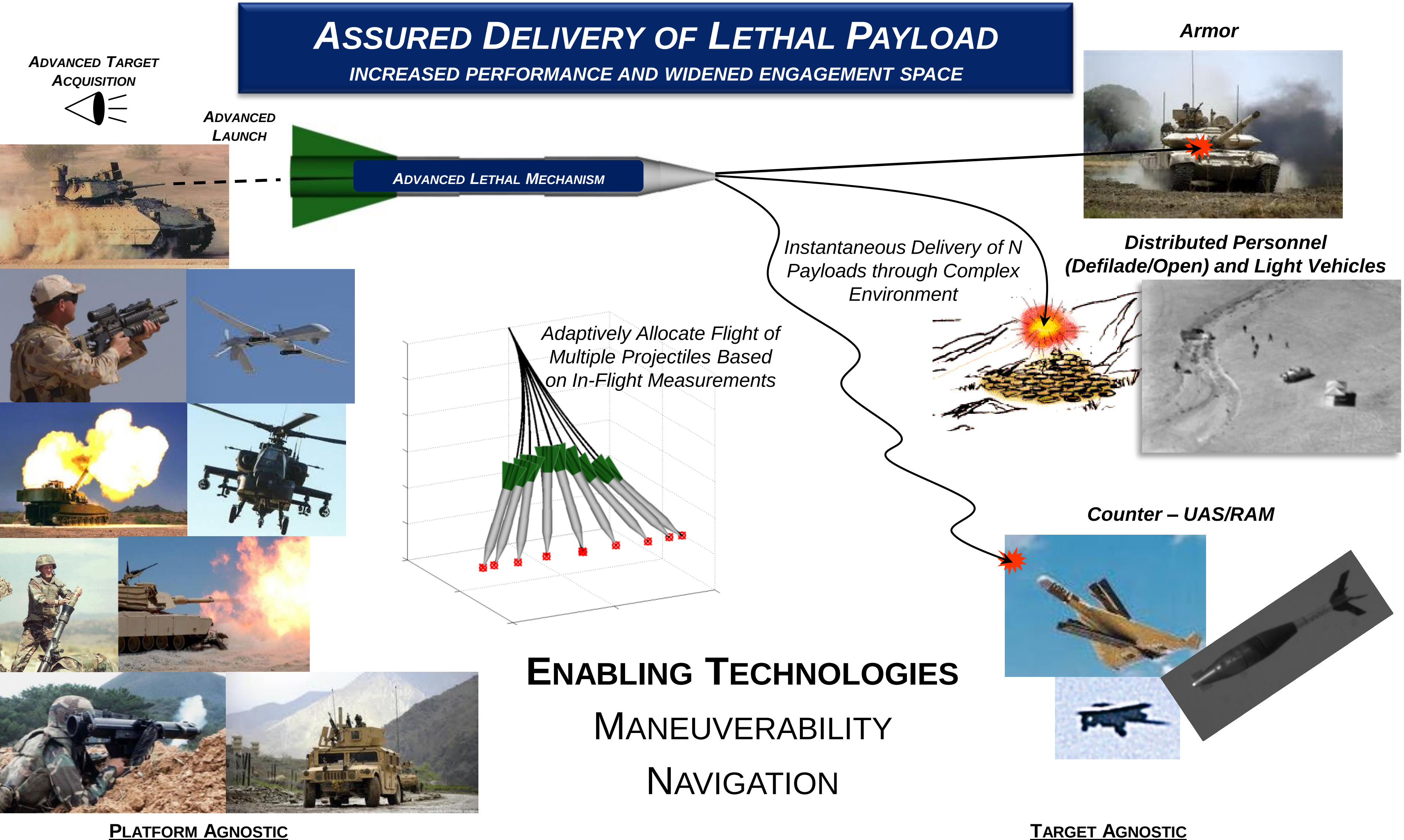
Collaborative Cooperative Engagement – Parent Child Concept

Frank Fresconi, PhD

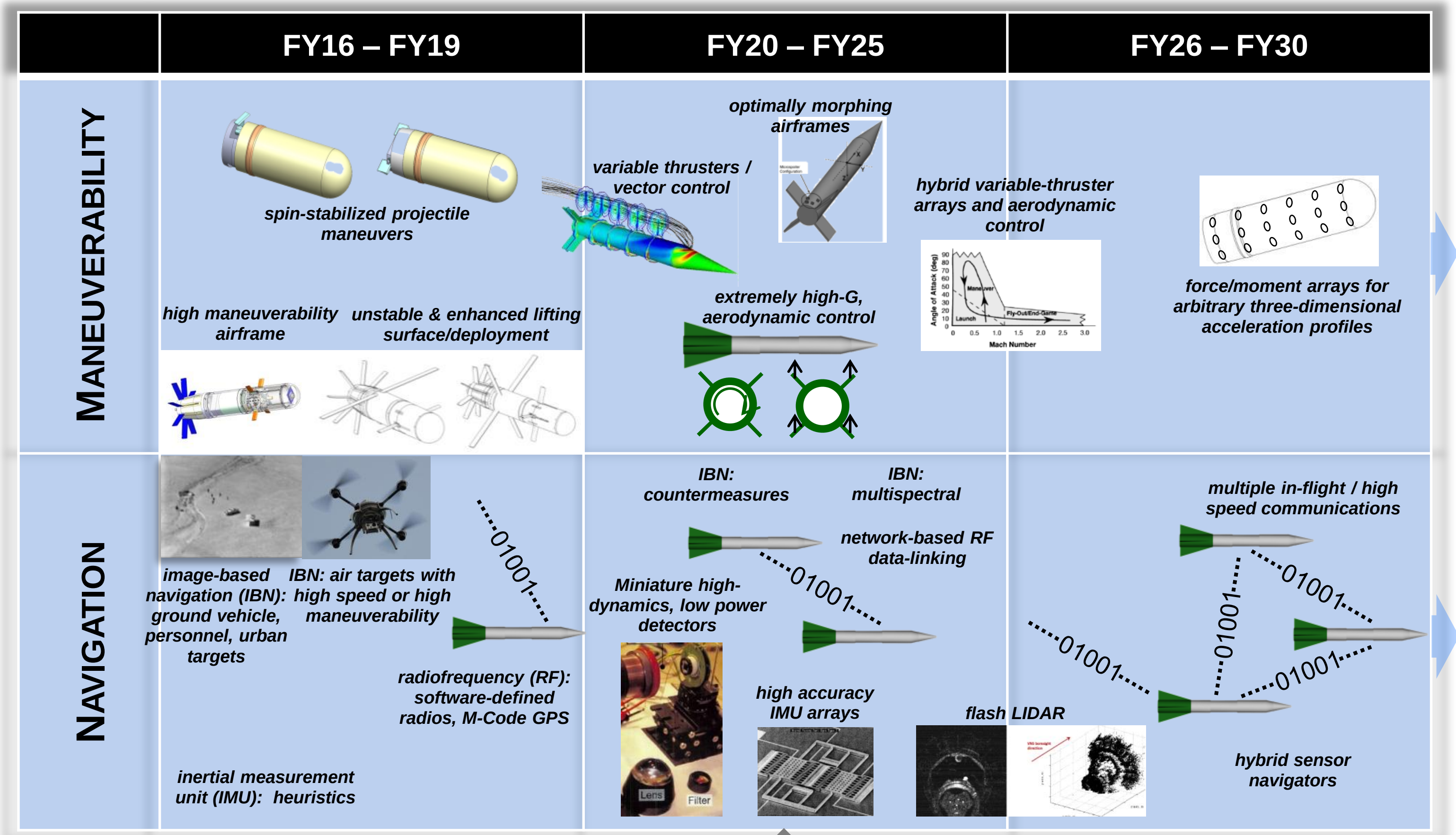
Guided Lethality

- Vision -

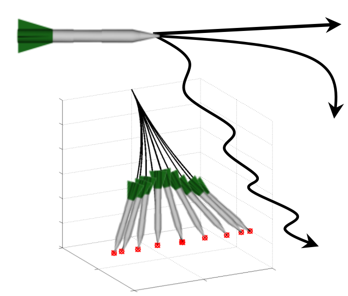


Sciences for Lethality and Protection Campaign

- ARL Technology Implementation Plan for Guided Lethality -



ASSURED DELIVERY



SMALLER CALIBER

LOWER COST

EXTREME ACCURACY

MORE COMPLEX ENVIRONMENT

FASTER DYNAMICS (MACH, SPIN RATE, TIME-OF-FLIGHT)

HIGHER GS

ADVANCED DELIVERY (SWARMING)

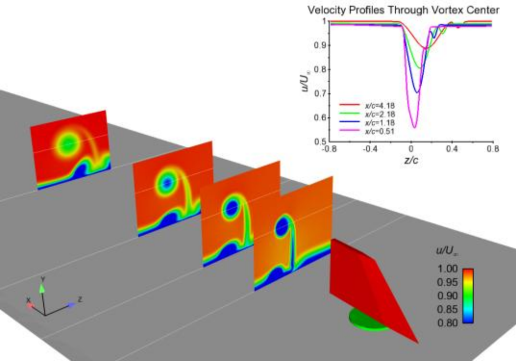
External Advancements in Performance and SWaP/C of:

- Processors (GPUs, …) → algorithms
- Measurements (IMUs, RF antenna / receiver, imagers / optics, …)
- Actuation Technologies

TECHNOLOGY IMPLEMENTATION PLAN FOR DESIRED LETHAL EFFECTS AT STANDOFF RANGES IN CONSTRAINED ENVIRONMENTS

Guided Lethality

- Resources / Core Capabilities -

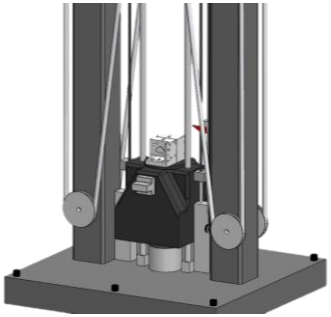


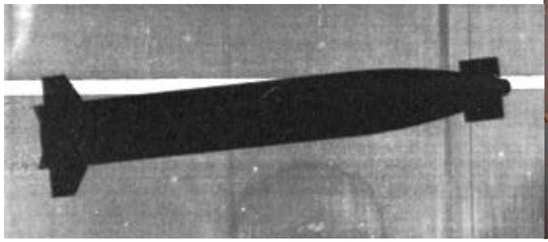
Personnel:

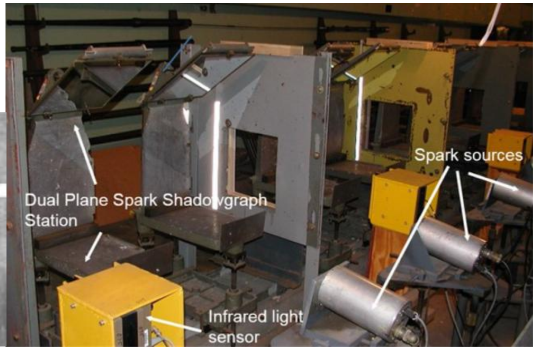
- 23 Scientists & Engineers (50% PhD, 50% Masters/Bachelors)
  - mechanical, aerospace, electrical, computer science, physics
- 13 Technicians

Facilities:

- High-Performance Computing
- Shock Tables and Air Guns
- GNC Laboratories
  - processor/hardware-in-the-loop
  - GPS simulation
  - munitions sensor/actuator characterization
  - anechoic chamber
  - component fabrication
- Free-Flight Ranges
  - 2x spark (small/med cal, med/large cal)
  - firing range instrumentation (high-speed photo, radar, X-ray, pressure, MET, yaw cards, survey)





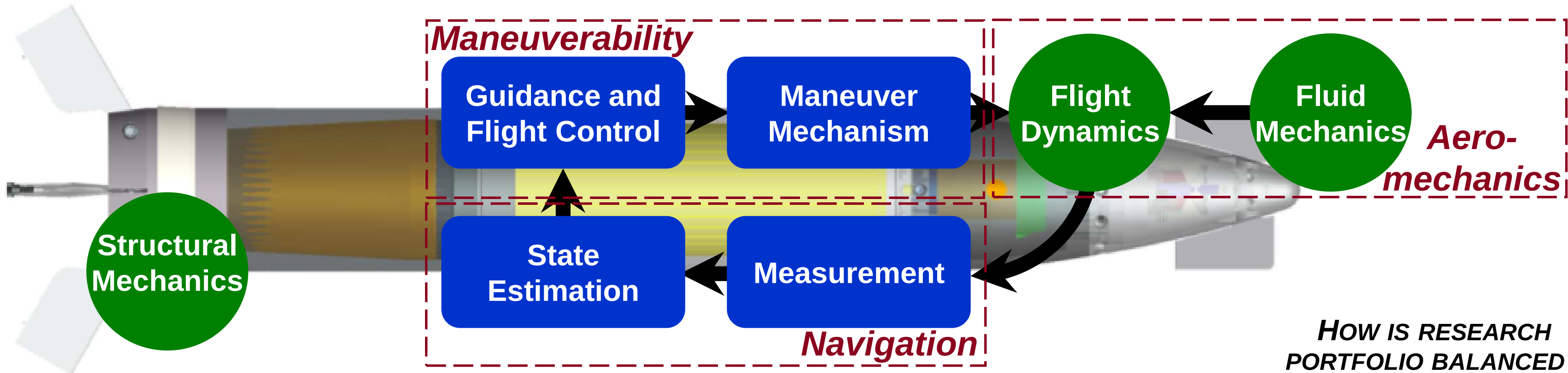


UNDERSTAND LAUNCH, FLIGHT, AND GUIDED DELIVERY TECHNOLOGIES

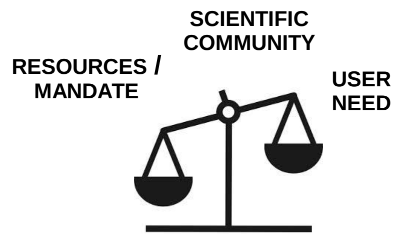
U.S. ARMY RDECOM

PCWFD
- Disciplines and Structure -

ARL



HOW IS RESEARCH PORTFOLIO BALANCED?



Army Warfighting Challenges Addressed:
AWFC 3: Provide security force assistance
AWFC 13: Establish and maintain security across wide areas
AWFC 15: Conduct combined arms air-ground maneuver
AWFC17: Coordinate and integrate Army and joint, inter-organizational, and multi-national fires and conduct targeting across domains
AWFC 18: Deliver fires and preserve freedom of maneuver

FY16 Research Areas	
Survivability and Reliability of GNC Components	Navigation Estimation Algorithms
Fundamental Flow Fields of Complex Airframes	Emerging Non-Vision and Inertial Navigation Technologies
Fluid Mechanics of Maneuvering Projectiles	EO/IR-based Navigation
Dynamic Flight Behavior of Maneuvering Projectiles	Assured Navigation Theory
Maneuver Technologies	Omnisonic Mechanics and Control

U.S. ARMY RDECOM

Current Focus: Moving Target Challenge

ARL

NAVIGATION WITHOUT GPS

COMMERCIAL COMPONENTS

GUN HARD

MODERATE SIZE/WEIGHT/POWER

LABORATORY DEMONSTRATION (TRL 3-4)

RELEVANT APPLICATIONS

- MORTARS
- ARTILLERY
- SHOULDER-LAUNCHED
- AIR DROPPED
- MISSILES
- TANKS
- 40MM AND BELOW…

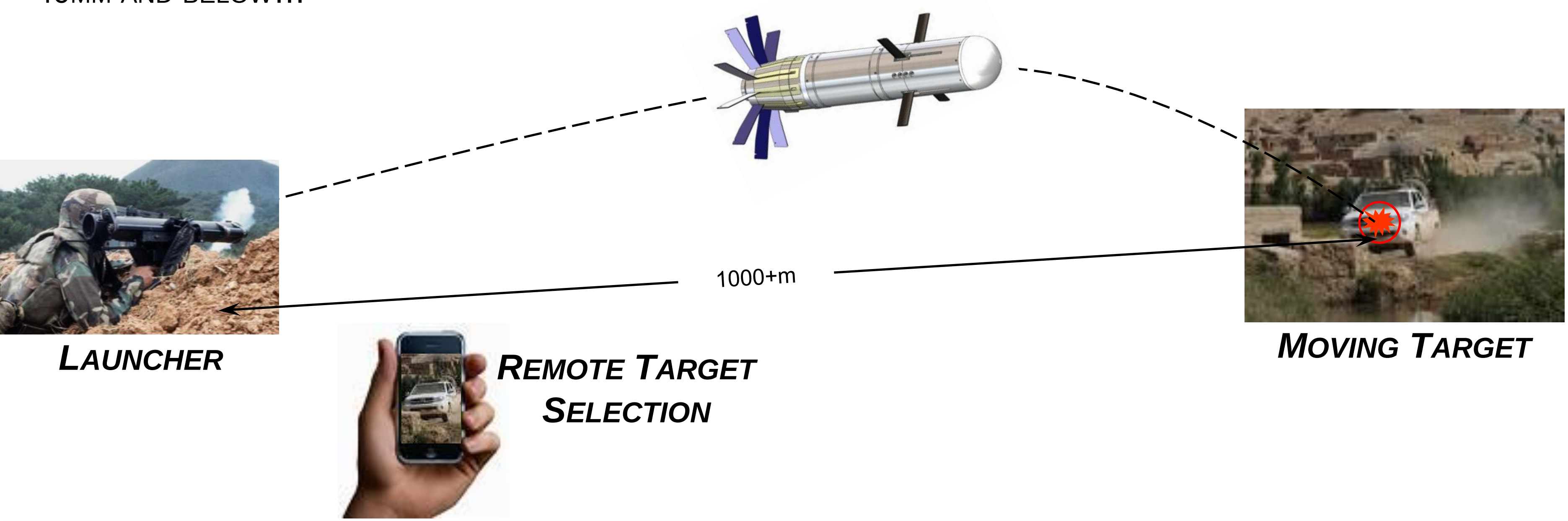
MUNITIONS TECHNOLOGIES

HIGH MANEUVERABILITY AIRFRAME

- AIRFRAME (STRUCTURES/AEROMECHANICS)
- MANEUVER MECHANISM
- FLIGHT CONTROL ALGORITHMS

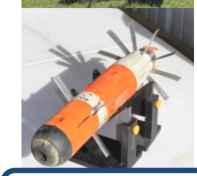
IMAGE-BASED NAVIGATION

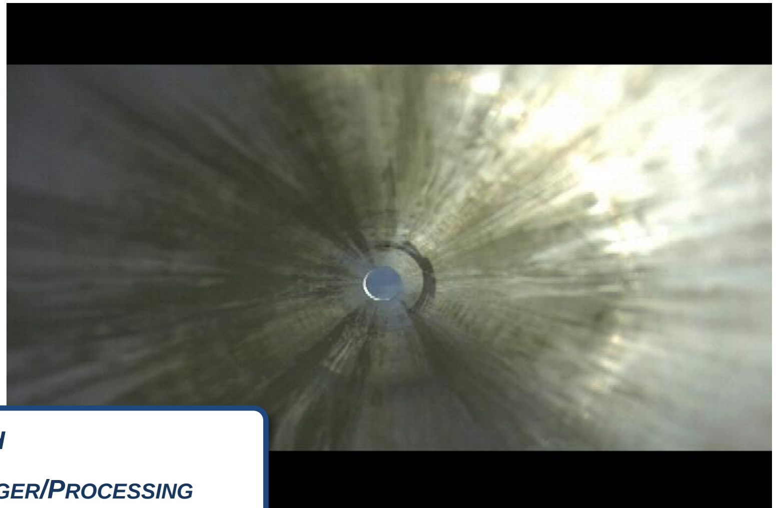
- EMBEDDED IMAGER/PROCESSING
- TARGET ACQUISITION/TRACKING ALGORITHMS
- STATE ESTIMATION ALGORITHMS



Current Focus: Moving Target Challenge

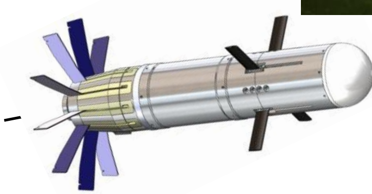
- Status -





Soft Launch

- Embedded Imager/Processing
- Acquisition/Tracking Algorithms
- State Estimation Algorithms
- Flight Control Algorithms
- Control Actuation
- Airframe

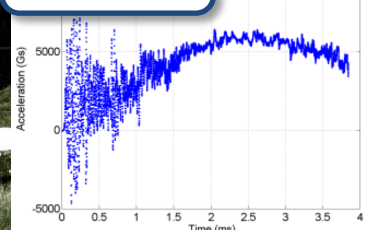


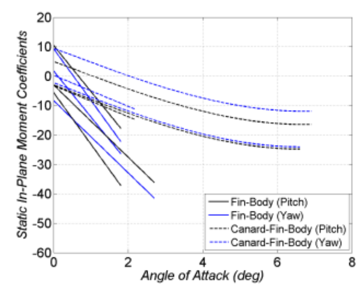
Wind Tunnel

- Flight Control
- Control Actuation
- Airframe

Gun Launch

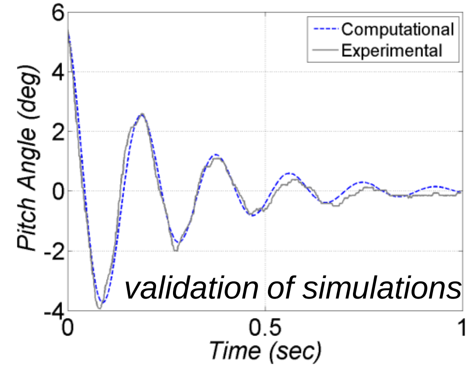
- Airframe



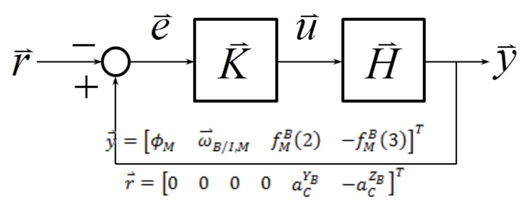


Model: Challenge platform maintains cohesion/focus and drives critical experiments

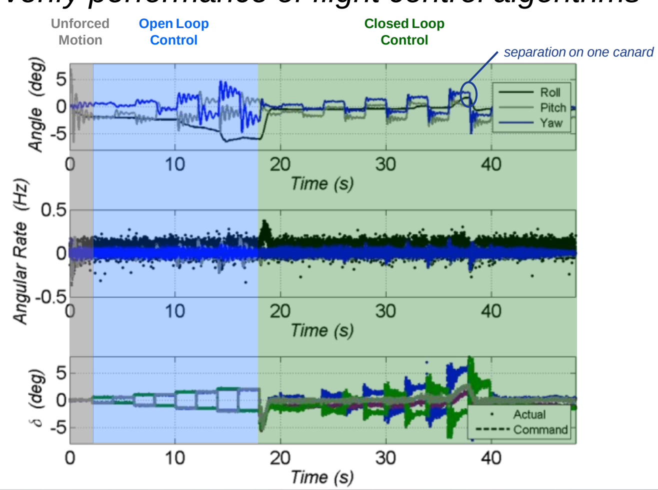
High Maneuverability Airframe

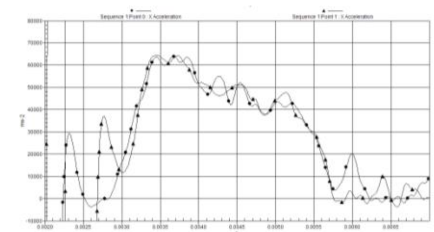


understanding of maneuvering flight behavior
- *aerodynamic modeling*
- *flight interactions (roll and pitch/yaw)*
- *flight control with coupled fluid/flight/actuator dynamics*



verify performance of flight control algorithms





understanding of maneuver mechanism
- *structural response to gun launch*
- *dynamic modeling*

$$\ddot{\delta}(t) + 2\xi\omega\dot{\delta}(t) + \omega^2\delta(t) = \delta_C(t - t_D)$$

damping ratio · *natural frequency* · *canard deflection* · *canard command* · *time delay*

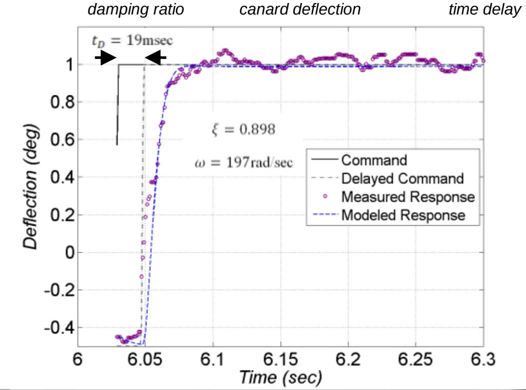
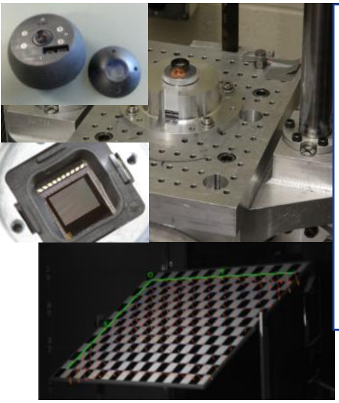
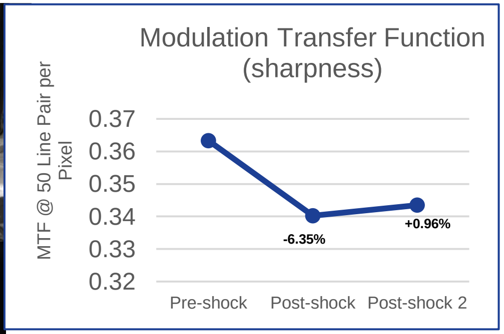


Image-based Navigation

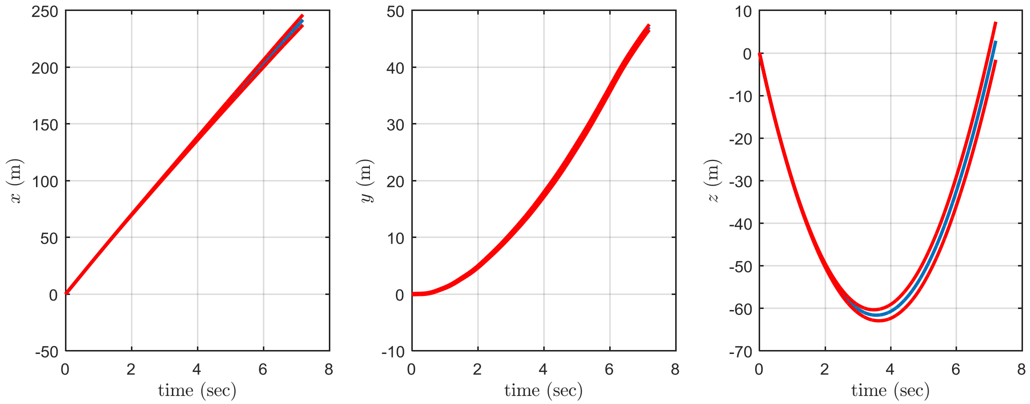
understanding of COTS embedded imagers in ballistic environment
- *modeling (sharpness, re-projection, etc.)*
- *structural response to gun launch*



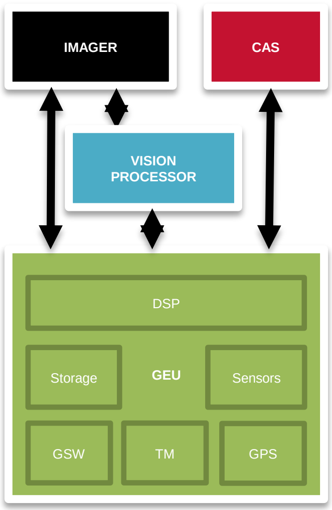


verify performance of state (line-of-sight rate, attitude) estimation algorithms

$$\begin{bmatrix} \delta\dot{p} \\ \delta\dot{v} \\ \dot{\alpha} \\ \delta\dot{\omega} \\ \delta\dot{a} \end{bmatrix} = \begin{bmatrix} 0 & I & 0 & 0 & 0 \\ 0 & 0 & -\hat{R}_b^i[\hat{a}\times] & 0 & \hat{R}_b^i \\ 0 & 0 & -[\hat{\omega}\times] & I & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \delta p \\ \delta v \\ \alpha \\ \delta\omega \\ \delta a \end{bmatrix} + w$$



real-time processing of algorithms / embedded electronics

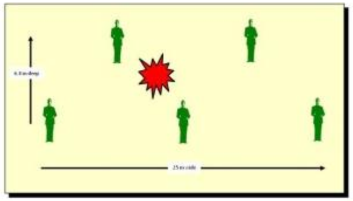


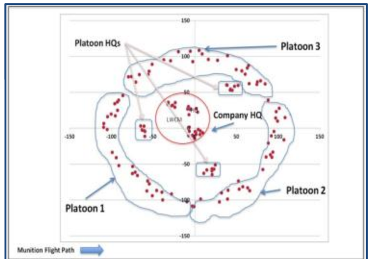
understand relationship between acquisition/tracking algorithm complexity and performance in sparse/varied environments

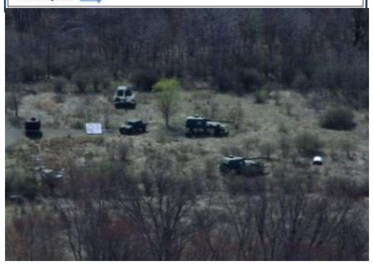
Future Direction: Swarming Munitions

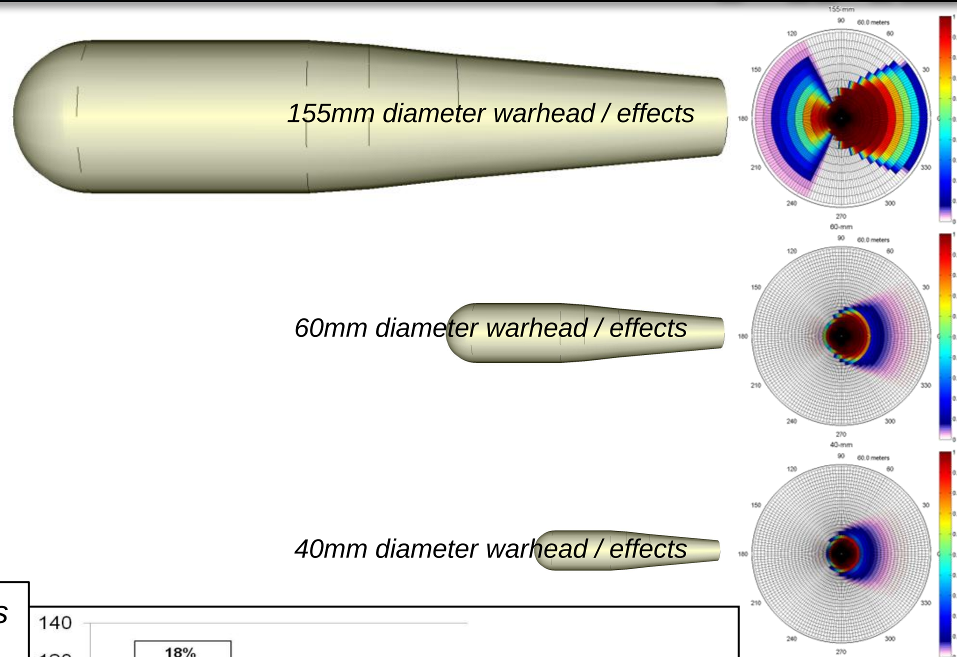
- Motivation -

Mixed Target Sets

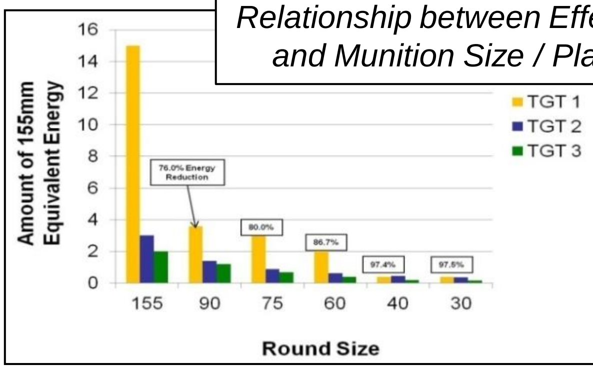


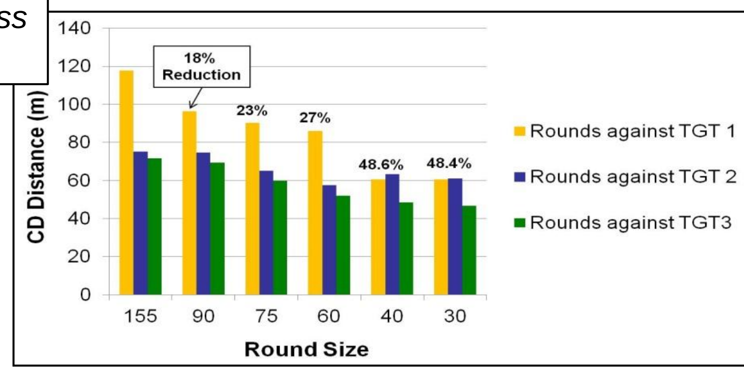






Relationship between Effectiveness and Munition Size / Placement





LETHALITY OF 155MM WITH 10% OF THE ENERGY AND 50% REDUCED COLLATERAL DAMAGE THROUGH MODULARITY

HOW TO ACHIEVE LOW-COST DELIVERY AGAINST COMPLEX TARGET LAYOUTS IN CONTESTED ENVIRONMENTS?

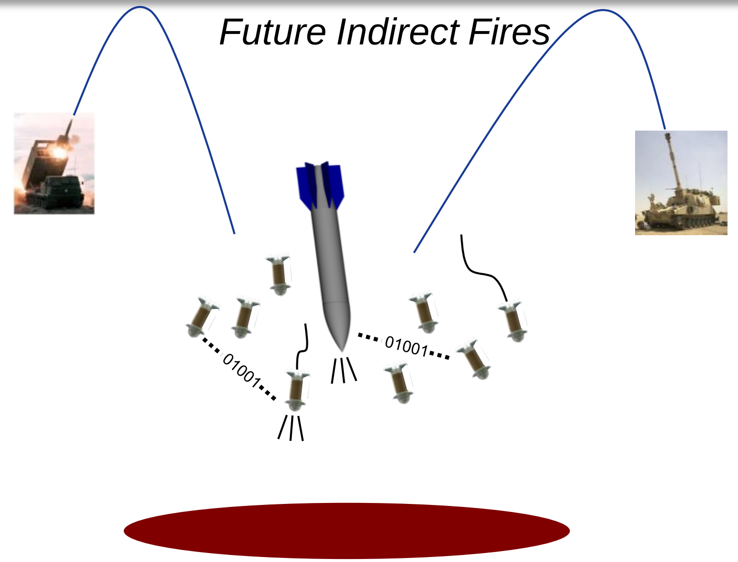
- TIGHT DISTRIBUTION TO CRITICAL POINTS OF HARD TARGETS
- TAILORED DISTRIBUTION TO LIGHT VEHICLES AND DISTRIBUTED PERSONNEL

HOW TO UNDERSTAND MULTIPLE/COMBINED EFFECTS?

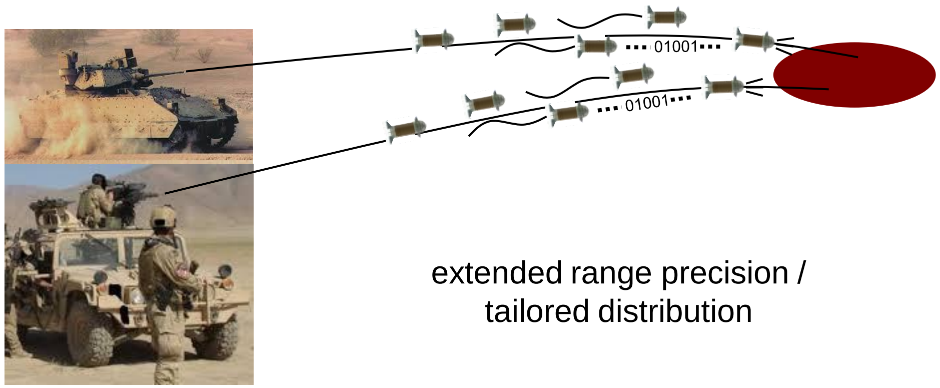
Swarming Munitions

- Vignettes -

Future Indirect Fires

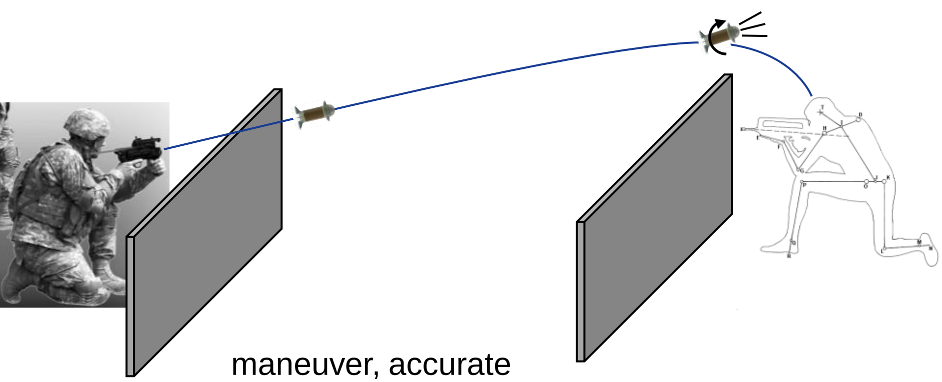


Future Direct Fires



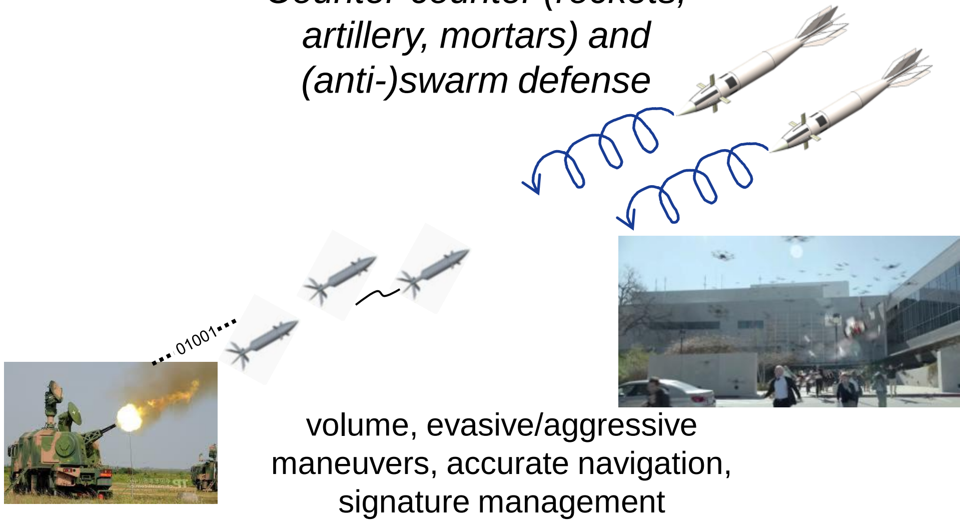
extended range precision / tailored distribution

Counter-Defilade



maneuver, accurate navigation, magazine depth

Counter-counter (rockets, artillery, mortars) and (anti-)swarm defense



volume, evasive/aggressive maneuvers, accurate navigation, signature management

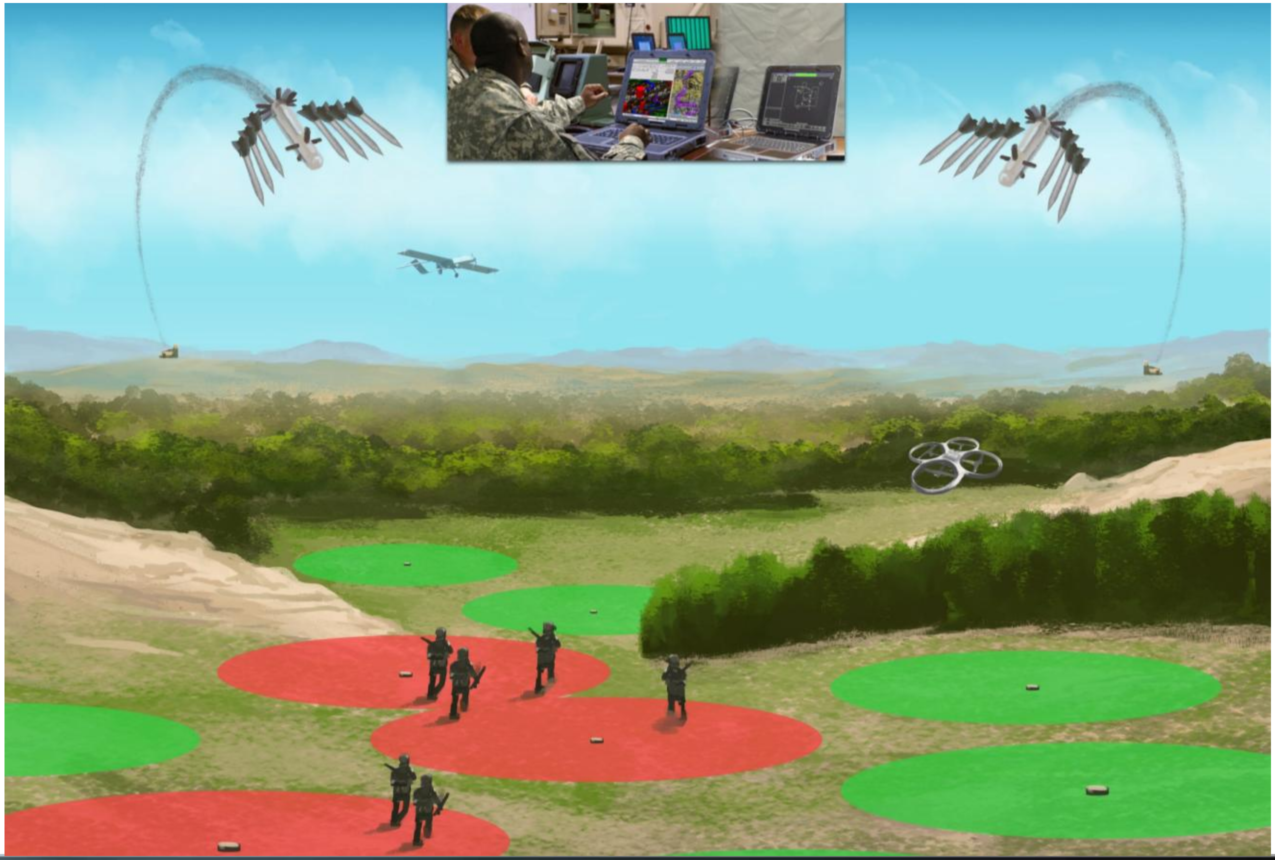
THEMES: MASSED FIRES OF SMALLER BODIES, COMPLEX THREAT, DISTRIBUTED NAVIGATION INFORMATION, AGGRESSIVE MANEUVERS

Swarming Delivery Concepts
- Parent-Child -

Swarming Delivery Concepts

Parent Entity with Superior Information Capabilities Enables Guidance to Threat
- *image-based navigation, ranging, and communications technologies*
- *parent glides for extended range and deploys children for coordinated delivery*

Child Vehicles Equipped with Minimal Components Maneuvers Off Parent Entity
- *mix of ranging/communications technologies*
- *maneuver to desired pattern*



U.S. ARMY RDECOM

Guided/Swarming Delivery

- Challenges -

ARL

Understanding of flow separation, vortex interactions, turbulent eddy scales, shock-shock / shock-boundary layer interactions, transient flow phenomena, turbulence modeling and smart meshing

Nonlinear dynamics and stability theory

Physics of flight and discovery of novel maneuver effectors

- high maneuverability control mechanisms/airframes

Flight control algorithms for novel measurement and maneuver technologies with minimal feedback, constrained input, uncertainties and nonlinear (e.g., coupled roll-pitch-yaw) dynamics

- high-level flight control architectures for collaborative/swarming behaviors

Assured weapon navigation: target acquisition/tracking/state estimation algorithms derived from various measurements with coupled modeling of technologies in sparse environments

- innovative sensing and multi-agent estimation algorithms

Rapid, high-fidelity, validated, multi-disciplinary design modeling and simulation

Cost-effective, accurate experimental techniques

Extreme Environment

- Velocity scales (0.2 < *Mach* < 5+)
- Time scales (1s < *time-of-flight* < 100s+)
- Size scales (0.50 caliber < *diameter* < 155mm+)
- Loading/survivability scales (100 < *Gs* < 100,000+)
- Information/action poor: sensing in high dynamics/sparse (e.g., GPS denied) environments, embedded processing limitations, actuation technology constraints
- Contested/counter-measured, highly-dynamic, military conditions (reliability, temp/vibe, accuracy…)

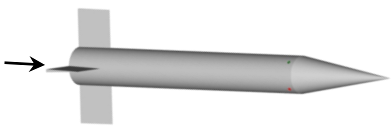
Affordability

Capability/threat-driven: maintain/increase performance and widen engagement space

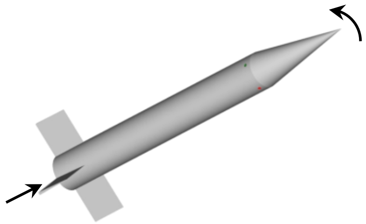
Scientific Challenge Focus
- Omnisonic Mechanics and Control -

MOTIVATION

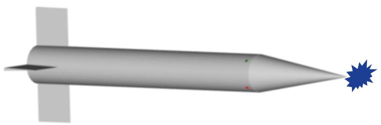
Army flies bodies transiting hypersonic to subsonic Mach regimes and many missions would benefit from enhanced maneuverability through uncertain, cluttered, and contested environments



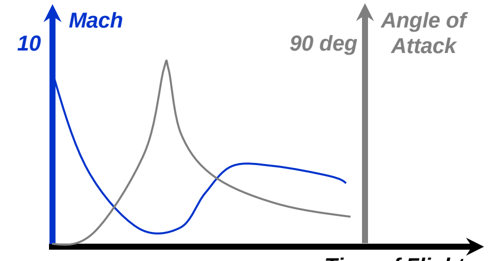
LAUNCH SMALL DIAMETER BODY



EXTREME MANEUVERS (STOP-TURN-START)



INTERCEPT EVADING THREAT



CHALLENGES to understanding flight behaviors of maneuvering bodies across omnisonic regimes

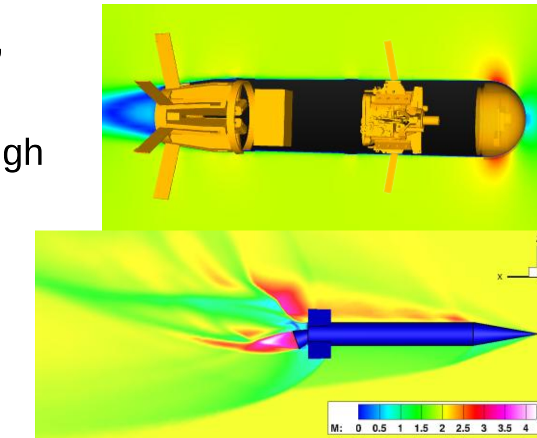
Fluid mechanics: flow separation, vortex interactions, turbulent eddy scales, shock-shock interactions, …

Flight dynamics/stability/control: algorithms for coupled roll-pitch-yaw and high angle-of-attack, nonlinear stability theory, integrated guidance and control algorithms to reduce sensor/actuator burden, …

APPROACH

Accurately predict flight physics

Exploit understanding of flight physics:
- Discover mechanisms to produce favorable forces and moments
- Nonlinear control theory



Predicting/Understanding Flight Behaviors with Aerodynamic and Thrust-Vector Control Mechanisms

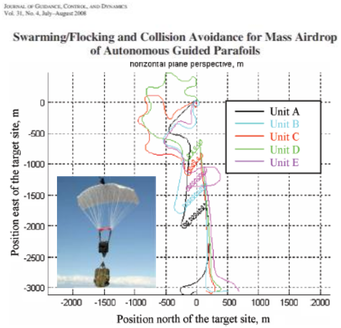
THEORETICAL BASIS FOR OVERCOMING THE SCIENTIFIC BARRIERS TO MANEUVERABILITY OF ATMOSPHERIC FLIGHT VEHICLES

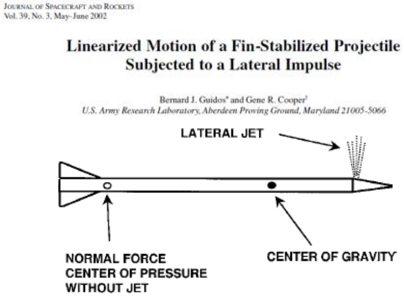
Swarming Delivery Challenges
- Formation Flight Control -

- Child airframe equipped with low cost components (thrusters, relative position)
- Control algorithm based on flight modeling

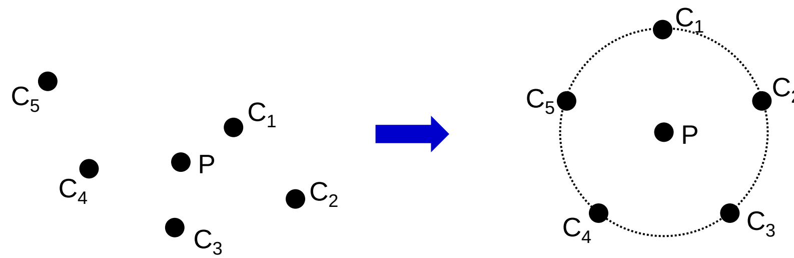
$$\tilde{r}_A = -k_t^2 (C_{L\alpha}/C_{M\alpha})\left[(s - s_0)\tilde{\xi}_0' + (s - s_1)\tilde{\mathcal{J}}_1^*\right]$$

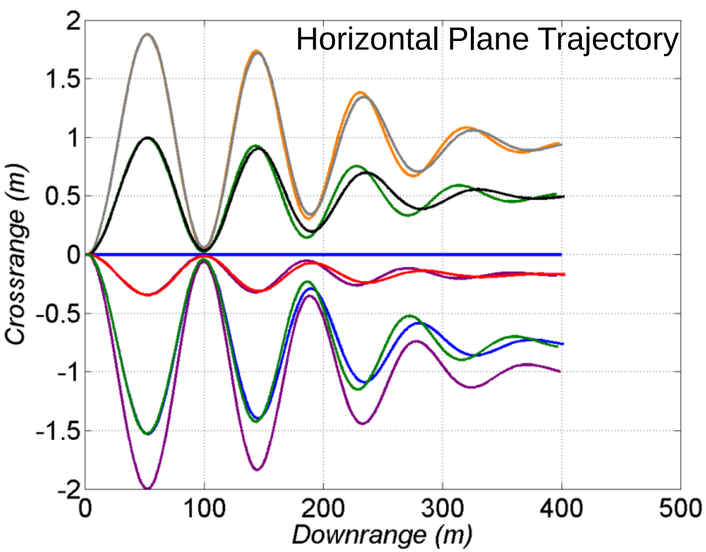
Feedback — System Properties (e.g., Mass, Aero) — Control





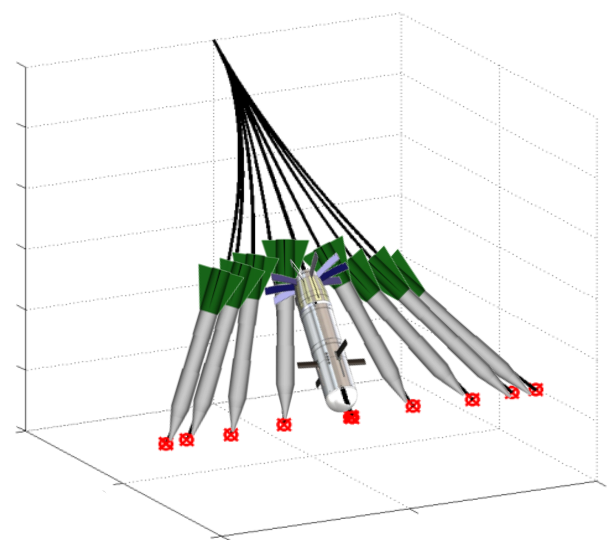
- Optimization routine used to resolve desired delivery formation of multiple bodies in flight





Numerical Experiments:

10 Bodies (Parent, 9 Children) Launched (150m/s) from Unmanned Aerial System with Targets at (400, 0) and desired circular pattern with 1m radius



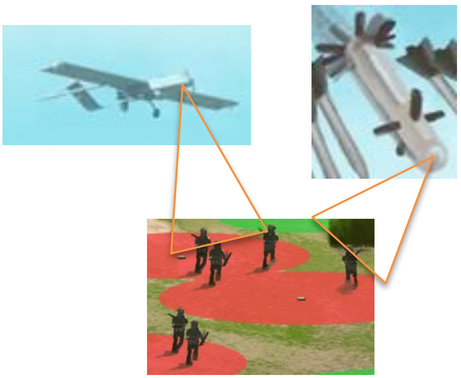
Swarming Delivery Challenges
- Collaborative Navigation -

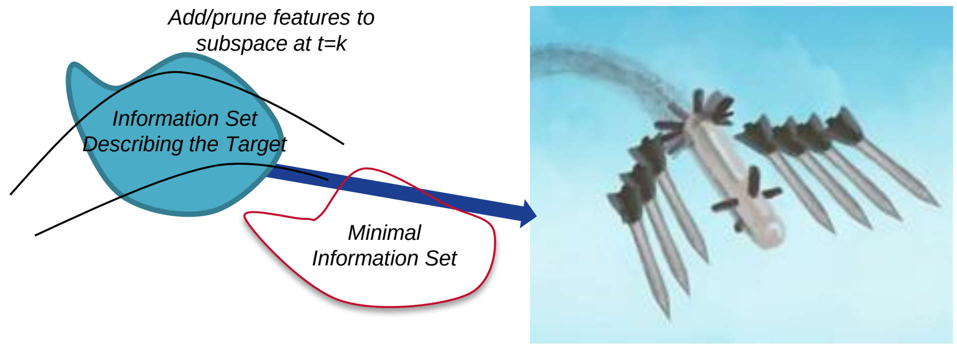
What is the minimal information for swarming navigation technology performance?

• heterogeneous mix of imager, ranging, communications on multiple vehicles

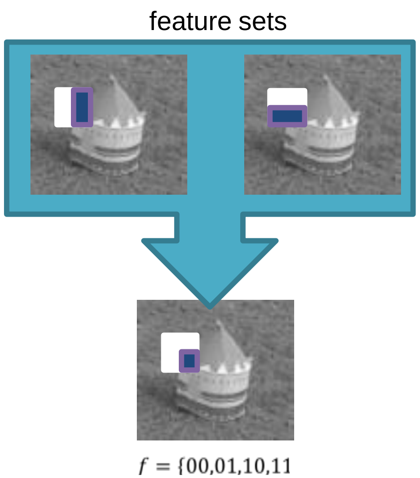
• algorithms with local and distributed processing nodes

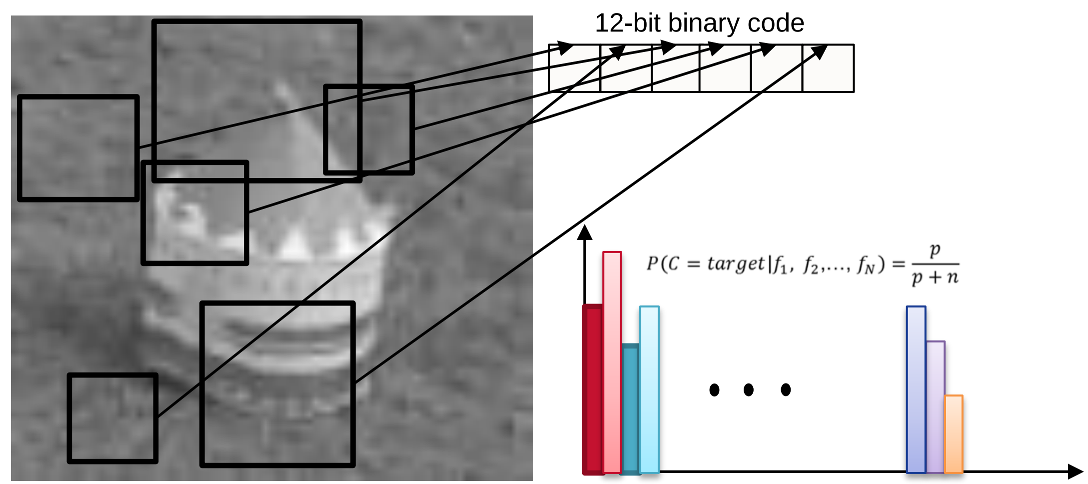
Can we improve position accuracy with multiple vehicles flying with poor measurements (latencies, update/link, bias, etc.)?





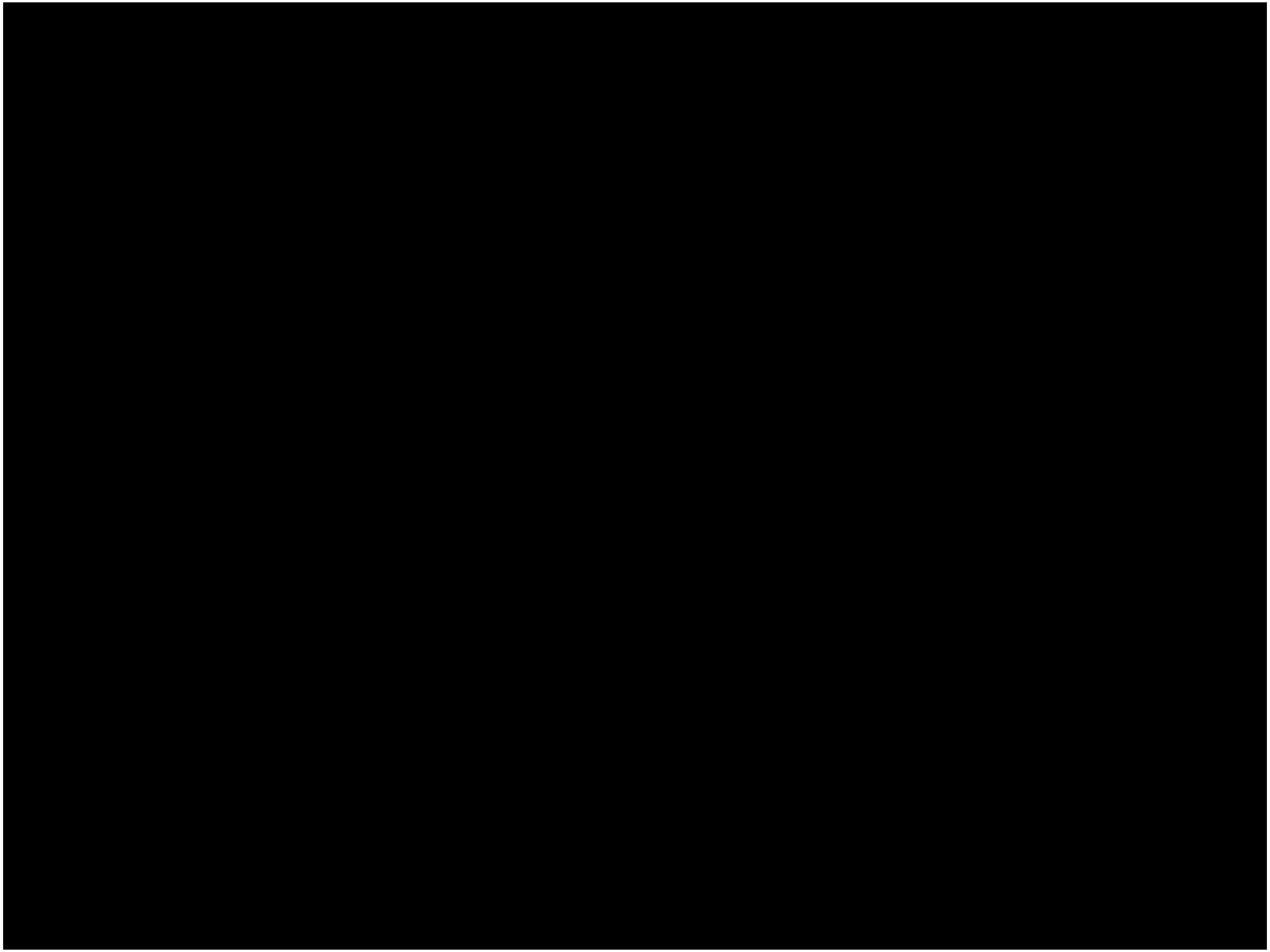
Example of algorithms for minimal information flow: low throughput adaptive classifiers for imagers





Swarming Delivery Challenges

- Collaborative Navigation -



PCWFD

- FY17+ Strategy -

Precision and Cooperative Weapons Flight and Delivery

Omnisonic Mechanics and Control/Ballistic Mechanics

Omnisonic Mechanics and Control: discover how to achieve next generation increase in maneuverability of flight bodies

Assured and Collaborative Navigation Theory: innovate theories to navigate in contested environments across a variety of conditions, likely using multiple agents with RF- or EO/IR-based measurements

Low Cost Hyper-Accurate Munitions Technology

Moving Target Technology: demonstrate moving target (e.g., image-based navigation, high maneuverability airframe) technologies

Maneuvering Flight Bodies for Small-Diameter Munitions: demonstrate control mechanism for

1. low speed/setback environment (child vehicle, counter-defilade/small UAS)
2. high speed/setback environment (CCRAM/anti-swarm, combat vehicle)

Swarming Weapons

Morphing Airframe Technologies: demonstrate launch and flight technologies for gliding parent vehicle which deploys parent vehicles

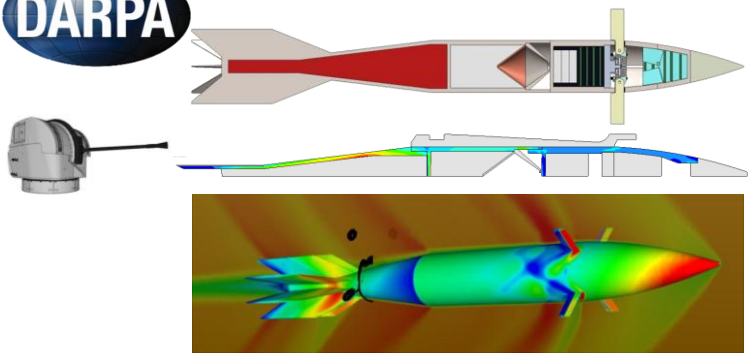
Swarming Navigation Technologies: demonstrate navigation technologies for swarming munitions in contested/denied/counter-measured environments

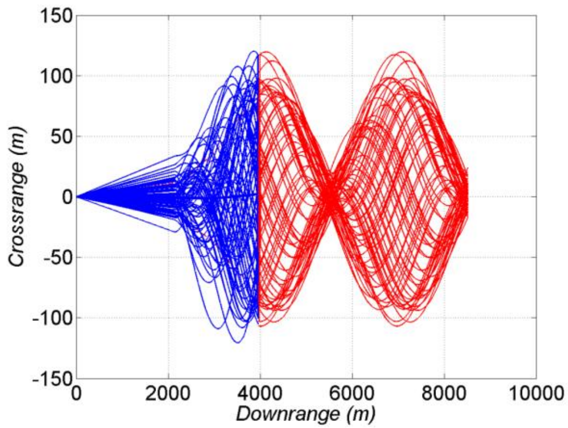
TRANSITION KNOWLEDGE FROM 6.1 TO 6.2 PROGRAMS

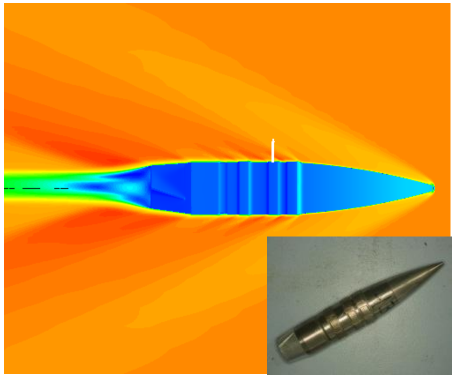
DEMONSTRATE TECHNOLOGIES (TRL3-4) FROM 6.2 PROGRAM TO ASSIST TRANSITION TO PARTNERS

Guided Lethality

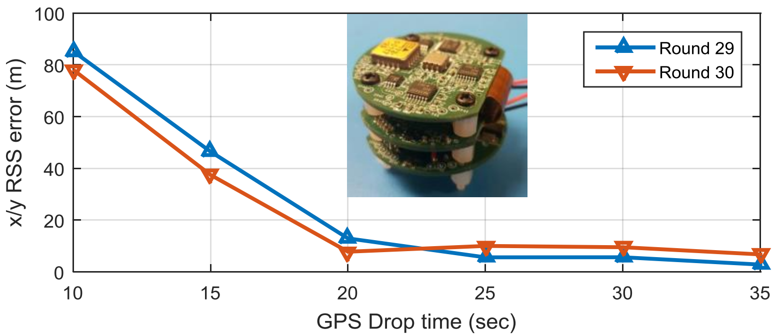
- Recent Transitions/Partners -



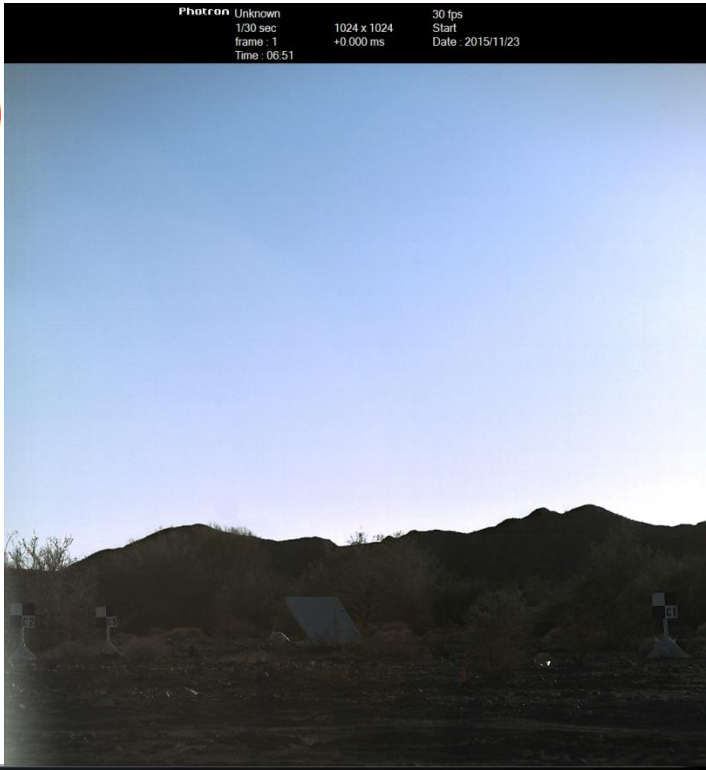




Guided Small/Medium Caliber Munitions



Guided Indirect Fires



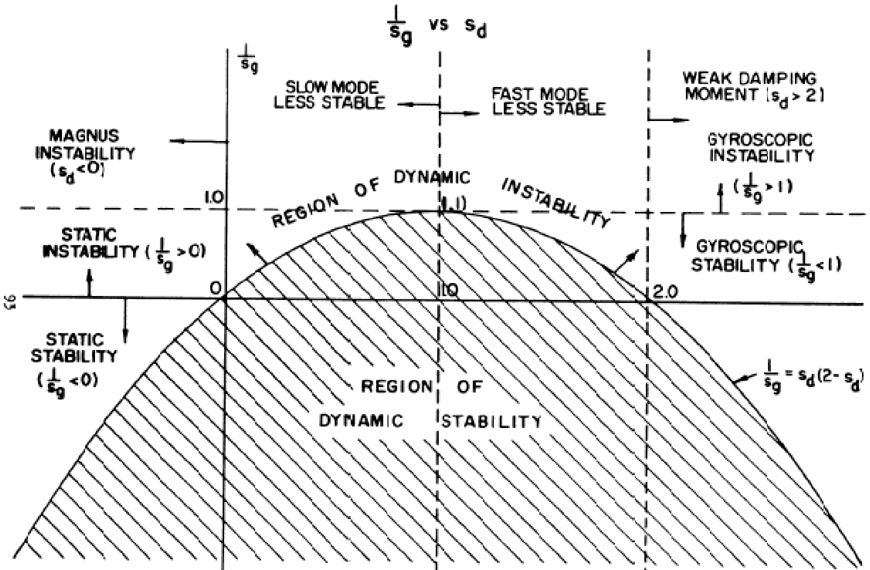
Backup

Guided Lethality

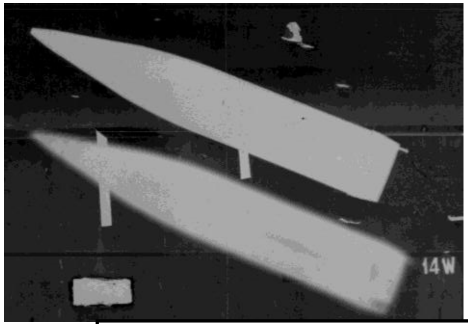
- Background -

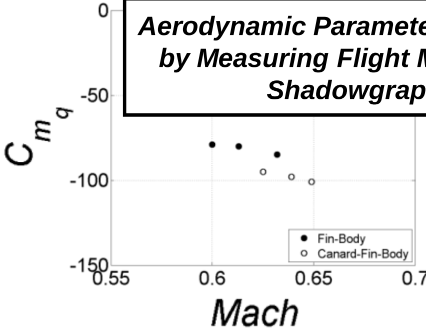
Predecessors of our Group (Ballistics Research Lab) → *understand flight of munitions*

- Flight Dynamics and Stability Theory



- Spark Ranges





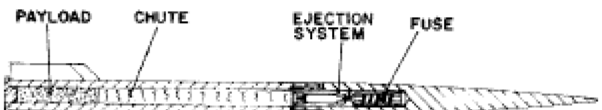
Aerodynamic Parameter Estimation by Measuring Flight Motion with Shadowgraphs

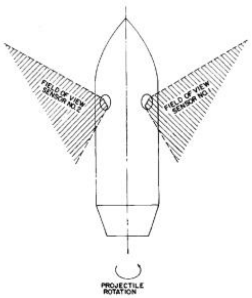
- Survivable/Miniature Onboard Sensors and Telemetry

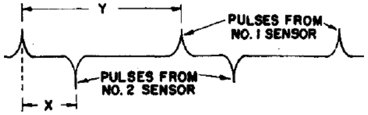
J. SPACECRAFT AUGUST 1971 VOL. 8, NO. 8

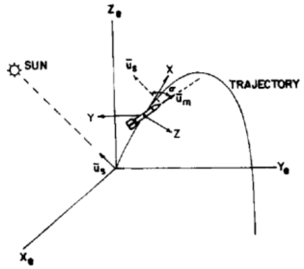
High-g Resistant Electronic Fuse for Projectile Payloads

William H. Mermagen*
Ballistic Research Laboratories, Aberdeen Proving Ground, Md.









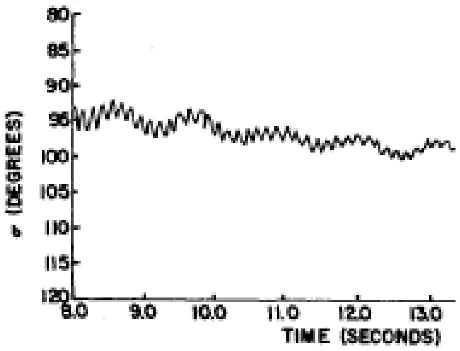
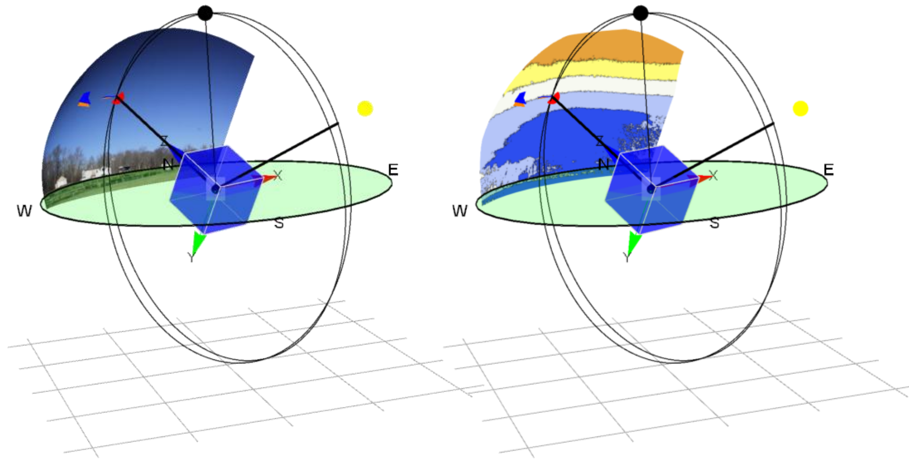


Image-based Navigation

Exploit skylight polarization as navigational cue in ballistic environment (passive, jam/spoof proof, drift and GPS free)

- *Rayleigh-sky modeling and algorithms for azimuth/elevation*



Novel measurement techniques (compressive sampling / spectral imaging) for small size/weight/power form factor weapons