Background Oriented Schlieren (BOS) of a Supersonic Aircraft in Flight

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Introduction

- Schlieren imaging for aerodynamics research was limited to ground test facilities

- Weinstein introduced the first reliable method for flight test in 1994

- Retroreflective Background Oriented Schlieren was demonstrated to work for full-scale aircraft in flight in 2012 (DLR Goettingen)

- NASA’s Commercial Supersonic Technology Program developed the next generation airborne schlieren methods for supersonic flight testing. First AirBOS flight in April, 2011 was successful, but restricted.
The BOS Method

Wind tunnel reference, data image and result of an abort motor tower at M=1.3
The AirBOS Method

Instrument platform altitude

Target plane altitude

Instrument platform

Target plane

Sun angle

Reference  Time 1  Time 2  Time 3
AirBOS Implementation

- Fly in the Supersonic Corridor near Edwards AFB
- Characterize the Mojave Desert flora in the Supersonic Corridor:
  Creosote bushes with scattered Joshua trees
- Bushes average 10 feet (3.1 m) diameter; too few trees to be of concern
- Dark green against light gray soil; red filter enhances contrast
Observer plane

NASA Beechcraft B-200 Super King Air

- Fly at 30,000 ft MSL (Highest practical altitude)
- Low stall speed – 90 knots (75 knots at full-flap)
- Already equipped with high-quality nadir port window
- GPS navigation
Target plane

Air Force T-38, operated by the Test Pilot School at Edwards AFB

Supersonic flight achieved by full acceleration during a shallow dive, leveling for the flyby
Imaging system design

- Calculate the proper lens focal length to optimize speckle size
  - Phantom V641, with 2650 x 1600 pixel and 10 – micron pitch
  - Speckle distribution should be 2-5 pixels
- Spreadsheet calculates pixel resolution and field of view on ground and at target location

<table>
<thead>
<tr>
<th>Lens fl (mm)</th>
<th>Camera</th>
<th>Half Angles</th>
<th>Altitudes</th>
<th>FOV at Target Aircraft</th>
<th>FOV at Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X (Deg)</td>
<td>Y (Deg)</td>
<td>Observer a/c (Ft)</td>
<td>Target a/c (Ft)</td>
</tr>
<tr>
<td>105</td>
<td>640</td>
<td>4.36</td>
<td>3.49</td>
<td>27000</td>
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<tr>
<td>180</td>
<td>2560</td>
<td>4.07</td>
<td>2.54</td>
<td>30000</td>
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<td>28000</td>
</tr>
</tbody>
</table>

Sample of table for two cameras and target aircraft separation distances
AirBOS Implementation

- Survey the Black Mountain SS Flight Corridor at 30,000 ft altitude
  - Photographically survey large area, find consistent flora
  - Test for cross correlation performance
  - Design flight pattern to hit the “sweet spot” where the acceleration can be achieved, but turn around is within the corridor
Determining the Sweet-spot

Evaluate two successive frames from the reconnaissance flight using cross correlation
Determining the Sweet-spot

Assure SNR of 5 or higher in the cross-correlation product using the anticipated window size.
Flight Plan

Ridgecrest

Background “sweet spot”

King Air Track

Target Aircraft Track

Black Mountain SSC perimeter

Ft. Irwin

Cal. City

Mojave

Rosamond

Edwards AFB

Lancaster

Barstow

Palmadale

Tehachapi

Latitude, deg

Longitude, deg
Cameras and Layout

Phantom V641 monochrome, 2560 x 1600 pixels, 10 micron pitch, 180 mm lens
- 8 GB of internal memory, ~ 2 seconds of record time @ 1000 fps
- #25 Red filter, enhance contrast of bushes against the bright soil

Two cameras: redundancy and potential for stereo and multi-stream referencing

Legacy camera for 2011 work: Goodrich SUI SU640-SDWHVis-1.7RT InGaS
- 640 x 512 pixel sensor, 25 micrometer pixel pitch, and fitted with a 105 mm lens
- Used mainly as real-time spotting camera

Schematic of cabin layout

Two cameras, mounted vertically
Data Processing

1. Reference-to-data registration: First-order projective transform
   - Aligns the displaced backgrounds caused moving observer
   - Corrects perspective distortion caused by pitch and roll during acquisition

\[
x = \frac{a_1x' + a_2y' + a_3}{c_1x' + c_2y' + 1}
\]

\[
y = \frac{b_1x' + b_2y' + b_3}{c_1x' + c_2y' + 1}
\]

   - Four points at corner of images are chosen, large-window CC performed
   - Cross correlation between the two images yields \( \Delta x \) and \( \Delta y \) at each location, \( x' \) and \( y' \) are solved to then calculate the eight coefficients

\[
x' = x + \Delta x
\]

\[
y' = y + \Delta y
\]

2. Image cross correlation at defined grid nodes yields \( D_x \) and \( D_y \) due to density gradient shift
AirBOS Results

Sample movie of raw imagery, two frames skipped for brevity
AirBOS Results

T-38 at 45 deg. roll, M=1.05, single frame, cross correlated to reference image
AirBOS Results

Results from 200 sequences aligned and averaged
Optical Flow: A new refinement

Movie of Optical flow-processed sequence, two frames skipped for brevity
AirBOS Results

Cross correlation average vs. Optical flow average
AirBOS Results

T-38 at Mach=1.05, wings-level optical flow with 100 sequences aligned and averaged
Summary

Background Oriented Schlieren has been successfully adapted to full-scale supersonic flight.

The planning and system design permit predictable results.

Image processing has made the data of high quality – better than wind tunnel data.

Technique permits testing of maneuvers, monitoring tip vortex trajectories, and subsonic wakes.
Acknowledgements

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