Collaborative Cooperative Engagement
– Parent Child Concept

Frank Fresconi, PhD
Guided Lethality
-Vision-

Assured Delivery of Lethal Payload

Increased Performance and Widened Engagement Space

Advanced Target Acquisition

Advanced Launch

Advanced Lethal Mechanism

Instantaneous Delivery of N Payloads through Complex Environment

Adaptively Allocate Flight of Multiple Projectiles Based on In-Flight Measurements

Enabling Technologies

Maneuverability

Navigation

Platform Agnostic

Target Agnostic

Armor

Distributed Personnel (Defilade/Open) and Light Vehicles

Counter – UAS/RAM
### Technology Implementation Plan for Desired Lethal Effects at Standoff Ranges in Constrained Environments

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**Sciences for Lethality and Protection Campaign**

- **ARL Technology Implementation Plan for Guided Lethality**

<table>
<thead>
<tr>
<th>FY16 – FY19</th>
<th>FY20 – FY25</th>
<th>FY26 – FY30</th>
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<tbody>
<tr>
<td><strong>MANEUVERABILITY</strong></td>
<td></td>
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<tr>
<td>spin-stabilized projectile maneuvers</td>
<td>variable thrusters / vector control</td>
<td>hybrid variable-thruster arrays and aerodynamic control</td>
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<tr>
<td>high maneuverability airframe</td>
<td>extremely high-G, aerodynamic control</td>
<td>force/moment arrays for arbitrary three-dimensional acceleration profiles</td>
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<td>unstable &amp; enhanced lifting surface/deployment</td>
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<tr>
<td><strong>NAVIGATION</strong></td>
<td></td>
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<tr>
<td>image-based navigation (IBN): high speed or high maneuverability</td>
<td>IBN: countermeasures</td>
<td>multiple in-flight / high speed communications</td>
</tr>
<tr>
<td>IBN: air targets with ground vehicle, personnel, urban targets</td>
<td>IBN: multispectral</td>
<td></td>
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<tr>
<td>inertial measurement unit (IMU): heuristics</td>
<td>network-based RF data-linking</td>
<td></td>
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<tr>
<td>radiofrequency (RF): software-defined radios, M-Code GPS</td>
<td>high accuracy IMU arrays</td>
<td>IBN: navigators</td>
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<td></td>
<td>flash LIDAR</td>
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**External Advancements in Performance and SWaP/C of:**

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

**ASSURED DELIVERY**

- SMALLER CALIBER
- LOWER COST
- EXTREME ACCURACY
- MORE COMPLEX ENVIRONMENT
- FASTER DYNAMICS (MACH, SPIN RATE, TIME-OF-FLIGHT)
- HIGHER GS

**ADVANCED DELIVERY** *(SWARMING)*
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)

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Guided Lethality
- Resources / Core Capabilities -

UNDERSTAND LAUNCH, FLIGHT, AND GUIDED DELIVERY TECHNOLOGIES
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
AWFC 17: 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

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

LAUNCHER
REMOTE TARGET SELECTION
MOVING TARGET
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Current Focus: Moving Target Challenge
- Status -

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

**Gun Launch**
- Airframe

**Wind Tunnel**
- Flight Control
- Control Actuation
- Airframe

**Model**: Challenge platform maintains cohesion/focus and drives critical experiments
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High Maneuverability Airframe

- Validation of simulations
- Understanding of maneuver mechanism
  - Structural response to gun launch
  - Dynamic modeling

- Understanding of maneuvering flight behavior
- Aerodynamic modeling
- Flow interactions (roll and pitch/yaw)
- Flight control with coupled fluid/flight/actuator dynamics

- Verify performance of flight control algorithms

\[
\begin{bmatrix}
\dot{\theta} \\
\dot{\phi} \\
\dot{\psi}
\end{bmatrix} =
\begin{bmatrix}
\alpha_{\text{roll}} \\
\alpha_{\text{pitch}} \\
\alpha_{\text{yaw}}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\delta(t) + 2\xi\omega\delta(t) + \omega^2\delta(t) = \delta_C(t - t_D)
\end{bmatrix}
\]

\[
\begin{bmatrix}
\text{damping ratio} \\
\text{canard deflection} \\
\text{time delay}
\end{bmatrix}
\]

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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

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**

- **155mm diameter warhead / effects**
- **60mm diameter warhead / effects**
- **40mm diameter warhead / effects**

**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

Counter-Defilade

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

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

maneuver, accurate navigation, magazine depth

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 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
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
**MOTIVATION**

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

**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

**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

\[ \ddot{r}_A = -k_1 \left( \frac{C_{L\alpha}}{C_{M\alpha}} \right) \left[ (s - s_0) \ddot{z}_0 + (s - s_1) \ddot{f}_1 \right] \]

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

- Flight Dynamics and Stability Theory
- Spark Ranges
- Survivable/Miniature Onboard Sensors and Telemetry

High-g Resistant Electronic Fuse for Projectile Payloads

WILLIAM H. MERMAGEN
Battelle Research Laboratories
Aberdeen Proving Ground, Md.
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