Videogrammetric Determination of Aircraft Position and Attitude for Vision-Based Autonomous Landing

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Objectives

• To study videogrammetric methods for vision-based landing based on natural ground features

• To develop algorithms for virtual reality simulation and real flight control system

• To evaluate the accuracy of videogrammetric methods
Generic Vision System for Landing

- Pattern/target Recognition
- Position, attitude and velocity determination

NASA LaRC OV-10:

*Two cameras* at wing tips;
*One camera* at left vertical tail
Natural Features on Ground:

*High contrast, parallel runway edges*
Photogrammetry (I)

Perspective projection transformation

3D Object Space  ➔  2D Image Plane
Photogrammetry (II)

Collinearity Equations

\[
x - x_p + dx = -c \frac{m_{11}(X - X_c) + m_{12}(Y - Y_c) + m_{13}(Z - Z_c)}{m_{31}(X - X_c) + m_{32}(Y - Y_c) + m_{33}(Z - Z_c)}
\]

\[
y - y_p + dy = -c \frac{m_{21}(X - X_c) + m_{22}(Y - Y_c) + m_{23}(Z - Z_c)}{m_{31}(X - X_c) + m_{32}(Y - Y_c) + m_{33}(Z - Z_c)}
\]

Exterior Orientation

Parameters:
\((\omega, \varphi, \kappa, X_c, Y_c, Z_c)\)

Interior Orientation

Parameters:
\((c, x_p, y_p, K_1, K_2, P_1, P_2, S_h / S_v)\)
Photogrammetry (III)

**Camera Orientation**

To determine exterior orientation parameters: \((\omega, \varphi, \kappa, X_c, Y_c, Z_c)\)

**Camera Calibration**

To determine interior orientation parameters: \((c, x_p, y_p, K_1, K_2, P_1, P_2, S_h / S_v)\)

**Analytical Techniques:**

- Direct Linear Transformation (DLT)
- Closed-Form Resection Solution
- Optimization Method
Photogrammetry (IV)

The Point Correspondence Problem

Generalized Longuet-Higgins Relation:

\[
(x^\alpha_{h(2)} + \delta x^\alpha_{h(2)}) Q_{\alpha\beta} (x^\beta_{h(1)} + \delta x^\beta_{h(1)}) = 0
\]
Photogrammetry (V)

3D Target Field for Camera Orientation
Determining Aircraft Position and Attitude

**Two-Camera Method**

**Requirements:**
- Two calibrated cameras
- Two parallel runway edges (Edge detection)
Aircraft Euler Angles and Position Coordinates

Relation between the ground and aircraft coordinate systems

\[ \mathbf{e}_{1g} = \frac{\mathbf{P}_1\mathbf{P}_2}{|\mathbf{P}_1\mathbf{P}_2|} = \sum_{i=1}^{3} r_{1i} \mathbf{e}_{iac} \]

\[ \mathbf{e}_{2g} = \mathbf{e}_{3g} \times \frac{\mathbf{P}_1\mathbf{P}_2}{|\mathbf{e}_{3g} \times \mathbf{P}_1\mathbf{P}_2|} = \sum_{i=1}^{3} r_{2i} \mathbf{e}_{iac} \]

\[ \mathbf{e}_{3g} = \frac{\mathbf{P}_1\mathbf{P}_3 \times \mathbf{P}_1\mathbf{P}_2}{|\mathbf{P}_1\mathbf{P}_3 \times \mathbf{P}_1\mathbf{P}_2|} = \sum_{i=1}^{3} r_{3i} \mathbf{e}_{iac} \]

Roll, Pitch and Yaw Angles:

\[ \tan \phi = \frac{r_{32}}{r_{33}} \]

\[ \sin \theta = -r_{31} \]

\[ \tan \psi = \frac{r_{21}}{r_{11}} \]
Simulation Case #2

Position & Attitude: \((X_{g_{ac}}, Y_{o_{ac}}, Z_{o_{ac}}) = (4477, 40, 118) \text{ feet}\)
\[\phi = -2^\circ, \quad \theta = 5^\circ, \quad \psi = 3^\circ\]

Camera Parameters: \((\omega, \varphi, \kappa, X_c, Y_c, Z_c) = (85^\circ, -88^\circ, 0^\circ, 0, 0, 16 \text{ ft})\)
\[(85^\circ, -88^\circ, 0^\circ, 0, 0, -16 \text{ ft})\]

Left-wing camera

Right-wing camera
Random Noise Effects (Case #2)

**Position Errors**

![Graph showing position errors vs. normalized random noise on edges for Case 2.](image)

**Attitude Errors**

![Graph showing attitude errors vs. normalized random noise on edges for Case 2.](image)

Case 2, Average runway horizontal scale: 101.9 pixels
Wing Deformation Effects (Case #2)

**Position Errors**

**Attitude Errors**
Lens Distortion Effects (Case #2)

**Position Errors**

![Position Errors Graph](image)

**Attitude Errors**

![Attitude Errors Graph](image)
Simulation Case #3

**Position & Attitude:** \((X_{goac}, Y_{goac}, Z_{goac}) = (4014, 20, 50)\) feet
\(\phi = -2^o\) \(\theta = 5^o\) \(\psi = 3^o\)

**Camera Parameters:** \((\omega, \varphi, \kappa, X_c, Y_c, Z_c) = (85^o, -88^o, 0^o, 0, 0, 16\ ft)\)
\((85^o, -88^o, 0^o, 0, 0, -16\ ft)\)
Random Noise Effects (Case #3)

Position Errors

Attitude Errors

Case 3, Average runway horizontal scale: 398.8 pixels
Wing Deformation Effects (Case #3)

**Position Errors**

**Attitude Errors**

[Diagrams showing the effects of wing deformation on position and attitude errors.]
Lens Distortion Effects (Case #3)

**Position Errors**

![Position Errors Graph](image)

**Attitude Errors**

![Attitude Errors Graph](image)
Determining Aircraft Position and Attitude

**Single-Camera Method**

Image coordinate system is aligned with aircraft body coordinate system

**Special collinearity equations:**

\[
- \frac{x}{c} = \frac{Y_{ac}}{X_{ac}} = \frac{r_{12}(X_g - X_{gO_{ac}}) + r_{22}(Y_g - Y_{gO_{ac}}) + r_{32}(Z_g - Z_{gO_{ac}})}{r_{11}(X_g - X_{gO_{ac}}) + r_{21}(Y_g - Y_{gO_{ac}}) + r_{31}(Z_g - Z_{gO_{ac}})}
\]

\[
- \frac{y}{c} = \frac{Z_{ac}}{X_{ac}} = \frac{r_{13}(X_g - X_{gO_{ac}}) + r_{23}(Y_g - Y_{gO_{ac}}) + r_{33}(Z_g - Z_{gO_{ac}})}{r_{11}(X_g - X_{gO_{ac}}) + r_{21}(Y_g - Y_{gO_{ac}}) + r_{31}(Z_g - Z_{gO_{ac}})}
\]
Vanishing Point and Horizon

At the vanishing point,

\[-\bar{x}_{\text{vp}} = \frac{r_{12}}{r_{11}}\]

\[-\bar{y}_{\text{vp}} = \frac{r_{13}}{r_{11}}\]

At the horizon,

\[k_{oh} = -\tan \phi\]
Simulation Cases
(Single-camera method)
Random Noise Effects (Case #2)  
(Single camera method)

**Position Errors**

**Attitude Errors**
Horizontal Line Effects (Case #2) (Single camera method)

**Position Errors**

**Attitude Errors**

![Graph showing position errors and attitude errors](image-url)
Conclusions

Two-Camera Method

• **Requirements:** *Camera Calibration/Orientation, Runway Edges*

• **Estimated Errors:**
  
  *Pitch, Yaw (0.01-0.1 deg) & Roll Angles (0.1-1 deg)*
  
  *Altitude, Lateral (0.1-3 ft) & Longitudinal Coord. (20-40 ft)*

Single-Camera Method

• **Requirements:** *Horizontal line, Runway Edges*

• **Estimated Errors:**
  
  *Pitch, Yaw (0.01-0.1 deg) & Roll Angles (0.03-0.14 deg)*
  
  *Altitude & Lateral Coord. (0.03-5 ft)*
Future Development: Lunar and Planetary Landing

Four-Camera Vision for Landing