Characterizing Aircraft Landing and Taxiing Patterns by LiDAR

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Outline

- Introduction
  - Motivation
  - Remote sensing concept
- Laser scanning technologies
  - Sensor selection
  - Initial test results
- LiDAR point cloud processing
  - Methods
    - Data Preprocessing
    - Center of Gravity (COG)
    - Iterative Closest Point (ICP)
    - Volume minimization (VM)
- Tests with taxiing aircraft
  - 4-LiDAR sensor configuration
    - Results and statistical analysis
- Tests with landing aircraft
  - 5-LiDAR sensor configuration
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- Conclusion/Summary
- Backup materials
Project Objective

Using remote sensing technologies, estimate the positions of aircraft relative to runway centerline along the course of aircraft departure and arrival profiles, so as to determine the amount of safety area may be required for specifications such as total pavement width, taxi lane separation, and safety area width to ensure against wingtip conflicts and base landing gear deviations from pavement, for relatively large aircraft on relatively small taxiways and runways.

No cooperation is needed!
Feasibility study:
- Prototype a mobile, easily deployable sensor system
  - Main component: laser scanning technology
  - GPS-based georeferencing and time base
  - Optional optical sensing
- Acquire sample data
- Processing
  - Develop aircraft specific feature extraction algorithm to extract aircraft body shape form laser point cloud
  - Parameterize extracted geometric parameters with accuracy term estimates
  - Estimate velocity and attitude (X, Y, Z) of aircraft
  - Model aircraft trajectory
- Report on results and recommendations
Potential

- Tracking and accurate estimation of navigation parameters of moving aircraft, including:
  
  Wingtip clearance, airfield separation

Source: ACRP Report 51, Risk Assessment Method to Support Modification of Airfield Separation Standards
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Laser Sensor Comparative Tests

- Laser technology is rapidly advancing
- Application specific sensors are introduced (UAS, autonomous driving)
- Performance evaluation needed
  - to optimize sensor selection
  - to provide reference for low-end sensors
- Profilers/scanners considered:

  **Velodyne VLP-16:**
  - 16 channels
  - 100+ m range
  - 300K points/second
  - Dual-return capability
  - 360° x 30° FOV
  - Small size: 100 mm x 65 mm
  - Weight: 600 grams
  - Low power requirements
  - Easy to install
  - No external rotating parts
  - Relatively inexpensive sensor
Initial Tests

- Site location: OSU Don Scott Airport
- The sensors attached to a data acquisition platform (GPSvan)
- Test aircraft: Cessna 172
- Scenarios: aircraft passing diagonally and perpendicularly w.r.t sensors at various velocities (3, 6, 9, 12 knots)
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Data Preprocessing

1. Point cloud filtering: remove non-aircraft body points, such as runways, buildings, light fixtures, etc.
2. Filtering by time: select those time intervals when aircraft was in the field of view of the sensor
Methods: Challenges

- Sparse point cloud
- Difficult to model aircraft body

Sample raw data
Methods under Investigation

1. Center of Gravity (COG)
   - Point cloud center of gravity estimated and tracked

2. ICP-based
   - 2-DoF – 3D ICP (only heading and velocity estimated)

3. Volume minimization (VM) – new approach, specifically developed for the study
   - Bin-based random optimization (entropy minimization)

Motion Models

**Uniform motion**
Trajectory is a straight line

\[
\begin{align*}
  x &= v_x t \\
  y &= v_y t
\end{align*}
\]

**Curvilinear motion**
Trajectory is a 2\textsuperscript{nd} order polynomial

\[
\begin{align*}
  x &= v_x t + \frac{a_x}{2} t^2 \\
  y &= v_y t + \frac{a_x}{2} t^2
\end{align*}
\]

**Free motion**
Trajectory is a higher order polynomial

\[
\begin{align*}
  x(t) &= a_0 + a_1 t + a_2 t^2 + \cdots + a_n t^n, \\
  y(t) &= b_0 + b_1 t + b_2 t^2 + \cdots + b_n t^n
\end{align*}
\]
Method 3: Volume metric

Decimating space into cubes (voxels); optimized to average point cloud density; 0.5x0.5x0.5 m was used

The “goodness” of the reconstruction is measured by the number of cubes occupied by the reconstruction
<table>
<thead>
<tr>
<th>Arrangement</th>
<th>Center of Gravity</th>
<th>Iterative Closest Point</th>
<th>Volume Minimization</th>
<th>Ground Truth</th>
</tr>
</thead>
<tbody>
<tr>
<td>40° FOV</td>
<td>~10 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0° FOV</td>
<td>~10 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0° FOV</td>
<td>~40 m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Statistical Comparison**

- COG may provide good solution but the full aircraft body has to be captured; difficult to achieve
- ICP is able to provide acceptable results only in short ranges and when the motion direction w.r.t sensors is close to \( \sim 45^\circ \); in other cases, it is likely to fail
- VM (volume/entropy minimization) gives the best and most robust solution

<table>
<thead>
<tr>
<th>Distance</th>
<th>Cloud size</th>
<th>Sample size</th>
<th>Method</th>
<th>X [m/s]</th>
<th>Y [m/s]</th>
<th>RMSE 2D [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>~10 m</td>
<td>~10k</td>
<td>7</td>
<td>COG</td>
<td>2.64</td>
<td>0.34</td>
<td>2.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ICP</td>
<td>5.05</td>
<td>0.35</td>
<td>5.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>VM</td>
<td>0.45</td>
<td>0.04</td>
<td>0.72</td>
</tr>
<tr>
<td>~40 m</td>
<td>~2k</td>
<td>6</td>
<td>COG</td>
<td>0.70</td>
<td>0.06</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ICP</td>
<td>6.93</td>
<td>0.68</td>
<td>7.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>VM</td>
<td>0.61</td>
<td>0.06</td>
<td>0.88</td>
</tr>
</tbody>
</table>
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Main Tests
TypicalRawData
Point Clouds

Point clouds acquired by all sensors (rear view)

Point clouds acquired by all sensors (top view)
## Aircraft Variations

<table>
<thead>
<tr>
<th>Info</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft type</td>
<td>Cessna</td>
<td>Learjet</td>
</tr>
<tr>
<td>Operation</td>
<td>Landing</td>
<td>Taxiing</td>
</tr>
<tr>
<td>Number of sensors</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Observation time [s]</td>
<td>7</td>
<td>6.1</td>
</tr>
<tr>
<td>Observed length [m]</td>
<td>~100</td>
<td>~27</td>
</tr>
<tr>
<td>Number of backscattered points</td>
<td>5,970</td>
<td>13,133</td>
</tr>
</tbody>
</table>
Trajectory Estimation
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Tests
Sensor Network Configuration

~40 m

~30 m

~100 m
Obtaining Reference: Surveying

- **Goals:**
  - Precise centerline reference
  - Precise global coordinates
  - Aiding sensor calibration

- **Equipment:**
  - GPS static solution for control points
  - Total Station for mass points
Sensor Configuration

Station 1
(2 horizontal, 1 vertical)

Station 2
(2 horizontal)

GPS Antenna

Sensor

GPS Receiver

Interface Box

Cabling
UTP & Power

Logging laptops, batteries
Using Planar Target for Sensor and Intra-sensor Calibration

Sensor station

Calibration board
Captured by the LiDAR sensors

4 prisms installed at corners
Board corners in global system are measured by Total Station
Data Acquisition

Landing airplane

Sensor station
Estimated Velocities
Results
Centerline Deviation: -0.39 m
\(v_x = \text{NaN} \text{ m/s}\) \(v_y = \text{NaN} \text{ m/s}\) \(v_z = \text{NaN} \text{ m/s}\)
Estimated Altitudes (34 planes)
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LiDAR technology allows tracking taxiing and landing aircraft

- Single LiDAR sensor configuration may not provide acceptable results, depending on the sensor quality (affordability)
- A multi-LiDAR prototype system developed
- The interactive target-based sensor network calibration process provided good accuracy
- During a real four-hour long test, the landing and/or taxiing of 34 aircrafts were recorded and processed
- From the LiDAR point clouds, 2D and 3D trajectories were estimated

~10 cm level accuracy was obtained; depending on sensor-object distance, aircraft and sensor types

The reconstruction of the entire aircraft body has additional advantages to analyze moving aircraft, as reference data can improve the matching process, resulting in better motion parameter estimation
Future Work

- Assess the reliability and accuracy of the system using GPS reference on aircraft (DGPS, cm-level accuracy)

- The optimal sensor network formation and configuration have still open questions

- There is a need to develop a highly automated sensor inter-calibration

- Tests with larger aircraft

- Very little or no effort has been devoted to investigate the use of complementary sensors, such as cameras and radar/UWB

- Point cloud processing has advanced and more sophisticated feature extraction techniques could be exploited for plane type detection

- There have been rapid sensor developments, so the affordability of a sensor configuration for an entire runway is becoming a reality
  - Ford signed an agreement with Velodyne targeting a $500 unit price