Optimized Snapshot-Based Visual Homing for UAVs

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Outline

- Problem
- Theoretical Background
- Approach
- Results

Problem: Visual Homing

- Return to starting location
- Determining possible optimal return flights
- Practical applications
- Increases safety for users

Motivation for Visual Approach

- Issues with GPS: loss of signal, jamming, or spoofing
- Cameras are lightweight and can multitask
- Sparse representation of the environment
- More reliable than maps or GPS

Background

- Biologically inspired systems use visual cues for navigation
- Retracing steps through feature matching
- Potential for path optimization
- Project points from current view to reference images
- Homography control for snapshot-based navigation

Homography

- Relates two images using common features viewed from different angles

$$p_r = \boldsymbol{H} p_c$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

Computing the Homography

- Given four points in current camera view and corresponding points in reference image:

$$\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x_1x'_1 & -y_1x'_1 & -x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -x_1y'_1 & -y_1y'_1 & -y'_1 \\ x_2 & y_2 & 1 & 0 & 0 & 0 & -x_2x'_2 & -y_2x'_2 & -x'_2 \\ 0 & 0 & 0 & x_2 & y_2 & 1 & -x_2y'_2 & -y_2y'_2 & -y'_2 \\ x_3 & y_3 & 1 & 0 & 0 & 0 & -x_3x'_3 & -y_3x'_3 & -x'_3 \\ 0 & 0 & 0 & x_3 & y_3 & 1 & -x_3y'_3 & -y_3y'_3 & -y'_3 \\ x_4 & y_4 & 1 & 0 & 0 & 0 & -x_4x'_4 & -y_4x'_4 & -x'_4 \\ 0 & 0 & 0 & x_4 & y_4 & 1 & -x_4y'_4 & -y_4y'_4 & -y'_4 \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{31} \\ h_{32} \\ h_{33} \end{bmatrix} = \vec{0}$$

Homography Control Law

- Compute direction vector to align UAV with reference image
- Based on center of gravity of feature points

$$\bar{p}_r = \frac{1}{n}\sum_{i=1}^{n} p_{r_i} \qquad \bar{p}_c = \frac{1}{n}\sum_{i=1}^{n} p_{c_i}$$

$$\vec{v} = \frac{\bar{p}_r{}^T \boldsymbol{H} \bar{p}_c}{\bar{p}_r{}^T \bar{p}_c} \bar{p}_r - \bar{p}_c$$

Simulation Framework

- Downward facing “camera”
- Exploratory journey:
  - Random walk
  - Snapshot taken periodically and stored along the way
- Return journey:
  - Periodically compute homography estimation
  - Homography control law directs UAV to snapshot
  - Normalized direction vectors to navigate

Approach to Problem

Visual Homing

- Sparse snapshots represent environment
- Homography control law navigates between snapshots
- Series of local homing problems, visiting waypoints and retracing steps

Visual Path Optimization

- Option for path optimization on return journey
- Brute force feature matching between snapshots
- If snapshots are close together, UAV does not retrace path between them

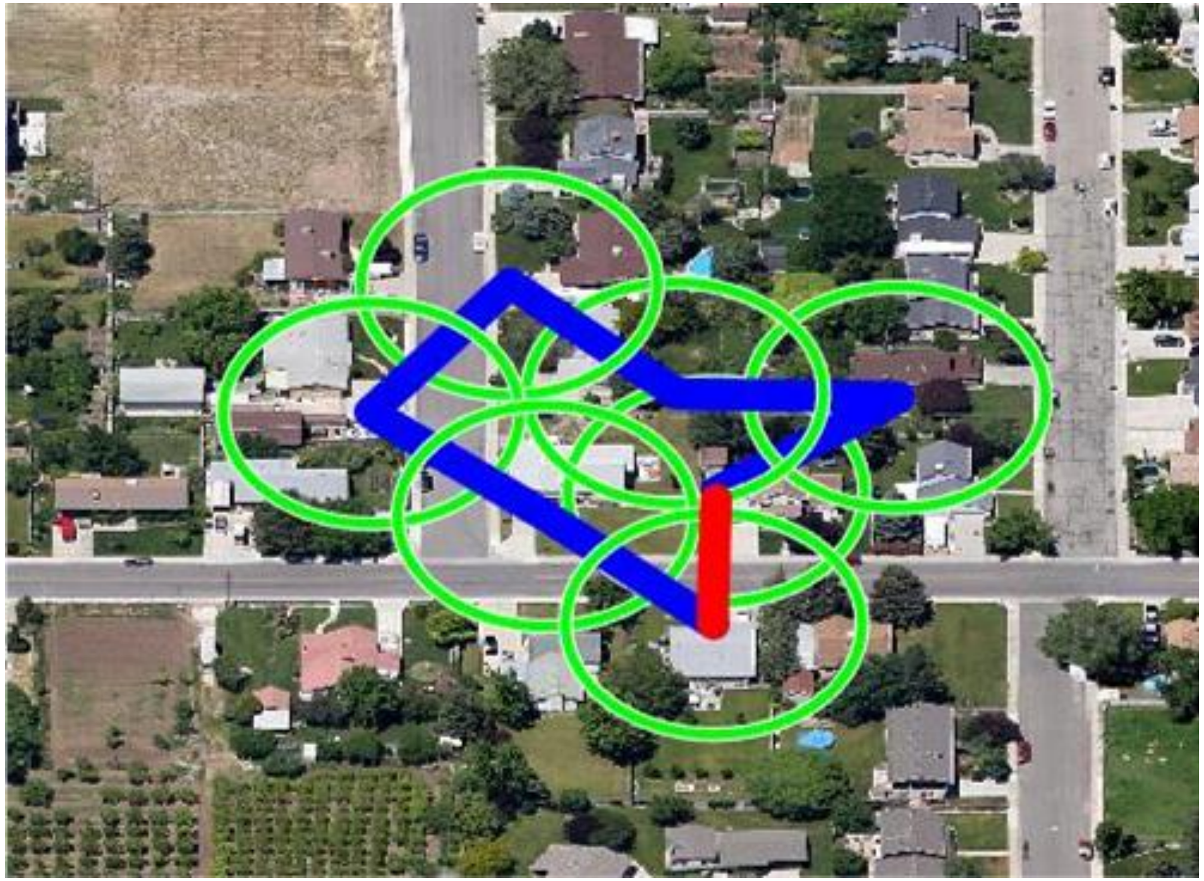
Tools

- MATLAB
  - Simulink
  - Robotics Operating System (ROS)
- Python
- OpenCV

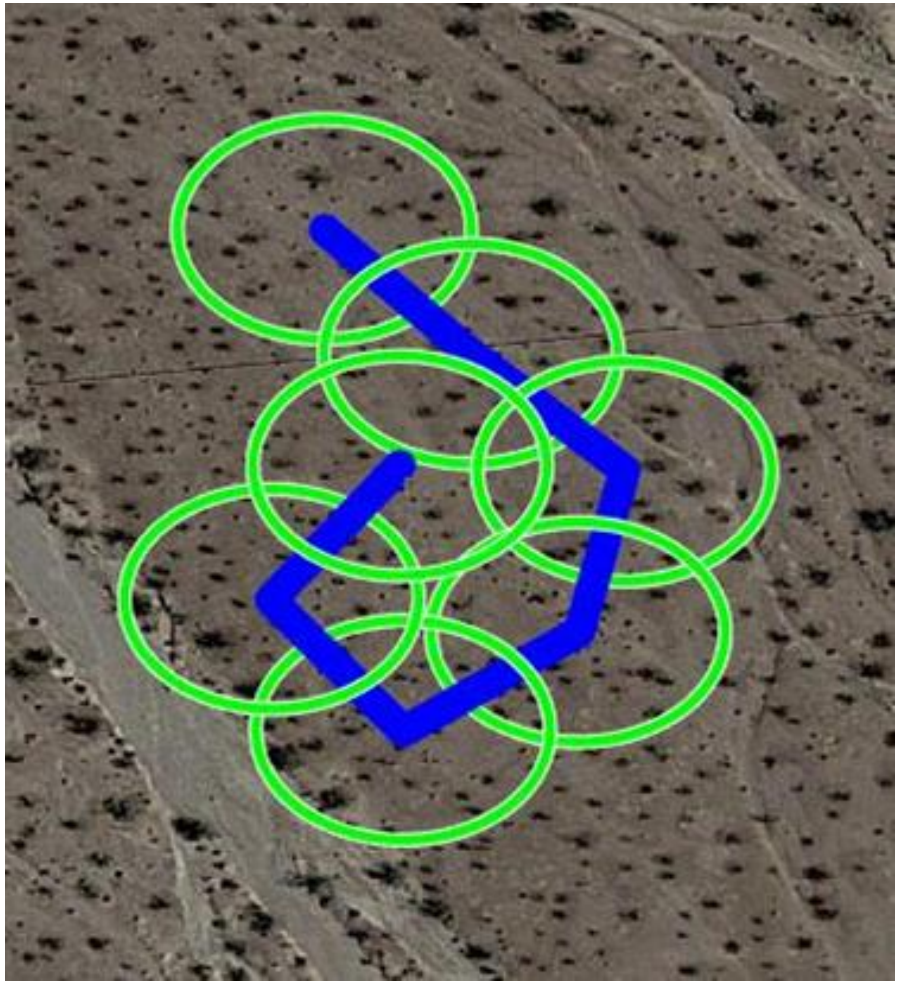
Experiments

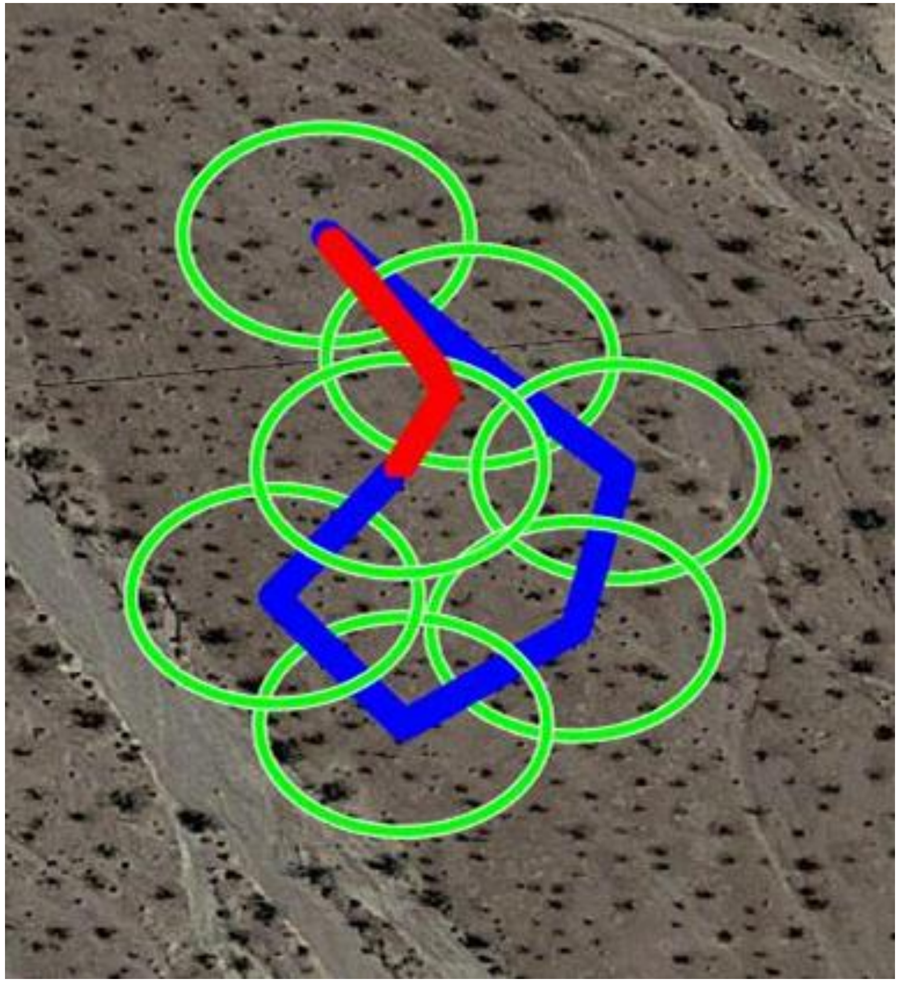
- Visual homing with and without path optimization
- Three environments
  - Suburb
  - Desert
  - Forest
- Tested 15 random paths across 5 different positions on map

Sample Suburb Experiment

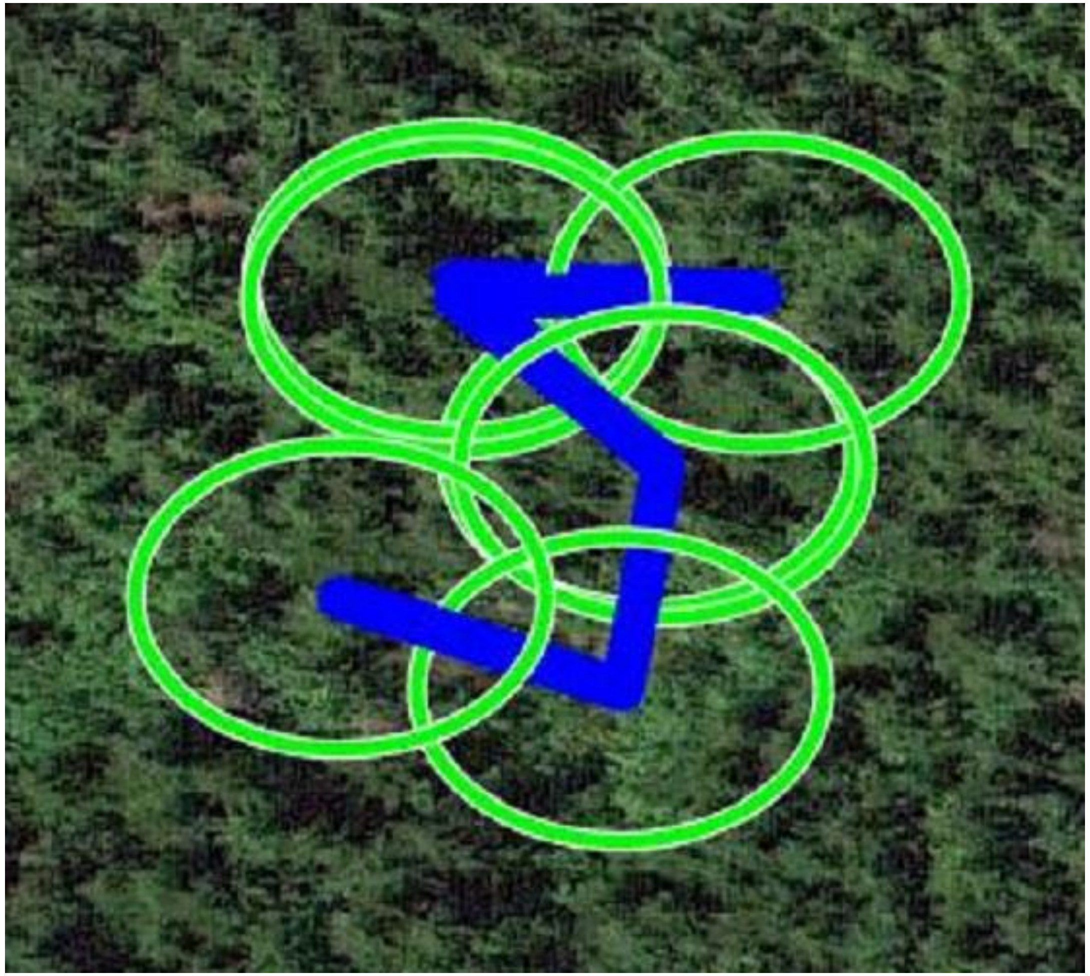


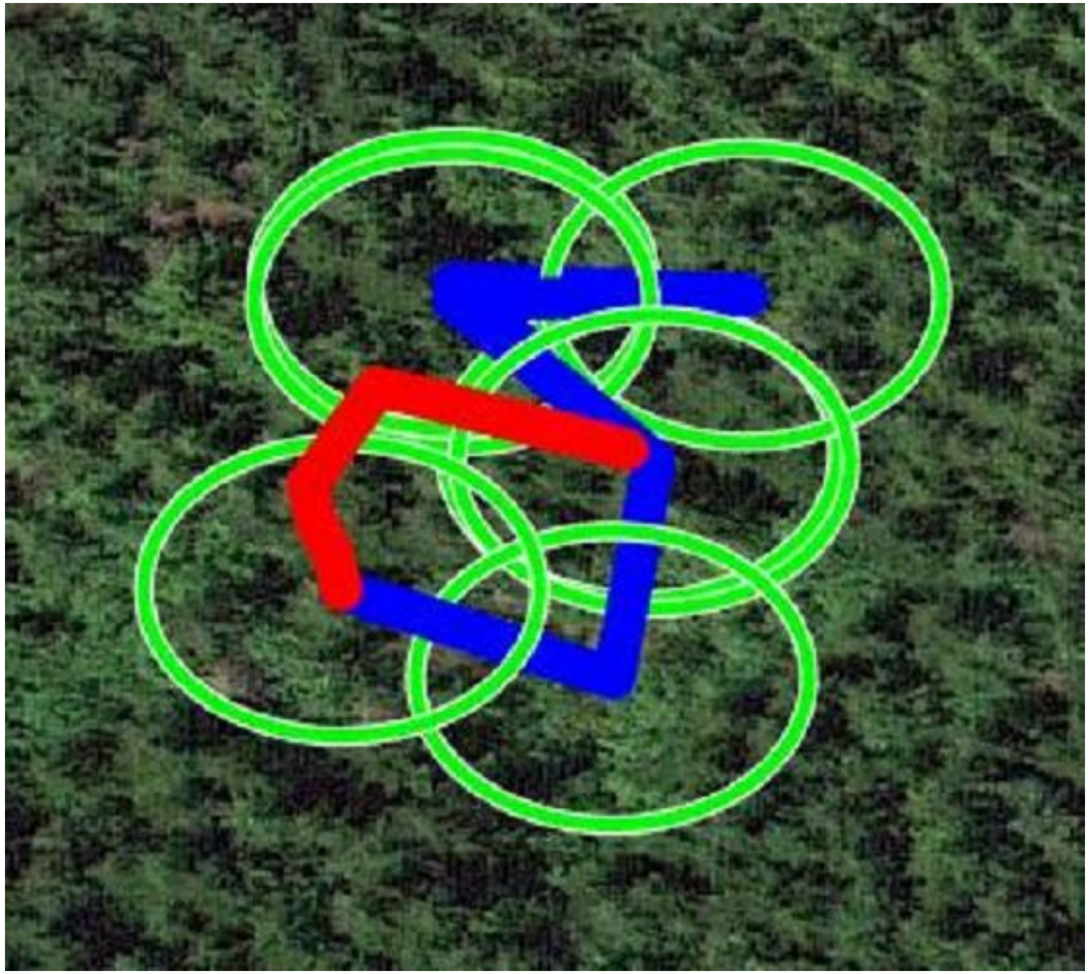
Sample Desert Experiment





Sample Forest Experiment





Results

Test	Successful Homing	Successful Optimized Homing	Average Distance Reduced
Suburb	87%	85%	48%
Desert	100%	67%	54%
Forest	93%	50%	59%
Overall	**93%**	**67%**	**53%**

Summary

- Visual homing motivated by issues with GPS
- Our approach combined ideas from several papers
  - Sparse snapshot representation
  - Homography control law
  - Visual path optimization possible
- Simulations show successful visual homing
- Optimized paths significantly reduced travel distance
- Application of multiple view geometry in computer vision

Select Bibliography

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Deriving Homography Matrix Equation

- We want to find the matrix that relates two matched points in different images:

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$x' = xh_{11} + yh_{12} + h_{13}$$
$$y' = xh_{21} + yh_{22} + h_{23}$$
$$1 = xh_{31} + yh_{32} + h_{33}$$

Deriving Homography Matrix Equation

- We know:

$$x' = xh_{11} + yh_{12} + h_{13}$$
$$1 = xh_{31} + yh_{32} + h_{33}$$

$$x' * 0 = 0$$
$$x' * (1 - 1) = 0$$
$$x' * \left(1 - (xh_{31} + yh_{32} + h_{33})\right) = 0$$
$$x' - xx'h_{31} - yx'h_{32} - x'h_{33} = 0$$
$$xh_{11} + yh_{12} + h_{13} - xx'h_{31} - yx'h_{32} - x'h_{33} = 0$$

Deriving Homography Matrix Equation

- We know:

$$y' = xh_{21} + yh_{22} + h_{23}$$
$$1 = xh_{31} + yh_{32} + h_{33}$$

$$y' * 0 = 0$$
$$y' * (1 - 1) = 0$$
$$y' * \left(1 - (xh_{31} + yh_{32} + h_{33})\right) = 0$$
$$y' - xy'h_{31} - yy'h_{32} - y'h_{33} = 0$$
$$xh_{21} + yh_{22} + h_{23} - xy'h_{31} - yy'h_{32} - y'h_{33} = 0$$

Deriving Homography Matrix Equation

- We have shown:

$$xh_{11} + yh_{12} + h_{13} - xx'h_{31} - yx'h_{32} - x'h_{33} = 0$$
$$xh_{21} + yh_{22} + h_{23} - xy'h_{31} - yy'h_{32} - y'h_{33} = 0$$

- We can rewrite into a matrix equation

$$\begin{bmatrix} x & y & 1 & 0 & 0 & 0 & -xx' & -yx' & -x' \\ 0 & 0 & 0 & x & y & 1 & -xy' & -yy' & -y' \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{31} \\ h_{32} \\ h_{33} \end{bmatrix} = \vec{0}$$

Deriving Homography Matrix Equation

$$\begin{bmatrix} x & y & 1 & 0 & 0 & 0 & -xx' & -yx' & -x' \\ 0 & 0 & 0 & x & y & 1 & -xy' & -yy' & -y' \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{31} \\ h_{32} \\ h_{33} \end{bmatrix} = \vec{0}$$