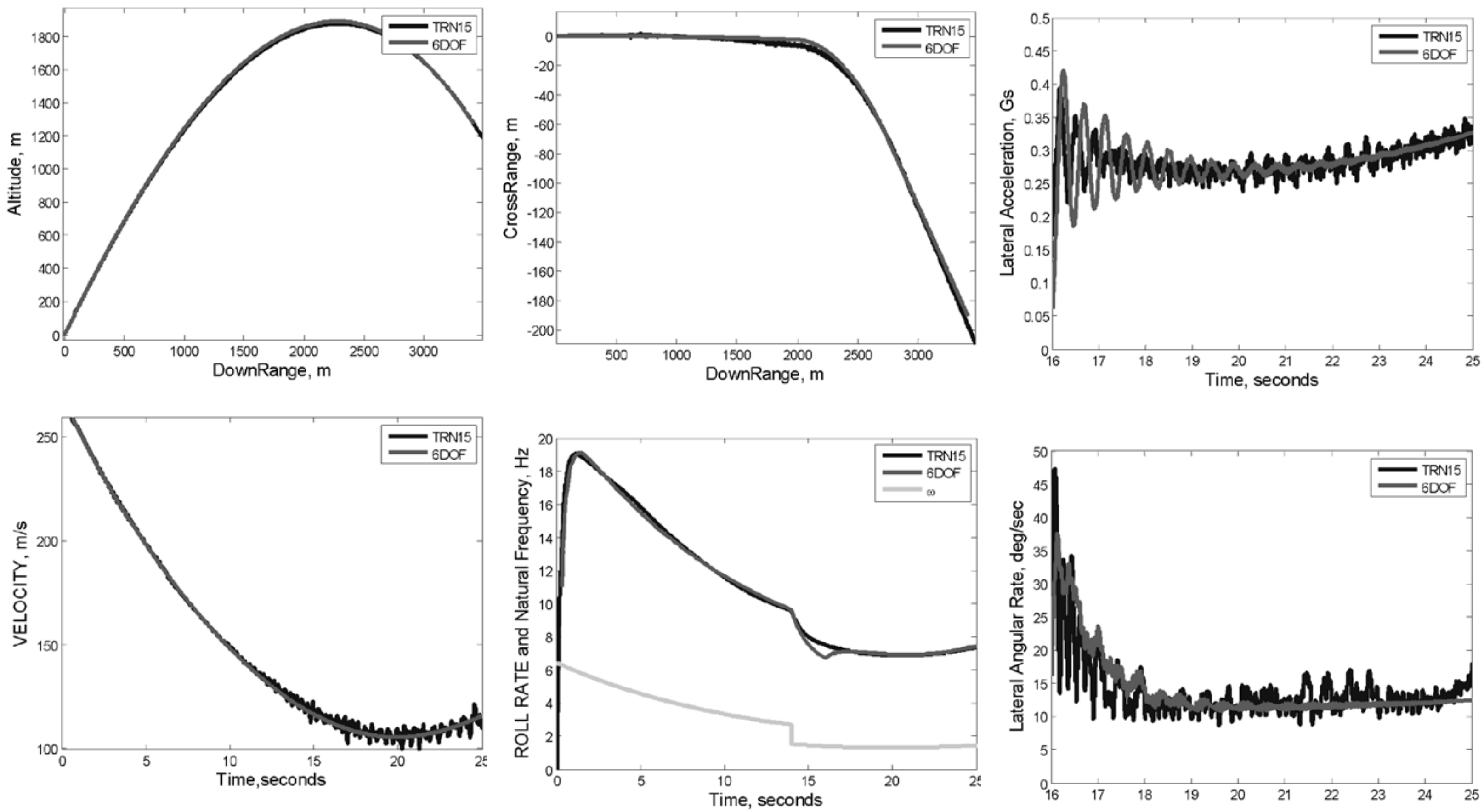
$$\left\{\begin{aligned} F_x &= C_x * qS \\ F_y &= C_Y * qS = C_{y\beta} * \beta + C_{Yp\alpha} * \alpha \\ F_z &= -C_N * qS = -(C_{N\alpha} * \alpha + C_{N\delta} * \delta + C_{Yp\alpha} * \beta * \frac{pd}{2V_\infty}) * qS \end{aligned}\right.$$

Moments

$$\left\{\begin{aligned} M_x &= C_l * qSd = (C_{l\delta} * \delta_{tail} + C_{lp} * \frac{pd}{2V_\infty}) * qSd \\ M_y &= C_m * qSd = (C_{m\alpha} * \alpha + C_{m\delta} * \delta + C_{mq} * \frac{qd}{2V_\infty} + C_{np\alpha} * \beta * \frac{pd}{2V_\infty}) * qSd \\ M_z &= C_n * qSd = (C_{n\beta} * \beta + C_{nr} * \frac{rd}{2V_\infty} + C_{np\alpha} * \alpha * \frac{pd}{2V_\infty}) * qSd \end{aligned}\right.$$

81 mm Mortar Example: Matching Flight Data with 6DOF

Maneuvers and flight trajectory verified from flight and 6DOF modeling



Sample FCMortar flight test (FE2) data (verification of aerodynamics and maneuver authority of airframe)

Guidance, Navigation, and Control (GNC)

Generalized Explicit (GENEX) Guidance

- Generalized Explicit (GENEX) guidance is designed to achieve “zero miss” and a desired flight path angle in an optimal sense.

GENEX Cost function

$$\boxed{J = \int_0^{T_0} \frac{u^2}{2T_{go}^{\,n}}\,dT}$$

- Using a form of optimal control theory known as the Hamilton-Jacobi approach, the control input can be formulated as a lateral acceleration command given by:

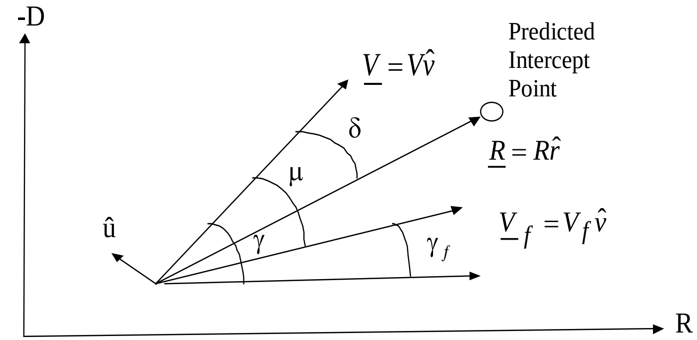
$$\boxed{\underline{u} = \frac{1}{T_{go}^{\,2}}\left[K_1(\underline{R}_f - \underline{R}_M - \underline{V}_M T_{go}) + K_2(\underline{V}_f - \underline{V}_M)T_{go}\right]}$$

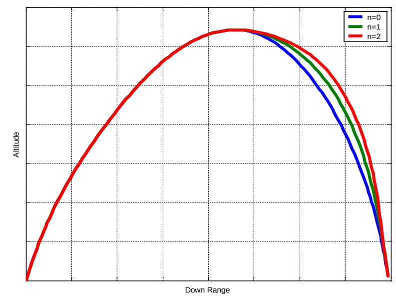
$$\boxed{\underline{u}_\perp = \frac{V^2}{R}\left[K_1(\hat{r} - \hat{v}\cos\delta) + K_2(\hat{v}_f - \hat{v}\cos\mu)\right]}$$

- The guidance gains are given by

$$\boxed{\begin{aligned} K_1 &= (n+2)(n+3) \\ K_2 &= -(n+1)(n+2) \end{aligned}}$$

Typical Engagement Geometry



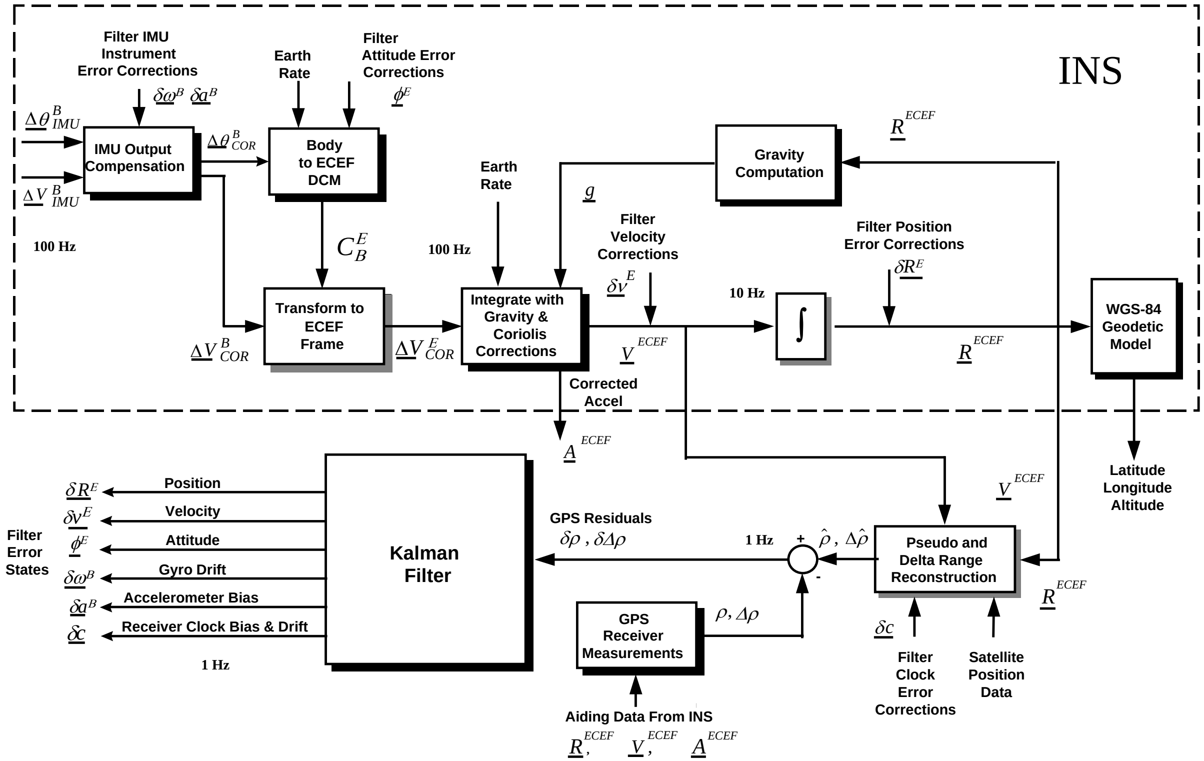


GENEX formulation allows for a customizable guidance strategy that can yield “zero” miss distance at impact while shaping the flight trajectory to achieve a desired objective (e.g. arriving vertically over a target area)

Reference: Generalized Vector Explicit Guidance, Ohlmeyer E.J. and Phillips, C. A., Journal of Guidance, Control and Dynamics, Vol.29, No.2

Tightly Coupled GPS/INS Integrated Navigation

- “Tight coupling” means in place of GPS derived position/velocity raw measurements such as pseudo-range and delta pseudo range are directly used in the extended Kalman filter
- Suitable for guidance packages that rely on low cost MEMS and GPS sensors
- Combines benefit of long term stability and accuracy of GPS with short term accuracy of MEMS sensors to produce stable and accurate navigation data to support onboard guidance and control functions



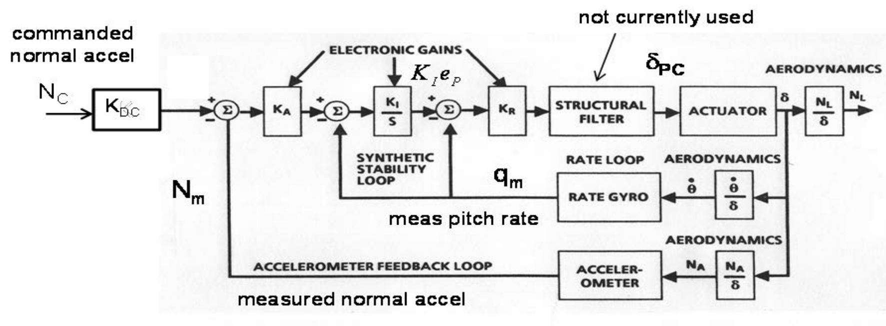
Reference: Ohlmeyer, E.J., et.al., “Assessment of Integrated GPS/INS for the Extended Range Guided Munition”, 1998 AIAA Guidance, Navigation and Control Conference, pp. 1374-1389, Boston, MA

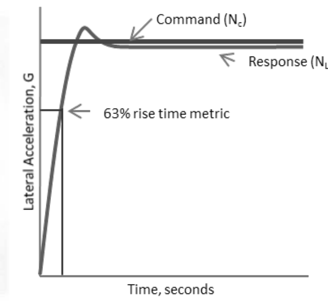
3-Loop Autopilot Topologies for Pitch, Yaw and Roll Control

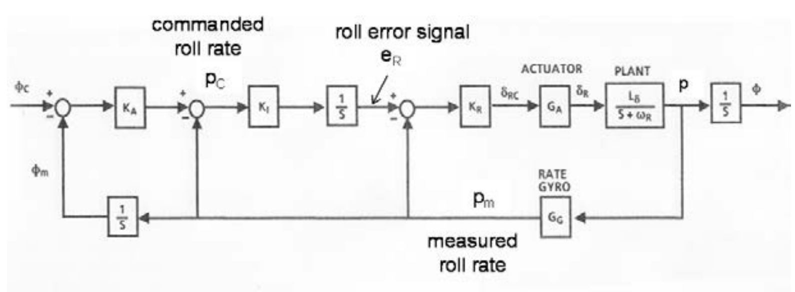
- Originally developed for supersonic missiles but easily adaptable to suit gun/mortar projectile autopilot architectures

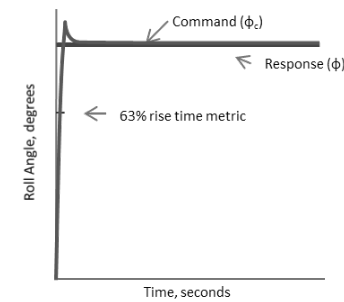
- 3-loop Autopilot topologies are an application of classical feedback control methods and can be effectively applied to gun/mortar airframes

- Appeared in the open literature









Three gains in the feedback path can be selected and "scheduled" based on flight conditions (e.g. Mach number and angle of attack) and enable the GNC designer to manage control criteria such as response rise time (time constant) and damping characteristics to be defined and met for a given flight requirement

Reference: Zarchan P., Tactical and Strategic Missile Guidance, Fourth Ed., AIAA Progress in Astronautics and Aeronautics series, 2002

State Estimation

Small Boat Tracking: Particle Filter Example

- Developed under NSWCDD in-house discretionary project for developing advanced tracking algorithms for nonlinear non Gaussian tracking situations

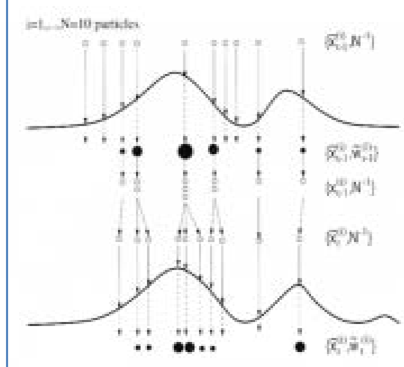
- Case study for tracking small boats using actual GPS data and simulated nonlinear radar data corrupted with glint (non-Gaussian) noise

- Particle filter compared to EKF for reference
    - EKF performance degrades due to presence of nonlinearities and glint but PF performs satisfactorily

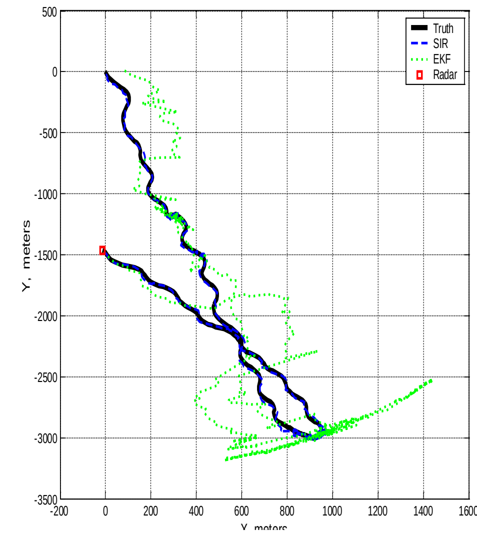
Reference: Pamadi, K.B, “Evaluating the Feasibility of a Particle Filtering Approach for Tracking Unmanned Surface Vehicles”, AIAA Guidance, Navigation and Control Conference, 10-13 August 2009, Chicago Illinois

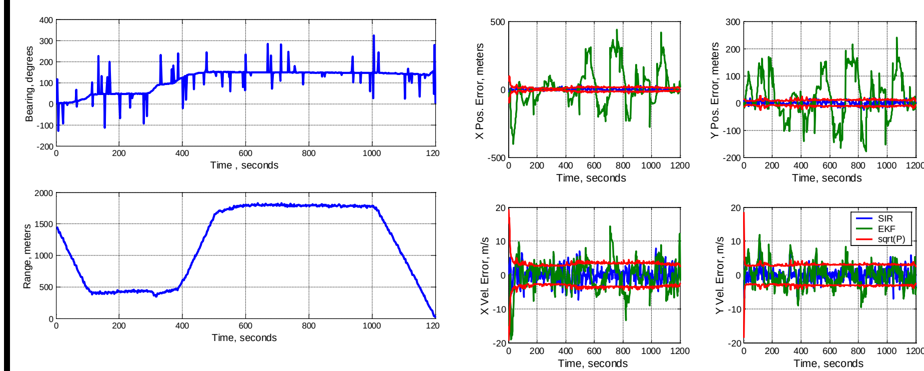
BASIC Principal of Particle Filter
Recursively propagate and update randomly drawn samples (particles) from state PDF given a set of noisy measurements

Particle Filter



$$p(\underline{x}_k \mid Z_k) = \frac{p(\underline{z}_k \mid \underline{x}_k)\cdot p(\underline{x}_k \mid Z_{k-1})}{p(\underline{z}_k \mid Z_{k-1})}$$

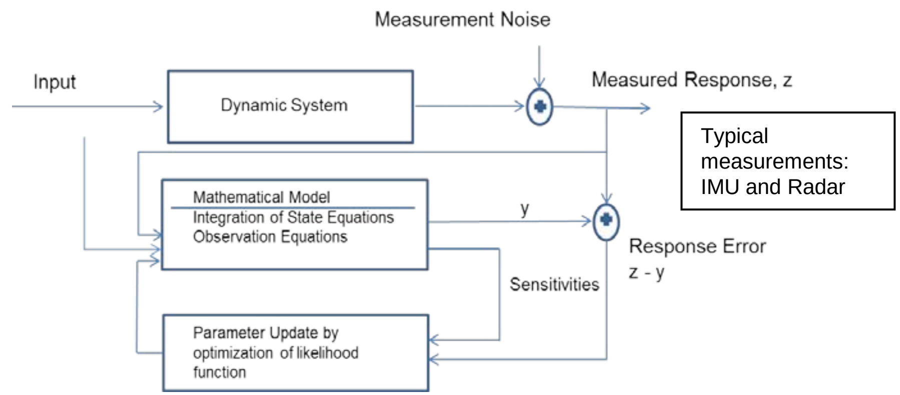




Post Flight Analysis- State Estimation Approach

- Developing data reduction/aero reconstruction methods based on Kalman filtering, maximum-likelihood principles to derive best estimates for complete set of aero coefficients from flight data
- Examples of state estimation based methods under development
  - **Output Error**
  - **Filter Error**
  - **Equation Error**
- The approach can be combined with both time domain (e.g. output error method) and frequency domain (e.g. Fourier Transform) to reduce aerodynamic uncertainties from flight data and measurement errors and to develop an integrated modeling and simulation approach to flight aero state estimation

Example: **Output Error** Method for Determining Aero Coefficients

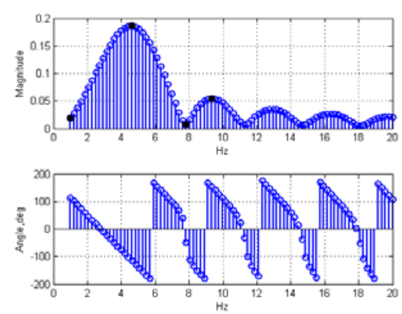


Aero coefficient extraction from flight

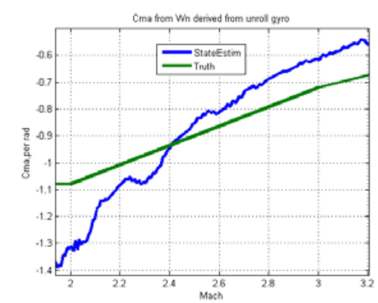
$$C_x = ma_{x(meas)} / Q_{meas} S_{ref}$$
$$C_y = ma_{y(meas)} / Q_{meas} S_{ref}$$
$$C_z = ma_{z(meas)} / Q_{meas} S_{ref}$$

$$C_l = \dot{p}_{meas} I_x / Q_{meas} S_{ref} d$$
$$C_m = \dot{q}_{meas} I_z + p_{meas} r_{meas} (I_x - I_z) / Q_{meas} S_{ref} d$$
$$C_n = \dot{r}_{meas} I_z - p_{meas} q_{meas} (I_x - I_z) / Q_{meas} S_{ref} d$$

Example Fast Fourier transform



Example Cma from FFT



In Closing

- NSWCDD's deep bench expertise in Aerosciences can benefit the DoD family in many ways:
  - **Reduce program risk and cost during various phases of a program with high fidelity flight modeling and simulation**
  - **Provide independent technical review of airframe concepts**
  - **Conduct trade studies and analysis of alternatives (AoA) for wide ranging airframe and GNC concepts**
  - **Develop "government owned" solutions (e.g. developing, testing and prototyping onboard flight algorithms)**
  - **Provide independent analysis of airframe performance, development and testing**