Characterization and Implementation of a Vision-Based 6-DOF Localization System

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Overview of Presentation

- Introduction and motivation
- Overview of NorthStar system
- IR Beacon Description and Characterization
- Detector Description and Characterization
- Modeling Approach
- Calibration Simulation
- Localization Simulation
- Conclusions
- Future work
Prox-Ops Ground-Test Facility

• Facility features
  - 6 degree-of-freedom (DOF) motion for multiple vehicles
  - Emulate on-orbit dynamics with hardware in the loop
  - Complete relative circumnavigation
  - Precise absolute and relative navigation
  - More than two vehicles
  - Cost effective
  - Portable
Relative Motion Vehicle (RMV)
Evolution Robotics - NorthStar System

- Designed for small indoor robots
- “Centimeter” level accuracy 3-DOF planar position output
- Each spot modulated at unique frequency, allowing Detector to identify up to 20 spots
- Detectors output pose estimate, spot locations in Detector frame, and spot magnitudes
6-DOF Beacon Mode

- IR LED beacons placed around target
- Space NorthStar Detectors around workspace
- Use line-of-sight (LOS) measurements to compute 6-DOF state estimate of target

Similar approach as used with VisNav sensor
NorthStar Detector

• Outputs spot IDs, centroid positions, intensity values at 10Hz
• Approximately 1.4” x 1.6” x 0.4” plus interface board
• 120° FOV
NorthStar Projector

- 4 TSAL7200 LEDs in 1” x 1” square
- LEDs can be turned on/off individually
- 32 selectable modulation frequencies
- Approx 3” x 3” board

- Fresnel lenses focus light in projection mode
- Mounting bracket with adjustable angle
Infrared LEDs

Vishay TSAL7200

- Forward current: 0.1 A
- Power dissipation: 0.21 W
- Half-angle: $\phi=17.5^\circ$
- NorthStar beacons: 4 LEDs
- 35mW total radiant power
- 60mW/sr radiant intensity

OSRAM SFH4231 Golden Dragon

- Forward current: 1 A
- Power dissipation: 2.4 W
- Half-angle: $\phi=60^\circ$
- Our beacons: 1 LED
- 500mW total radiant power
- 200mW/sr radiant intensity
Custom Beacons

- 1 SFH4231 IR LED
- 32 selectable modulation frequencies
- 1.5” x 1.5”

• Enclosure with 120° cone to limit emission
Noise Modeling Overview

1. Determine LOS vector and range from detector to beacon
2. Calculate LED emission intensity based on emission angle $\theta_b$
3. Calculate intensity falloff over distance
4. Calculate detector received intensity based on detector angle $\theta_d$
5. Calculate detector reference noise based on received intensity
6. Scale and rotate noise ellipse based upon centroid location on detector image plane
LED: Intensity vs. Emission Angle

- Intensity is strongly coupled with LED viewing angle
- Gaussian fit works well for the LEDs used based on data from manufacturer datasheets and from testing
Intensity vs. Distance

Measurements confirm that intensity is proportional to the inverse square of distance (as expected for a near point light source)
Detector: Intensity vs. Incidence Angle

- Intensity is strongly coupled with how far off bore-sight the beacon is from the Detector
- Data taken in 5° intervals from -60° to 60°
- Symmetric relationship, 2nd order polynomial fit
Detector Noise vs. Intensity

Noise is inversely proportional to the measured intensity.
Detector Noise in Sensor Plane

Boresight

45° off boresight

• 1000 samples taken at 75 different detector rotation angles in x (0°), y (90°), and 45° directions

• Using the 75,000 samples, data closely matches 2D Gaussian distribution:
  • 1-σ: 39.3% vs 39.4%
  • 2-σ: 86.5% vs 86.5%
  • 3-σ: 98.9% vs 98.9%
Noise Ellipse Axis Scalings

Semi-minor axis scaling:

\[ \cos \left( \frac{\pi}{2} \frac{d}{d_{\text{max}}} \right) \]

Semi-major axis scaling:

\[ 1 + 3.47 \sin \left( \pi \frac{d}{d_{\text{max}}} \right) \]
Noise Ellipse Rotation Angle

Ellipse is stretched with major axis along the line from detector center to centroid
Noise Modeling Review

1. Determine LOS vector and range from detector to beacon
2. Calculate LED emission intensity based on emission angle $\theta_b$
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4. Calculate detector received intensity based on detector angle $\theta_b$
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Implementation Strategy

- Distribute stationary detectors around the outside of the workspace
- Perform calibration to determine detector positions and orientations in an inertial frame
- Place beacons in known locations on robots or other target objects
- Track full 6-DOF position and orientation of target objects in real time
Calibration Method

• Place 4-sided square with beacons on each corner at center of workspace, in view of all Detectors
• Specify the center of the square as (0,0,0) and edges of square as x and y-axes
• Use GLSDC to find 6-DOF state of each Detector relative to calibration cluster
Calibration and Localization Method

- Measurement model based on pinhole camera model
- Gaussian Least-Squares Differential-Correction (GLSDC) used to calibrate detector positions and orientations relative to calibration apparatus
- As is done with VisNav, GLSDC is used to determine position and orientation of robot with known detector positions and locations

\[
J = \frac{1}{2} \sum_i (\hat{b}_i - \tilde{b}_i)^T W (\hat{b}_i - \tilde{b}_i) = \frac{1}{2} \sum_i \Delta b_i^T W \Delta b_i
\]

\[
b_i = \begin{bmatrix}
-x_i \\
-y_i \\
f
\end{bmatrix}
\]

\[
x = \begin{bmatrix}
X \\
\sigma
\end{bmatrix}
\]

\[
\Delta \mathbf{x} = (H^T W H)^{-1} H^T W \Delta \mathbf{b}
\]

\[
H_i = \frac{\partial f}{\partial x_d} = \begin{bmatrix}
\frac{\partial f}{\partial X_d} \\
\frac{\partial f}{\partial \sigma_d}
\end{bmatrix}
\]

\[
H = [H_1^T \quad H_2^T \ldots H_N^T]^T
\]
Calibration Simulation

- Calibration error scales linearly with size of square
- Error inversely proportional to square root of N
Localization Simulation

- Detectors evenly distributed on 13m radius circle for a 10m radius workspace and 2.4m off the floor
- Robot placed at center of workspace with 3 beacons per side
- 1 and 2 Detector error dominated by error along-axis
- Diminishing returns on >3 Detectors, but improved LOS issues for multiple robots
Accuracy with 4 Detectors

~5 cm accuracy (1-σ) achieved throughout majority of workspace
Conclusions

- Characterization of detector noise characteristics provides important information for modeling overall system performance
- NorthStar viable for 6-DOF state measurement in beacon mode using OSRAM high-power LEDs
- Meet requirements of portability and accuracy over large workspace
Future Work

- Distortion modeling and bias calibration
- Impact of modulation frequency interactions on noise characteristics
Questions?

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