Active Online Visual-Inertial Navigation and Sensor Calibration via BSP and Factor Graph Based Incremental Smoothing

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IROS, September 2017
High accuracy requirements in GPS-deprived environments

Relying on “local” sensors - requires calibration!

Camera offline calibration
Inertial sensor offline calibration
Inertial Sensor online calibration (pre-determined maneuvers)
Related Work

• Belief Space Planning (BSP)
  ▪ Performance improvement in SLAM
  ▪ Not considering IMU measurements

• Online Calibration
  [V. Indelman, 2012], [J. Maye, 2016]
  ▪ SLAM considering IMU and extrinsic parameters calibration
  ▪ Calibration is not considered while planning

• Planning Considering active Calibration
  ▪ Extrinsic parameters calibration [W. Achtelik, 2013], [D.J. Webb, 2014], [J. Maye, 2016]
  ▪ IMU calibration assuming GPS availability [K. Hausman, 2016]
Contributions

• Online active calibration of IMU in GPS-deprived environments

• Incorporating the concept of pre-integrated IMU into BSP for longer planning horizons
Robot’s pose
\[ X_k \hat{=} \{ x_0, \ldots, x_k \} \]

IMU calibration params.
\[ C_k \hat{=} \{ c_0, \ldots, c_k \} \]

Observed landmarks
\[ L_k \hat{=} \{ l_0, \ldots, l_n \} \]

Joint State
\[ \Theta_k \hat{=} \{ X_k, C_k, L_k \} \]

Motion Model
Observation Model
Calibration Model

\[ b(\Theta_k) = p(\Theta_k \mid Z_{1:k}, U_{0:k-1}) \]

\[ \propto \text{priors} \prod_{i=1}^{k} p(x_i \mid x_{i-1}, c_{i-1}, z_{i-1}^{\text{IMU}}) p(c_i \mid c_{i-1}) p(z_i \mid \Theta_i^o) \]
Non-Myopic BSP using Factor Graph

- Efficient representation of the future belief, with planning horizon of $l$ steps:

$$b(\Theta_{k+l}) = p(\Theta_{k+l} \mid Z_{0:k+l}, U_{0:k+l-1})$$

$$= \eta b(\Theta_{k+l-1}) p(x_{k+l} \mid x_{k+l-1}, u_{k+l-1}, c_{k+l-1}) p(c_{k+l} \mid c_{k+l-1}) p(z_{k+l} \mid \Theta_{k+l})$$
Pre-Integrated IMU Factors

• Challenge:
  - High rate IMU measurements
  - Factor graph is updated at high rate

• The Solution:
  - Integrate multiple IMU measurements into a single factor
  - Add the factor at the frequency of slower sensors (e.g. camera)
  - Previous work uses this concept within inference only

[T. Lupton, 2012]
[V. Indelman, 2013]
Active Online Calibration

• Cost function - evaluates a single step update

\[ cf(b(\Theta_{k+l}), u_{k+l}) = \|X^*_k - X_{Goal}\|_M + \|z(u_{k+l})\|_{M_u} + \text{tr}(M_\Sigma \Sigma_{k+l} M^T_\Sigma) \]

penalizes reaching the goal
penalizes control actions
penalizes joint state uncertainty

• The overall cost function, over a planning horizon of \( l \) steps:

\[ J_k(b(\Theta_{k+L}), U_{k:k+L-1}) = \sum_{l=0}^{L-1} \mathbb{E}\left(cf_l(b(\Theta_{k+l}), u_{k+l})\right) + \mathbb{E}\left(cf_L(b(\Theta_{k+L})\right) \]

• Optimal control sequence:

\[ U^*_{k:k+L-1} = \arg\min_{U_{k:k+L-1}} J_k(b(\Theta_{k+L}), U_{k:k+L-1}) \]
Results - Scenario

• Aerial robot
  - Inertial Measurements Unit (IMU)
  - Monocular downward-looking camera

• Navigation in a partially unknown, GPS-deprived environment
  - Randomly scattered landmarks
  - Goal in a “dark corridor”

• Discrete action space
  - Shortest path to goal
  - Shortest paths to nearby clusters of landmarks

• MATLAB simulation using GTSAM library

• Assuming heading angle control only
Theorem:
Full observability requires the robot to undergo rotation and acceleration on at least two IMU axes

Heading angle control is not sufficient for full IMU calibration

Alternative:
Using a priori known regions with different levels of uncertainty to calibrate accelerometers

- Case study shows
  - To calibrate the accelerometers, must go through a region with low level of uncertainty
  - Regions with insufficient level of uncertainty would only affect the position

\[\text{[Achtelik13icra]}\]
Results - Comparison

BSP-Calib

BSP

Shortest-Path

\[ cf = \left\| X^*_k - X^{Goal} \right\|_M + \left\| \zeta \left( u_{k+1} \right) \right\|_M + tr \left( M \Sigma \Sigma_{k+1} M^T \Sigma \right) \]

Uncertainty = 10m

Uncertainty = 1e-5m

- Covariance

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Results - Performance Comparison

Position Covariance

"Dark Corridor"

Accel. Calibration Covariance

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Thank You