Outline

- Mission and performance requirements for VTOL MAV
- Teaming
- Propulsion system of two coaxial contra-rotating motors-propellers
- Propulsion evaluation
- Wind tunnel apparatus and test procedure
- Zimmermann wing testing at UA and SUPAERO
- Decoupling of aerodynamic and propulsive forces
- Zero-lift Drag
- VTOL MAV design and flight tests
Goals (overall three-year goal):

- Project brings together a team of experts from UA and SUPAERO
- Conduction of experimental and theoretical research studies on the most important aspects of aerodynamics, structure, stability and automatic controls of VTOL MAVs
- Designing and flight testing of autonomous VTOL MAVs
Mission and Performance Requirements

- Urban operation scenario
- Rapid ingress/egress
- Vertical take-off and landing
- Hovering
- High maneuverability in tight space, flying into windows and inside of buildings
Previous Relevant Work – SUPAERO Vertigo VTOL UAV System

Hover: large diameter of propeller
Fast forward flight: large surface of wing

- Tail-Sitter Span 650 mm
- In-line Propellers
- Control obtained by flow deflection

Conception and realization: Aerospace Laboratory, SUPAERO
Aerodynamics characterization: Aerodynamic Laboratory, SUPAERO
Previous Relevant Work – UA Autonomous MAV System

- Endurance of 30 min
- 45-50 mph
- Operate in winds of 25 mph
- Standard operational altitude of 300 ft AGL
- Low noise and visual signature
- GPS waypoint navigation system
- Hand launch, autonomous climb, fly through waypoints, return and land at last waypoint
- Allow for between flight and in-flight reprogramming

In March of 2006, the Dragonfly UA MAV was delivered to the US Army
VTOL MAV Concepts to be Studied

Single- and dual-propeller tilt-body MAV Concept

Tilt-wing MAV Concept

Thrust-vectoring MAV Concept

Single propeller propulsive system drawbacks:
- propeller torque
- P-factor
- effect of the rotational airflow
- gyroscopic moments
Propulsion system of two coaxial contra-rotating motors-propellers

- two propeller-motor sets, one directly behind the other in the axial direction, spinning in opposite directions
- space inside a stator allows a cross shaft through a motor
- no gear box needed
Propulsion Evaluation

- single vs dual – no gains, no losses
- pusher vs tractor – a significant form drag on tractor configuration
- 10 times lesser torque
Hot Wire Measurements

- velocity distributions – fuselage, wing, and controls design for vertical flight conditions
Propeller momentum theory

Velocity at the distance \( s \) from the propeller disk

\[
w(s) = 0.5 \left[ \sqrt{V_0^2 + \frac{2T}{\rho \pi R^2}} \left( 1 + \frac{s / R}{\sqrt{1 + (s / R)^2}} \right) \right] - V_0
\]

The radius of the streamtube

\[V(s)r^2 = V(0)R^2\]
Wind Tunnel Facilities

SUPAERO Wind Tunnel

- suction-based, open circuit tunnel with a test section of 0.9 x 1.2 m is capable of speeds from 2 to 50 m/s
- 6-component high precision balance

UA Wind Tunnel

- closed circuit tunnel with a test section of 0.45 x 0.45 m capable of speeds from 2 to 30 m/s
- 6-component high precision balance
Wind Tunnel Testing of Propulsion
## Wind Tunnel Model of Zimmermann Wing

### Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camber (%)</td>
<td>3</td>
</tr>
<tr>
<td>Wing Span, $b$ (in)</td>
<td>10</td>
</tr>
<tr>
<td>Root Chord Length, $c_0$ (in)</td>
<td>8.125</td>
</tr>
<tr>
<td>Camber Height, $h$ (in)</td>
<td>0.27</td>
</tr>
<tr>
<td>Thickness, $t$ (in)</td>
<td>0.02</td>
</tr>
<tr>
<td>Max Reflex Position, $d$ (in)</td>
<td>7.312</td>
</tr>
<tr>
<td>Wing Area, $S$ (in$^2$)</td>
<td>60</td>
</tr>
<tr>
<td>Inverse Camber, $h_i$ (in)</td>
<td>0.094</td>
</tr>
</tbody>
</table>

\[ t = 0.25\%; \ h_i / h = 1/3 \]
Zimmermann Wing Testing at UA and SUPAERO

Re = 100,000

CL vs Alfa UA

CD vs Alfa SUPAERO

Cd vs Alfa UA

CL vs Alfa SUPAERO
Effects of Motor-induced Flow on Aerodynamic Coefficients

PWM = 55%, Re = 100,000

Wing
Wing+motor

$C_l$ vs $\alpha$

$C_d$ vs $\alpha$

Wing
Wing+motor

AOA (deg)
Zero-lift Drag due to Prop Wash and Free Stream

![Graph showing the relationship between zero-lift drag and free stream velocity for different PWM settings: 55%, 60%, 65%, and 70%. The graph plots drag coefficient $D_0$ against free stream velocity $V_0$. The data points are marked with different symbols for each PWM setting.](image-url)
Zero-lift Drag due to Prop Wash and Free Stream

Propeller induced velocity at the distance $s$ from the propeller disk

$$w(s) = 0.5 \left[ \sqrt{V_0^2 + \frac{2T}{\rho \pi R^2}} \left( 1 + \frac{s}{R} \sqrt{1 + (s/R)^2} \right) - V_0 \right]$$

Ultimate Velocity

$$w_{ult} = w(s = \infty) = \sqrt{V_0^2 + \frac{2T}{\rho \pi R^2}} - V_0$$

Total Drag

$$D_0 = 0.5 \rho C_{D_0} \left[ S_0 V_0 + w_{ult}^2 + S_0 - S_p \ V_0^2 \right]$$

Zero-lift drag coefficient

$$C_{D_0} = \frac{D_0}{0.5 \rho \left[ S_0 V_0 + w_{ult}^2 + S_0 - S_p \ V_0^2 \right]}$$
Zero-lift Drag Coefficient in the Presence of Prop Wash and Free Stream

\[ C_{D0} = 0.0305 + 0.0024w_{ult} \]
Designing VTOL MAV to Hovering and Vertical Flight

Force balance in vertical direction

\[ T - W - D_0 = 0 \]

Thrust required

\[
T - W + 0.5 \rho \left[ 0.0305 + 0.0024 \left( \sqrt{V_0^2 + \frac{2T}{\rho \pi R^2}} - V_0^2 \right) \right] \left[ S_0 \left( V_0^2 + \frac{2T}{\rho \pi R^2} \right) + S_0 - S_p V_0^2 \right] = 0
\]
# VTOL MAV Design and Flight Testing

MAV specifications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wingspan (cm)</td>
<td>30</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>20</td>
</tr>
<tr>
<td>Wing area (cm²)</td>
<td>488</td>
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<tr>
<td>Elevon area (cm²)</td>
<td>60</td>
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<tr>
<td>Fin area (cm²)</td>
<td>47</td>
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<tr>
<td>Rudder area (cm²)</td>
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<tr>
<td>Weight (g)</td>
<td>185</td>
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<tr>
<td>Endurance (min)</td>
<td>~20</td>
</tr>
<tr>
<td>Speed (m/s)</td>
<td>0-20</td>
</tr>
</tbody>
</table>
Conclusions

1. In the present study, a tilt-body, tail-sitter concept for VTOL MAVs was analyzed and a novel design was proposed based on the contra-rotating propeller-motor electric propulsion system.

2. The maximum torque for the contra-rotating system was about 10 times lower than a torque measured on a single propeller-motor system. The pusher arrangement of the propeller generates 20-23% more thrust force than the tractor for the same inputted power.

3. The fluctuations in slipstream velocities in terms of a standard deviation were determined. They are indicative of non-stationary, pulsating flow behind the propellers. The results also explain the overall decrease of a thrust force for the tractor arrangement in comparison with the pusher one.
Conclusions (cont.)

• The aerodynamics of a wing-propeller combination was studied through wind tunnel measurements. The drag on the wing is generated from two mixing airflows: free stream and propeller slipstream. A simplified model for the flow similar to the one used in the classical propeller momentum theory is introduced in the present study, and a formula for the drag coefficient for the wing in the presence of a free stream and slipstream is derived.

• The drag coefficient increases three times, with induced speed increasing from 0 to 15 m/sec. This result indicates the change of transition mechanism in the boundary layer from a laminar to a turbulent state, which deserves further study.

• The results obtained in the present study were realized in a design of a VTOL MAV prototype that was successfully flight tested.
Derivation of Aerodynamic Coefficients

- Recalculated wing aerodynamics:
  \[ L_{\text{wing}} = L - L_{\text{prop}} \]
  \[ D_{\text{wing}} = D - T_{\text{prop}} \]
  \[ M_{\text{wing-c/4}} = M - M_{\text{prop}} \]

- Wing aerodynamic coefficients:
  \[ C_L = \frac{L_{\text{wing}}}{qS} \]
  \[ C_D = \frac{D_{\text{wing}}}{qS} \]
  \[ C_{M-c/4} = \frac{M_{\text{wing-c/4}}}{qSc} \]

- Propeller effects:
  \[ L_{\text{prop}}, T_{\text{prop}} \]
  \[ M_{\text{prop}} = d T_{\text{dyn}} \]
  \[ d = \sin \gamma \left( \frac{a}{\tan \gamma} + \frac{c}{4} \right) \]