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

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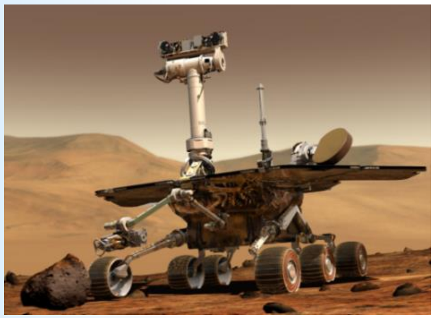
Introduction – Autonomous Navigation

High accuracy requirements in GPS-deprived environments

Space Exploration

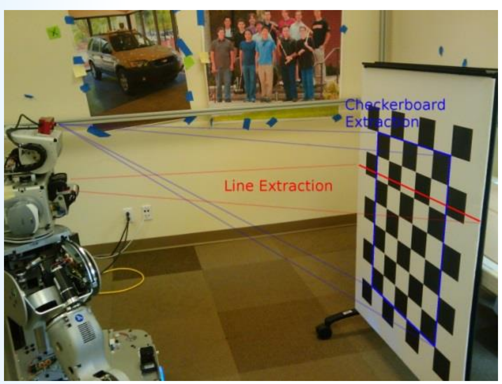


Underwater Exploration

Military

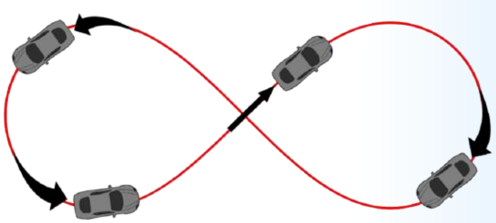
Mine/Tunnel Exploration

Relying on "local" sensors – <u>requires calibration</u>!



Camera offline calibration

Inertial sensor offline calibration



Inertial Sensor online calibration (pre-determined maneuvers)

Related Work

- **Belief Space Planning (BSP)**

  [V. Indelman, 2013], [G. A. Hollinger, 2014], [V. Indelman, 2015]

  - Performance improvement in SLAM
  - Not considering IMU measurements
- **Online Calibration**

  [V. Indelamn, 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

Problem Formulation

Robot's pose

$$X_k \doteq \{x_0, \ldots, x_k\}$$

IMU calibration params.

$$C_k \doteq \{c_0, \ldots, c_k\}$$

Observed landmarks

$$L_k \doteq \{l_0, \ldots, l_n\}$$

Joint State

$$\Theta_k \doteq \{X_k, C_k, L_k\}$$

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

$$\propto priors \cdot \prod_{i=1}^{k} p\left(x_i \mid x_{i-1}, c_{i-1}, z_{i-1}^{IMU}\right) p\left(c_i \mid c_{i-1}\right) p\left(z_i \mid \Theta_i^o\right)$$

Motion Model

Calibration Model

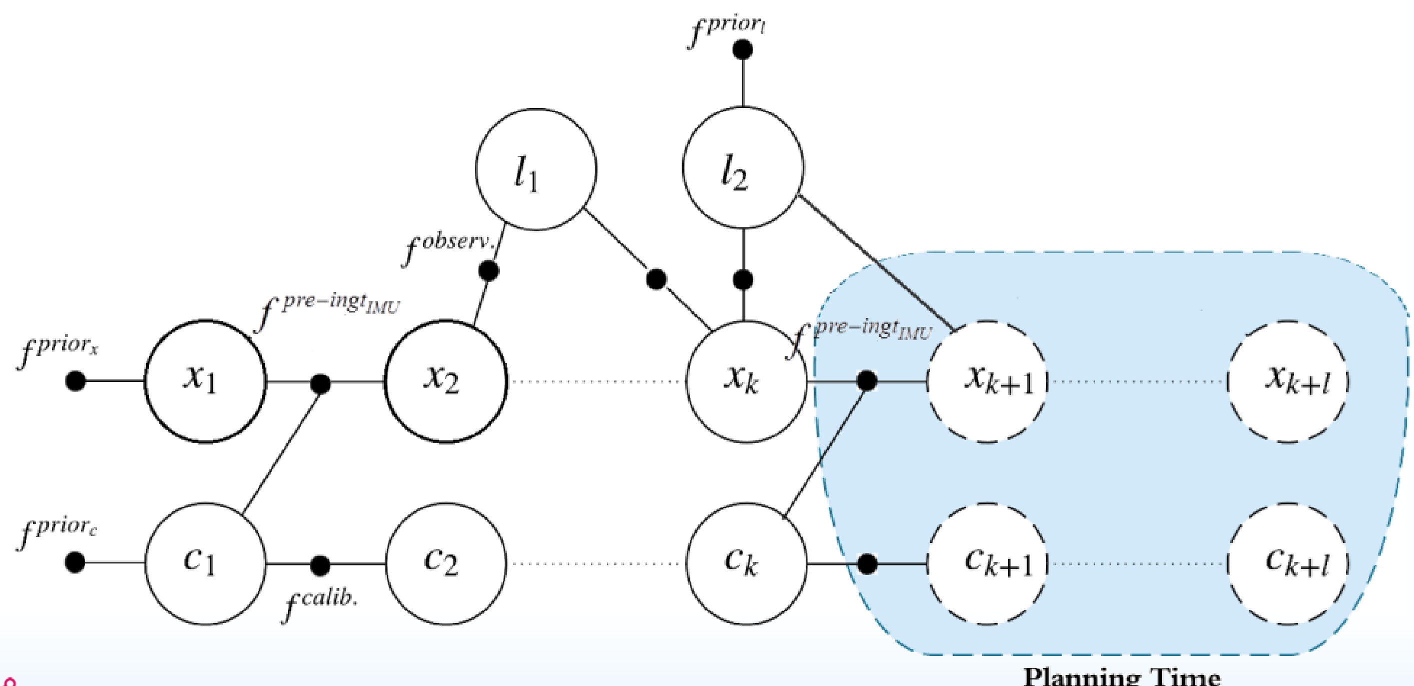
Observation Model

Non-Myopic BSP using Factor Graph

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

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

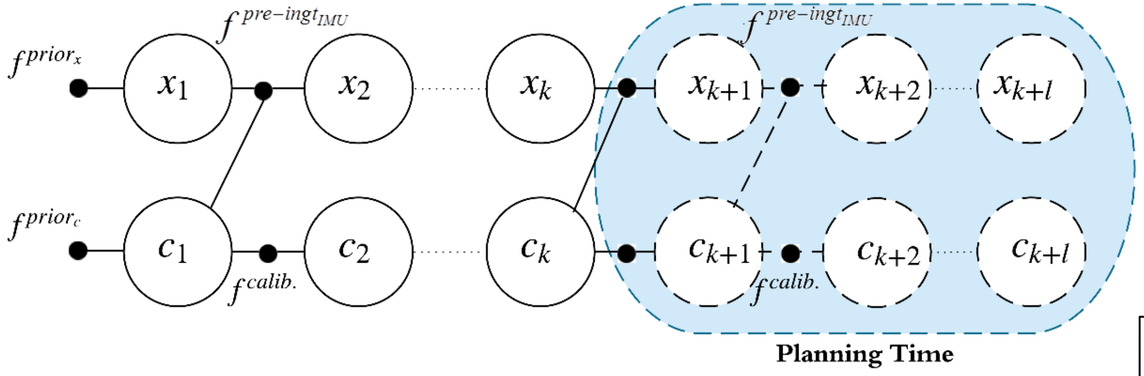
$$= \eta b\left(\Theta_{k+l-1}\right) p\left(x_{k+l} \mid x_{k+l-1}, u_{k+l-1}, c_{k+l-1}\right) p\left(c_{k+l} \mid c_{k+l-1}\right) p\left(z_{k+l} \mid \Theta^{o}_{k+l}\right)$$



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

$$cf\left(b\left(\Theta_{k+l}\right),u_{k+l}\right)=\underbrace{\left\|X^{\star}_{k+l}-X^{Goal}\right\|_{M_\Theta}}_{\text{penalizes reaching the goal}}+\underbrace{\left\|\zeta\left(u_{k+l}\right)\right\|_{M_u}}_{\text{penalizes control actions}}+\underbrace{tr\left(M_\Sigma\Sigma_{k+l}M_\Sigma^T\right)}_{\text{penalizes joint state uncertainty}}$$

- The overall cost function, over a planning horizon of l steps:

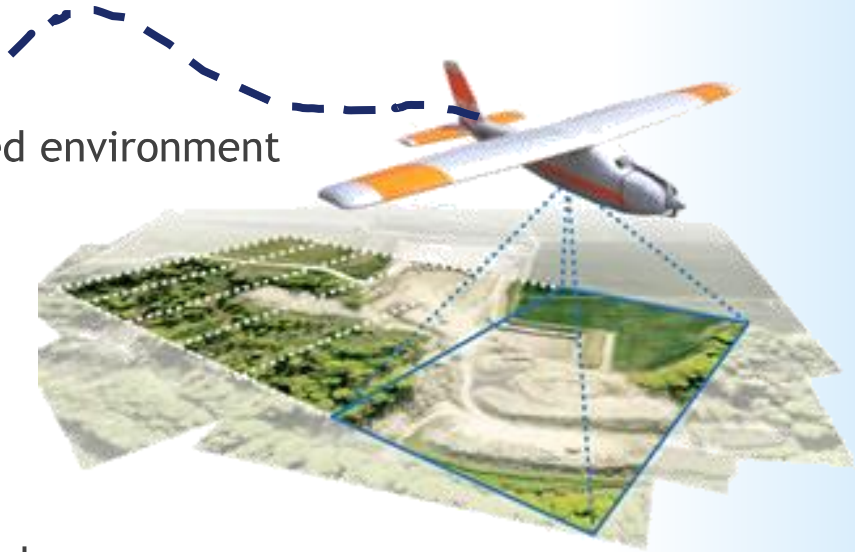
$$J_k\left(b\left(\Theta_{k+L}\right),U_{k:k+L-1}\right)\doteq\sum_{l=0}^{L-1}\mathbb{E}\left(cf_l\left(b\left(\Theta_{k+l}\right),u_{k+l}\right)\right)+\mathbb{E}\left(cf_L\left(b\left(\Theta_{k+L}\right)\right)\right)$$

- Optimal control sequence:

$$U^{\star}_{k:k+L-1}=\underset{U_{k:k+L-1}}{\operatorname{argmin}}\,J_k\left(b\left(\Theta_{k+L}\right),U_{k:k+L-1}\right)$$

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

IMU Calibration Observability

Theorem:

[Achtelik13icra]

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

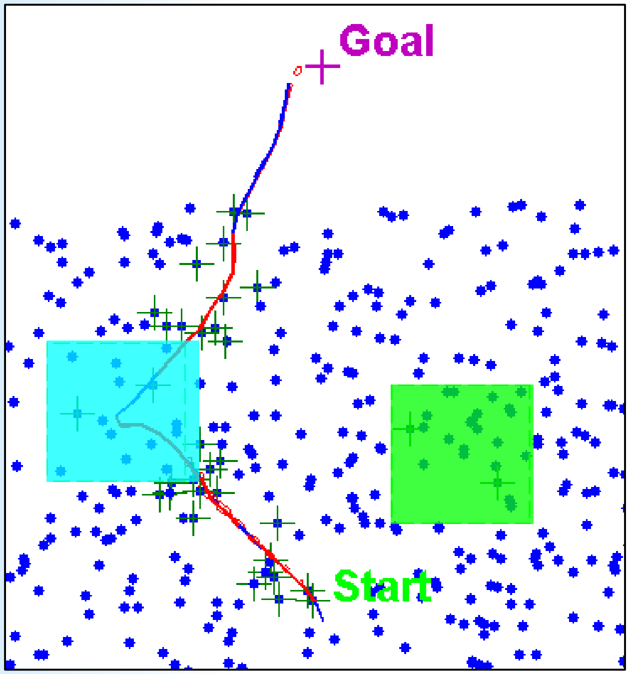
Alternative:

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

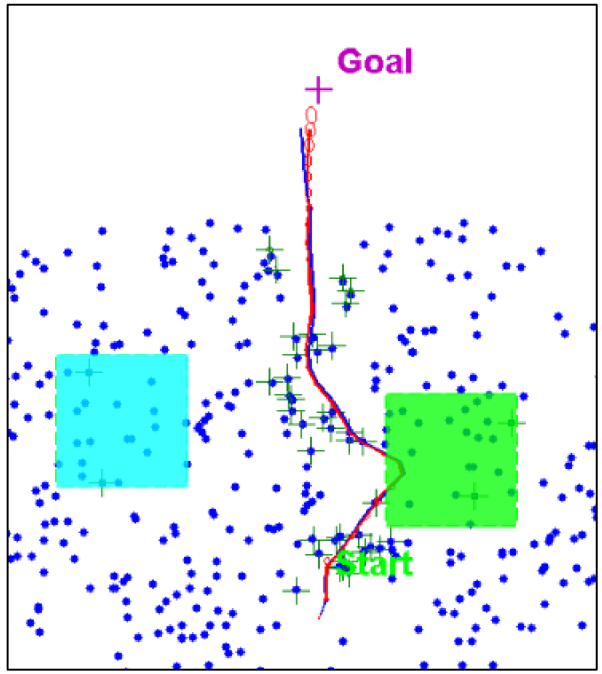
- Case study shows
  - To calibrate the accelerometers, must go through a region with low level of uncertainty
  - Regions with insufficient level of uncertainty would only affect the position

Results - Comparison

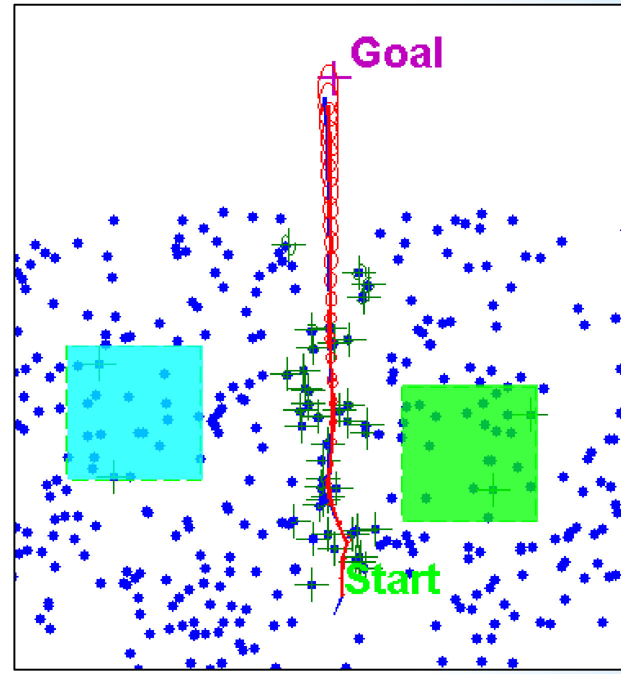
BSP-Calib



BSP



Shortest-Path



$$cf = \left\| X^{\star}_{k+l} - X^{Goal} \right\|_{M_{\Theta}} + \left\| \zeta\left(u_{k+l}\right) \right\|_{M_u} + tr\left(M_{\Sigma} \Sigma_{k+l} M_{\Sigma}^{T} \right)$$

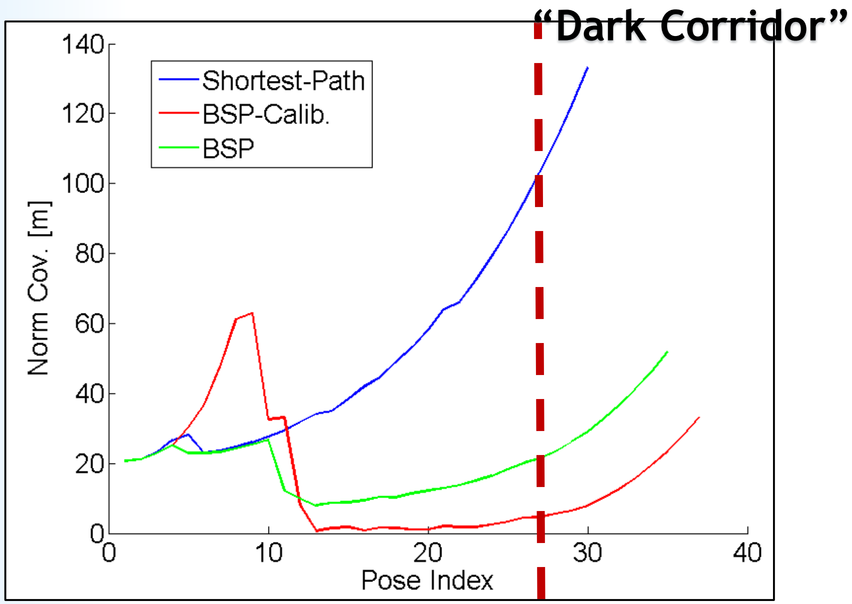
Uncertainty = 10m

Uncertainty = 1e-5m

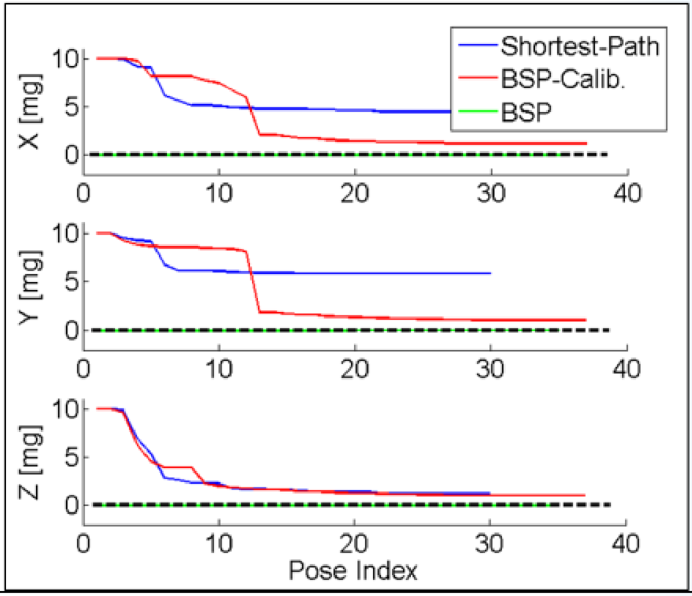
- Covariance

Results - Performance Comparison

Position Covariance



Accel. Calibration Covariance



Thank You

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