
Dr. Ron Barrett
Professor of Aerospace Engineering
Adaptive Aerostructures Laboratory Director

Ms. Lauren Schumacher
Self Graduate Fellow & Ph.D. Candidate

Aerospace Engineering Department
The University of Kansas, Lawrence, Kansas

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Outline:

I. Motivation

II. Background

III. New Classes of Adaptive Actuators

IV. Enabled Systems

V. Future Work
Motivation:

• **New Enabling Technologies**
  - lower caliber rounds via MASS designs...
  - new missions...

• **Lines blurred: Missiles ↔ Munitions**

• **Large Cost Savings Possible**
Brief Guided Round History

M712 Copperhead 1975

M247 Sergeant York, 40mm 1986...

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Flight Control Technologies

**Electromagnetic**  
*tens to hundreds of components*

- Electrical Energy Source
- Command Signal
- Position Feedback
- Gear stages
- Motor
- Push arms, linkages etc.

**Adaptive**  
*solid state, rugged*

- Electrical Energy Source
- Command Signal
- Position Feedback
- Adaptive actuator part of primary structure

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V. Future
Low Caliber Flight Control Actuator Needs...

- Setback tolerance: 5,000 - 100,000g’s
- Balloting, setforward, ringing impervious
- Compatible with supersonic control effectors
- Not affected by atmospherics (rain, dust, dirt, snow, etc.)
- 20 yr storage life
- -40 to +145° F
- Fully proportional deflections
- Lightweight (<1g), Low Volume (<1cc), Low Power (95+% electrical-to-mechanical conversion efficiency)
- High bandwidth (>200 Hz)
Overview of Programs with Lineage to Flying Adaptive UAVs

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Guiding Lower Caliber Rounds... More History

Barrel-Launched Adaptive Munition (BLAM) Program 1995 - '97

USAF/AFRL-MNAV

- Aerial Gunnery (20 - 105mm)
- Extend Range w/2g maneuver
- (Eglin AFB tests ‘97)
  (Mach 3.3 tests ‘96-'97)
- Increase hit probability
- Increase probability of a kill given a hit
- Reduce total gun system weight fraction
The First MAV... Driving Adaptive FCS

Conventional Electromagnetic

Adaptive Stabilators

+/- 90° Deflections @ 3 Hz

+/-11° Deflections @ >47Hz
**Advanced MAVs:** Driving the need for Adaptive Actuators -- faster, lighter, stronger

![Bandwidth Comparison Diagram]

**Adaptive Surfaces vs. Conventional Servos**
- 96% reduction in power consumption
- 16x increase in bandwidth
- 99.2% decrease in slop
- Order of magnitude reduction in part count
- 12% OWE savings

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Guiding Small Arms Rounds... More History

Range-Extended Adaptive Munition (REAM) IRAD
BAT-Lutronix Corp. developed supersonic piezoelectric FCS actuators

Max Power Consumption: 28 mW
Nominal Power Consumption: 3.5 mW
Static Power Consumption: < 1μW
Design Mach Range: 0.8 - 4.5, STP
Design Accelerations: 25k g's

10 mil stainless steel flight control surface

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Other Adaptive FCS Efforts

Rabinovitch & Vinson 2000 - present

again... low authority
can't survive balloting, setback unsteady aero...

Now Where???
Guiding Hard-Launched Rounds... The Epiphany!

Discoveries from Europe...

\[ F = k\Delta x \quad \text{F} \neq k\Delta x \]

Eureka!
Guiding Hard-Launched Rounds... The Epiphany!
Increasing Moment-Deflection Design Space
Guiding Hard-Launched Rounds... The Epiphany!

Weight & Cost constrained

Deflection, $\delta$ (deg)
Guiding Hard-Launched Rounds... The Epiphany!

- single-crystals
- Weight & Cost constrained
- interdigitated electrode
- hydraulic amplifiers
- stepper motors
- unusual element configurations

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Guiding Hard-Launched Rounds... The Epiphany!
Increasing Moment-Deflection Design Space

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Guiding Hard-Launched Rounds... The Epiphany!

Increasing Moment-Deflection Design Space

The Limiter: Strain on Convex Face

Tension $+\varepsilon$

Compression $-\varepsilon$
Guiding Hard-Launched Rounds... The Epiphany!

Increasing Moment-Deflection Design Space

Improvement: Precompression via CTE mismatch cure

Tension $+\varepsilon$

Compression $-\varepsilon$
Guiding Hard-Launched Rounds... The Epiphany!

- Require bump-stops to prevent overrotation
- Depoling/fracture boundaries limit deflection
- High in-plane tensile stresses on convex face leads to premature depoling under cyclical loading
- Assembly and tuning is very tricky
Guiding Hard-Launched Rounds... The Epiphany!
Increasing Moment-Deflection Design Space

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Guiding Hard-Launched Rounds... The Epiphany!
Increasing Moment-Deflection Design Space

Facing sheet engagement theories

• First order model: assumption: $y_{sp} = y_{fs}$

$$\tan \theta = \frac{4}{L_{sp}} (y_{0fs} - y_{sp}) \quad (5)$$

• Higher Fidelity model: assumption: $L_{sp} = L_{fs}$

$$L_{fs} = \int_{0}^{L_{sp}} \sqrt{1 + \left( \frac{dy_{fs}(x)}{dx} \right)^2} \, dx = \int_{0}^{L_{sp}} \sqrt{1 + \left( \frac{y_{0fs} \pi}{L_{sp}} \sin \left( \frac{2\pi x}{L_{sp}} \right) \right)^2} \, dx \quad (6)$$

$$L_{fs} = \int_{0}^{L_{sp}} \sqrt{1 + \left( \frac{dy_{sp}(x)}{dx} \right)^2} \, dx = \int_{0}^{L_{sp}} \sqrt{1 + \left( \frac{y_{0sp} \pi}{L_{sp}} \sin \left( \frac{2\pi x}{L_{sp}} \right) + \left( 1 - \frac{2x}{L_{sp}} \right) \tan \theta \right)^2} \, dx \quad (8)$$

Equating (6) and (8) allows solution for $\theta$
Guiding Hard-Launched Rounds... The Epiphany!

Increasing Moment-Deflection Design Space

- 2mm wide, 69µm graphite-epoxy facing strips
- 1.7mm thick silicone spacer
- Spacer, $y_{sp}=1.75$mm

\[ F_a = L \frac{\sin \left( \frac{\theta}{2} \right) \cos \xi}{\sqrt{\sin^2 \left( \frac{\theta}{2} \right) \cos^2 \xi + \frac{\kappa^2 D_b}{4F_a}}} \left( 1 - \sin^2 \left( \frac{\theta}{2} \right) \sin^2 \xi \right) \]  

- Uniform facing sheet engagement
- Excellent theory-experiment correlation
- Still pronounced DEAS effect
- 12% mass increase w.r.t. baseline PBP element
Guiding Hard-Launched Rounds... The Epiphany!
Increasing Moment-Deflection Design Space

Proper Dynamic Elastic Axis Shifting (DEAS) Design:

- Tension limit reached on convex face
- Compression limit reached on concave face
- Bond shear stresses below limit

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PBP Actuators: The FCS Solution

- Fraction of the weight, size & power consumption of conventional Actuators (i.e. much smaller actuator bays)
- 300+% deflection increases with full force/moment capabilities
- Mass production compatible
- ±0.01 deg. trimmable
- Extremely high bandwidth
- Lower g-sensitivity
- Very low cost
PBP Actuators: Assemblies

Assembled Hard-Launch Capable Actuator FCS Units:
PBP Actuators: Fastest around...

Best performance in the adaptive structures industry:

- 1kHz equivalent bandwidth
- Driving 0.40/.50 cal Mach 4.5 canards
## PBP Actuators: Munitions Comparisons

Smaller, Lighter, Less Expensive, More Rugged...

<table>
<thead>
<tr>
<th></th>
<th>Conventional Electromagnetic FCS</th>
<th>Adaptive/PBP FCS</th>
</tr>
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<tbody>
<tr>
<td>Volume</td>
<td>14cc</td>
<td>5.1cc</td>
</tr>
<tr>
<td>Mass</td>
<td>69g</td>
<td>4.2g</td>
</tr>
<tr>
<td>Peak Power</td>
<td>148W</td>
<td>2.6W</td>
</tr>
<tr>
<td>Deadband/Slop</td>
<td>±0.38°</td>
<td>±0.002°</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>22 Hz</td>
<td>189Hz</td>
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<tr>
<td>Acquisition Cost</td>
<td>$187 ea.</td>
<td>$12.30</td>
</tr>
<tr>
<td>(100,000 shipsets)</td>
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New Enabled Missions:

Conventional Air-to-Air Missile Replacement
- Airframe Shrinkage
- Force Multiplication
- Counter-Missile
- Self Defense
- LO Enhancement

AMRAAM

45mm MASS GHLM
New Enabled Missions:

Enhanced Aerial Gunnery Capabilities

- 30mm GAU-8/PGU-14 E\textsubscript{Impact} \leftrightarrow 25mm MASS Guided Hard-Launch Munition

- 25mm GAU-22/PGU-47 E\textsubscript{Impact} \leftrightarrow 20mm MASS Guided Hard-Launch Munition

- 20mm M61A1/PGU28 E\textsubscript{Impact} \leftrightarrow 16mm MASS Guided Hard-Launch Munition
New Enabled Missions:

FAC-130...

Air-to-Air...

Indirect Fire Support
New Enabled Missions:

Air-to-Air & Self-defense

FAC-17

Indirect Fire Support...
Questions?