Developmental History of a New Family of Subscale, Convertible, High Performance UAVs

Dr. Ron Barrett

Alumni Associate Professor
Aerospace Engineering Department
Auburn University, Alabama
USA

Visiting Professor
Faculty of Aerospace Engineering
Technical University of Delft
Netherlands

Micro Aerial Vehicles -- Unmet Technological requirements
Schloß Elmau, Germany 22 - 24 September 2003
# Developmental History of a New Family of Subscale, Convertible, High Performance, UAVs

**1. REPORT DATE**
23 JUL 2004  

**2. REPORT TYPE**
N/A  

**3. DATES COVERED**
-  

**4. TITLE AND SUBTITLE**
Developmental History of a New Family of Subscale, Convertible, High Performance, UAVs  

**5a. CONTRACT NUMBER**
-  

**5b. GRANT NUMBER**
-  

**5c. PROGRAM ELEMENT NUMBER**
-  

**6. AUTHOR(S)**
-  

**5d. PROJECT NUMBER**
-  

**5e. TASK NUMBER**
-  

**5f. WORK UNIT NUMBER**
-  

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Aerospace Engineering Department  
Auburn University, Alabama  
USA  

**8. PERFORMING ORGANIZATION REPORT NUMBER**
-  

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
-  

**10. SPONSOR/MONITOR’S ACRONYM(S)**
-  

**11. SPONSOR/MONITOR’S REPORT NUMBER(S)**
-  

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release, distribution unlimited  

**13. SUPPLEMENTARY NOTES**
See also ADM001689, EOARD-CSP-03-5073 Micro Air Vehicle Workshop., The original document contains color images.  

**14. ABSTRACT**
-  

**15. SUBJECT TERMS**
-  

**16. SECURITY CLASSIFICATION OF:**
-  

<table>
<thead>
<tr>
<th>a. REPORT</th>
<th>b. ABSTRACT</th>
<th>c. THIS PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>unclassified</td>
<td>unclassified</td>
<td>unclassified</td>
</tr>
</tbody>
</table>

**17. LIMITATION OF ABSTRACT**
UU  

**18. NUMBER OF PAGES**
25  

**19a. NAME OF RESPONSIBLE PERSON**
-  

Standard Form 298 (Rev. 8-98)  
Prepared by ANSI X34-18
Outline

1989 - ‘96 Enabling Materials and Experience

1994 - ‘97 The First DoD MAV

1998 - ‘00 DARPA’s MOUT MAVs

2001 - ‘03 Convertible Military MiAVs

2003 X/YQ-138 Handoff to Industry
1989 - ‘96 Enabling Materials and Experience

1st twist-active adaptive wing built & bench tested
(±0.8° static twist deflections)

1990

1st prototype pitch-active missile fin
(±5° static deflections)

1991

1st torque-plate rotor built
(±5° static deflections)

1992

USAF commissions 1st DAP missile fin study

1993

GD licenses DAP technology

Directional Attachment invented to generate twist deflections in aerodynamic surfaces
1989 - ‘96 Enabling Materials and Experience

Gamara, the first helicopter to use adaptive materials for all flight control

1994

DAP torque-plate rotor demonstrates ±8° static and dynamic deflections at up to 2.5/rev on Froude & Mach scaled rotors

1995

Mothra, the first aircraft to use adaptive materials for all flight control

1996

Adaptive gravity weapons

Piezoceramic lamina hardening techniques invented for Barrel Launched Adaptive Munition (BLAM) program

NSF sponsors UAV & DAP rotor work

Adaptive TOW-2B

Gamara, the first helicopter to use adaptive materials for all flight control
1994 - ‘97 The First DoD MAV

Sponsor: DoD CounterDrug Technology Office

Mission Challenge: counterdrug agents and animals die in border tunnels

Mission Specification:
• Max. 6” (15cm) dia. rotor
• Max. Range: 20m
• Max. Endurance: >24hr
• T/O distance: VTOL
• Max flight speed: 2mph (3kph)
• Coms link: hard wire
• Sensor: B/W 0.1 lux
• Stationkeeping: 5cm
• No chemical emissions

Mission Profile:
- Warmup
- Takeoff
- Underground Loiter > 24hr
- Hover out 20m
- Hover in 20m
- Ascent
- Shutdown

Kolibri
1994 - ‘97 The First DoD MAV

Kolibri

- High voltage tether
- CCD camera
- Piezoelectric gyros
- Counterrotating rotor
- High voltage rare-earth electric motor
- Graphite truss
- Piezoelectric stabilators

Kolibri Airborne Camera View

1st Flight September 1997
1994 - ‘97 The First DoD MAV

Enabling Technology: High Speed Piezoelectric Stabilators

- first natural frequency in pitch: 23 Hz
- pitch corner frequency: 47 Hz
- max power consumption: 14 mW
- max. static deflections: ±11°
- total mass 5.2g
- actuator mass: 380 mg
**1998 - 2000 DARPA’s MOUT MAVs**

**Mission Challenge:** reconnaissance in urban and subcanopy environments

“Military Operations in Urban Terrain is one of the top priorities for the DoD.”


**Mission Specification:**
- Max. 6” (15cm) dia. rotor
- Max. Range: 1km
- Max. Endurance: 20 min.
- All weather capable
- 15g wall strike
- T/O distance: n/a
- Max flight speed: 30 mph (48kph)
- Com link: RF
- Flight modes: 1st, 3rd person
- Sensor: B/W 0.1 lux

**Mission Profile:**
- Fly out 1km
- Urban Canyon/Subcanopy Loiter 10 min.
- Fly back 1km
- Land
- Descent
- Shutdown
- Warmup
**Motivation:**

“2/3 of eligible targets in the Balkans went undetected, let alone unengaged because of our reconnaissance deficiencies.”


Current UAVs offer monocular situational awareness with only one general view -- from above.

Panocular situational awareness is necessary in the modern battlefield.

M998 HMMWV Aerial Detection Exercise, Alabama July 1998
**Environment Survey:**

**Observed Structures In the Urban Canyon**

- freestream
- alley venturi & rotary gust
- doorway burble (cavity flow)
- corner vortex
- "street devil" (separated corner vortex)
- "street wave" (long period wave)
- doorway burble (cavity flow)
- "street devil" (separated corner vortex)
1998 - 2000 DARPA’s MOUT MAVs

MOUT & Subcanopy MAV Configuration Selection

Isotropic Gust Grid:
- 363 sample points
- 100 ft x 100 ft x 30 ft high (30m x 30m x 9m high)
- 1 min. per point, 10 days of sampling
- Blue sky sampling days only
1998 - 2000 DARPA's MOUT MAVs

MOUT & Subcanopy MAV Configuration Selection

Aerodynamics Challenges: Low $C_{l_{\text{max}}}$ at Low $R_n$... gusts... and rain

[Graphs and diagrams showing aerodynamic data and configurations]
1998 - 2000 DARPA’s MOUT MAVs

MOUT & Subcanopy MAV Configuration Selection: Turn Radii Required

Urban Setting Survey
200 intersections in Groningen, Netherlands within 1km of Station Nord

Subcanopy Survey
200 trees in the Tuskegee National Forest along Bartram National Recreation Trail

Aircraft Turn Radii

<table>
<thead>
<tr>
<th></th>
<th>-1 Std Dev.</th>
<th>Average</th>
<th>+1 Std Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>6.1ft</td>
<td>8.7ft</td>
<td>14.4ft</td>
</tr>
<tr>
<td>Subcanopy</td>
<td>8.8ft</td>
<td>14.7ft</td>
<td>32.9ft</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>-1 Std Dev.</th>
<th>Average</th>
<th>+1 Std Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>1.9m</td>
<td>2.7m</td>
<td>4.4m</td>
</tr>
<tr>
<td>Subcanopy</td>
<td>2.7m</td>
<td>4.5m</td>
<td>10m</td>
</tr>
</tbody>
</table>
1998 - 2000 DARPA’s MOUT MAVs

MOUT & Subcanopy MAV Configuration Selection:

- CURRENT FIXED-WING MAVs CANNOT MAKE THE TURNS IN URBAN TERRAIN
- FUTURE FIXED-WING MAVS REQUIRE T/W >1 TO NAVIGATE URBAN TERRAIN

![Graph showing CL and T/W required for urban flight turn radius](image)
1998 - 2000 DARPA’s MOUT MAVs

MOUT & Subcanopy MAV Configuration Selection: COLEOPTER

LuMAV-2
DARPA TTO 1998-1999

- Bench, Hover Stand and Wind Tunnel Test Article
- Aerodynamic Characteristics
- Power Requirements

LuMAV-2AS/GF
DARPA TTO 1998-2000

- 6” (15cm) Free-Flight Rotary-Wing Flight Vehicle
- 20 min. hover
- 22 kt flight speed
- 6 oz (171g) payload
- Perch Capability
- Indoor & Outdoor Flight
- Graphite-Epoxy Structure
- Stationkeeping with ±8 kt gusts
- Muffling to Background Levels @ 15m
- In-Flight Full Color & Low Light Video Link
- 1st Flight July 1999

LuMAV-3AS/GF
DARPA TTO 2000

- 6” (15cm) Recoverable Free-Flight Rotary-Wing Flight Vehicle
- 20 min. hover
- 32 kt flight speed
- 6 oz (171g) payload
- Perch Capability
- Indoor & Outdoor Flight
- Flight in rain to 14.5 in/hr, ±14 kts
- Urban Canyon Surveillance
- High Control Authority Emulation
- Improved Graphite-Epoxy Structure
- Stationkeeping with ±18 kt gusts
- Muffling to Background Levels @ 15m
- In-Flight Full Color & Low Light Video Link
- 1st Flight May 2000

MultiDisciplinary Optimization
1998 - 2000 DARPA’s MOUT MAVs

MultiDisciplinary Optimization Performed on:

- Structures
- Aerodynamics
- S&C
- Propulsion

![Graph showing weight distribution across different components]

- Max Gross Weight, MGWTC (441 gmf)
- Max payload weight, Wpl 171 g
- Operating empty weight, Woe 271 gmf
- Sensor & Transmitter 10 gmf
- Structure 107 gmf
- Propulsion 75 gmf
- Electronics and Electrical Systems 80 gmf

Distance, R (nm)

Endurance, E (min)
1998 - 2000 DARPA’s MOUT MAVs

LuMAV Testing

*acoustic signature*

test conditions:
72 - 78°F day, 65% humidity
winds 3 - 6 kts & variable, 9:00 - 11:00 am
testing conducted: East Central Alabama in March
suburban, open field & pine forest backgrounds

---

**Graph:**

- Sound Level, A (db)
- Distance, x (m)

**Lines and Symbols:**
- Blue line: Lawnmower
- Red line: Yard Blower
- Green line: Norvel .061 Std. Muffler
- Black line: LuMAV-3A
- Grey line: Suburban Background
- Cyan line: Open Field Background
- Purple line: LuMAV-2A
- Pink line: Wooded Background

**Data Points:**
- APC 5.7 x 3 rotor
  - 1405 - 1464 RPM
  - (23.4 - 24.4 Hz)
**Mission Challenge:**
MOUT Capable MILITARY Subscale UAV with High Dash Speed & Efficient Loiter

"We want a subscale UAV that can do it all.”  -Mr. Serh Ghee Lim, President, Singapore Technologies Aerospace Corp.

**XQ-138 Design Mission:**

<table>
<thead>
<tr>
<th>Mission Stage</th>
<th>Endurance (min)</th>
<th>Elapsed Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Startup</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2. VTO &amp; Climb</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>3. Xition</td>
<td>0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>4. Cruise, 10 km, 50 kts</td>
<td>6.5</td>
<td>8.5</td>
</tr>
<tr>
<td>5. Xition &amp; HOGE 10 min</td>
<td>10.0</td>
<td>18.5</td>
</tr>
<tr>
<td>6. Desc. &amp; HOGE 10 min</td>
<td>10.0</td>
<td>28.5</td>
</tr>
<tr>
<td>7. Climb &amp; HOGE 5 min</td>
<td>5.0</td>
<td>33.5</td>
</tr>
<tr>
<td>8. Release &amp; HOGE 5 min</td>
<td>5.0</td>
<td>38.5</td>
</tr>
<tr>
<td>9. Xition &amp; Descent</td>
<td>0.5</td>
<td>39.0</td>
</tr>
<tr>
<td>10. Cruise, 10 km, 50 kts</td>
<td>6.5</td>
<td>45.5</td>
</tr>
<tr>
<td>11. Xition</td>
<td>0.5</td>
<td>46.0</td>
</tr>
<tr>
<td>12. VL &amp; Shut-down</td>
<td>1.0</td>
<td>47.0</td>
</tr>
</tbody>
</table>

**Mission Specification:**
- Max. weight: 6 lb (2.7kg)
- All weather capable
- 25 kt gust penetration
- Com link: RF
- Dash speed: 80mph (130kph)
- Mission Range: 10km
- 12”/hr (31cm/hr) rain
- 15g MOUT wall strike
- 500g P/L
- Sensors: B/W 0.001 lux, Color 0.1 lux, FLIR
- Flight modes: 1st, 3rd person, fully autonomous w/waypoint navigation
- Design Mission Duration: 47 min.
- 100°F (38°C), 100% humidity
- Combat shotgun resistant @5m
- T/O distance: n/a
2001 - '03 Convertible MILITARY MiAVs

XQ-138 Design: MDO using best currently available technology

Upper Fuselage
- fuel
- GNC
- Sensor
- Coms

Upper Fuselage
- turning vane flap servos
- electrical & fuel feed lines
- turning vanes
- turning vane flaps
- rotor

Lower Fuselage
- powerplant
- empennage actuators
- muffler assembly
2001 - '03 Convertible MILITARY MiAVs

XQ-138: unique among UAVs

Gross Weight, W (kg)
Coleopter Pitchback Instability: 50 years of Experience

“We didn’t have the control authority needed for the prevailing conditions.”

Gary Downs, Director Allied UAV Systems following catastrophic crash of the iSTAR at Ft. Eustis in light but gusty wind conditions 10 September 2003 http://www.uvonline.com

Coleopter Pitchback Instability explained in OAV Proposal to DARPA 1/01

Unfortunately, this effect limited the forward speed to a mere 26 kph (16 mph) and caused erratic handling in windy conditions.” Smithsonian Air and Space Museum on the Hiller VZ-1 aircraft http://www.nasm.si.edu/nasm/aero/aircraft/hiller_vz1.htm
2001 - ‘03 Convertible MILITARY MiAVs

XQ-138 Flight Demonstration from LAV at Redstone Arsenal and Eglin AFB
Strong Gusty Conditions to 26 kts April - May 2002

1. Aircraft loaded & preflighted
2. Aircraft Release
3. Vertical Ejection @ ~ 10 ft/s (~ 3m/s)
4. Clearing Launcher
5. Transition
6. Flyaway

26 kt gusting winds @ Eglin Hellfire Range
2001 - ‘03 Convertible MILITARY MiAVs

Autonomy Package Development 6/02 - 6/03

Demonstrated multiple waypoint navigation in hover mode flight

Payload Delivery Testing 7/03
2001 - ‘03 Convertible MILITARY MiAVs

Hover or Horizontal Flight Endurance, E (min)

3000 (MGWTO)

Aircraft Weight, Wac (gmv)

Payload (GNC & Mission Packages)

Fuel

Straight Line Range, R (nmi)

0 10 20 30 40 50 60 70

0 1500 2000 2500 3000

0 200 400 600 800 1000 1200 1400

0 20 30 40 50 60 5% Min. Thrust Margin
2003 Handoff to Industry

Purchased by Singapore Technologies Aerospace Corp.

Limited rate production scheduled 2nd qtr/04

US Pat. 6,502,787

Future variants:
Elastic, modular design = too many to cover

Transition at Asia Aerospace Airshow

High Speed Flight Asia Aerospace Airshow

Rain Demonstration

Hover at Asia Aerospace Airshow

YQ-138

Unclassified All Material from Public Sources