EXTRINSIC CAMERA CALIBRATION USING MULITPLE REFLECTIONS

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Abstract

This paper presents a method for determining the six-degree-of-freedom (DOF) transformation between a camera and a base frame of interest, while concurrently estimating the 3D base-frame coordinates of unknown point features in the scene. The camera observes the reflections of fiducial points, whose base-frame coordinates are known, and reconstruction points, whose base-frame coordinates are unknown. In this paper we examine the case in which, due to visibility constraints, none of the points are directly viewed by the camera, but instead are seen via reflection in multiple planar mirrors. Exploiting these measurements, we *analytically* compute the camera-to-base transformation and the 3D base-frame coordinates of the unknown reconstruction points, without *a priori* knowledge of the mirror sizes, motions, or placements with respect to the camera. Subsequently, we refine the analytical solution using a Maximum-Likelihood Estimator (MLE), to obtain high-accuracy estimates of the camera-to-base transformation, the mirror configurations for each image, and the 3D coordinates of the reconstruction points in the base frame. We validate the accuracy and correctness of our method with simulations and real-world experiments.

Motivation

- Extrinsic camera calibration and 3D scene reconstruction are essential for many common tasks (e.g., robot navigation)

Challenge

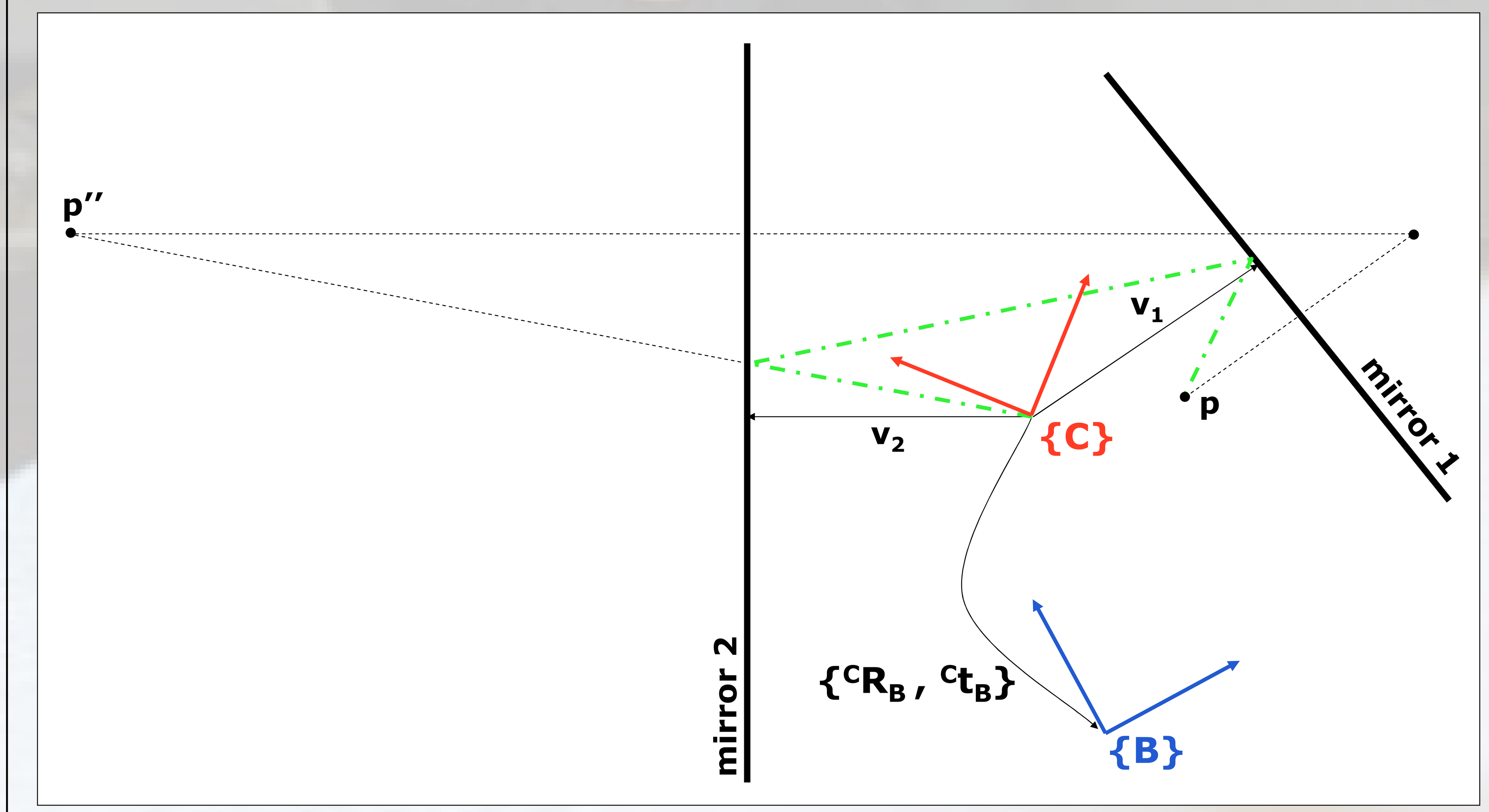
- Scene may only be visible through multiple-mirror reflections

Contributions

- Analytic method for the *N*-mirror problem
- Study of the number of solutions and solvable cases
- MLE to obtain highest accuracy estimates

Algorithm

- **Requirements:**
  - Track point features while moving mirrors w.r.t. camera
  - Mirror *N* must have three configurations for each configuration of mirror *N*-1
  - At least 3 fiducial points visible at all times
  - Each reconstruction point viewed at least twice
- **Analytically** compute initial solution for all parameters:
  - Solve equivalent P3P problem for each image
  - Recursively determine the mirror poses and the camera-to-base transformation
  - Triangulate each reconstruction point in the base frame
- Refine initial analytic solution using **Maximum-Likelihood Estimator**
  - Iterative Levenberg-Marquardt minimization



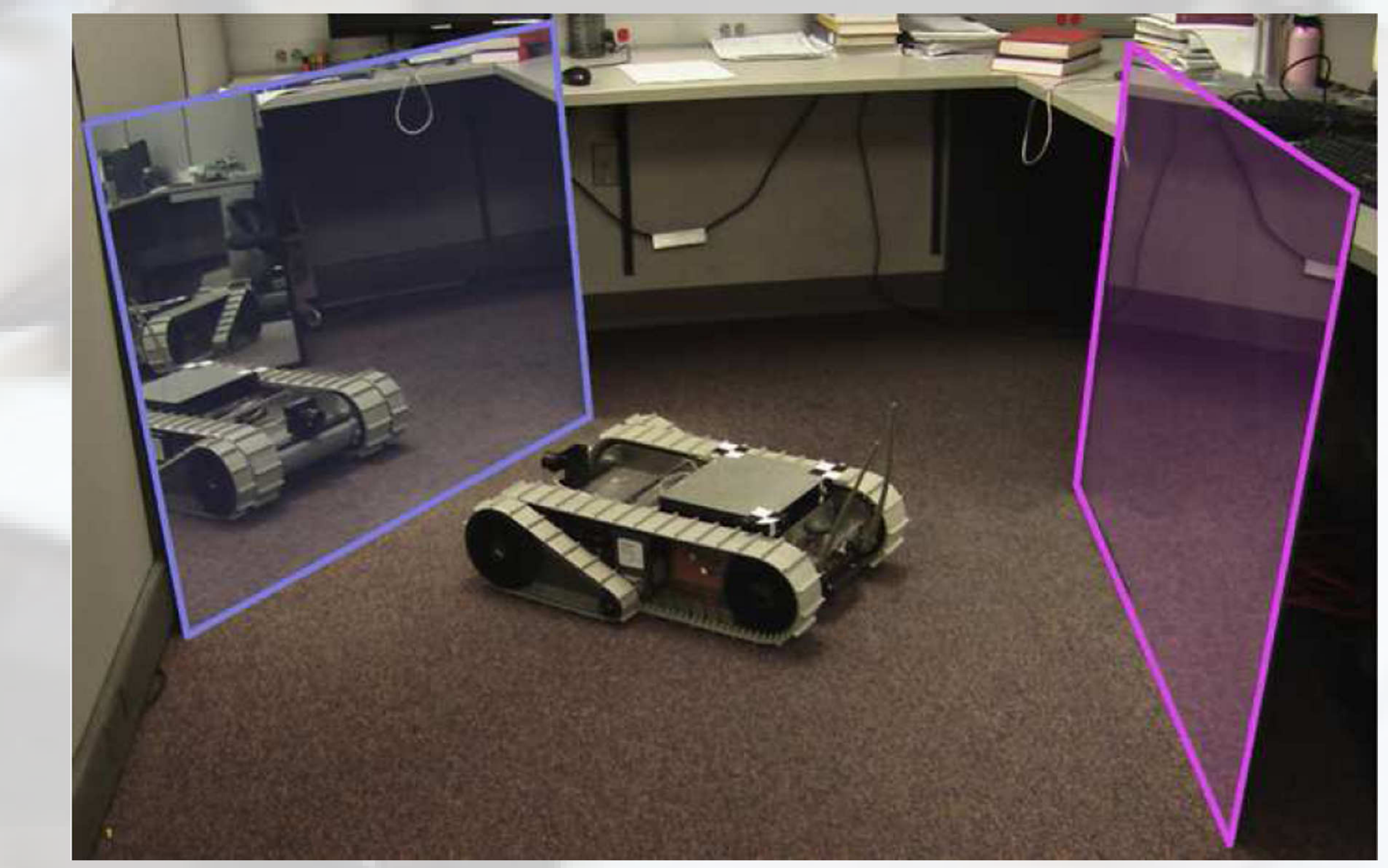
Two-mirror case: A single point, **p**, is observed through two reflections (green dashed line). Unknown parameters are the transformation $\{^C\mathbf{R}_B, {}^C\mathbf{t}_B\}$, between the camera frame **{C}** and the base frame **{B}**, as well as the mirrors vectors $\mathbf{v}_i$, i=1,2, respectively.

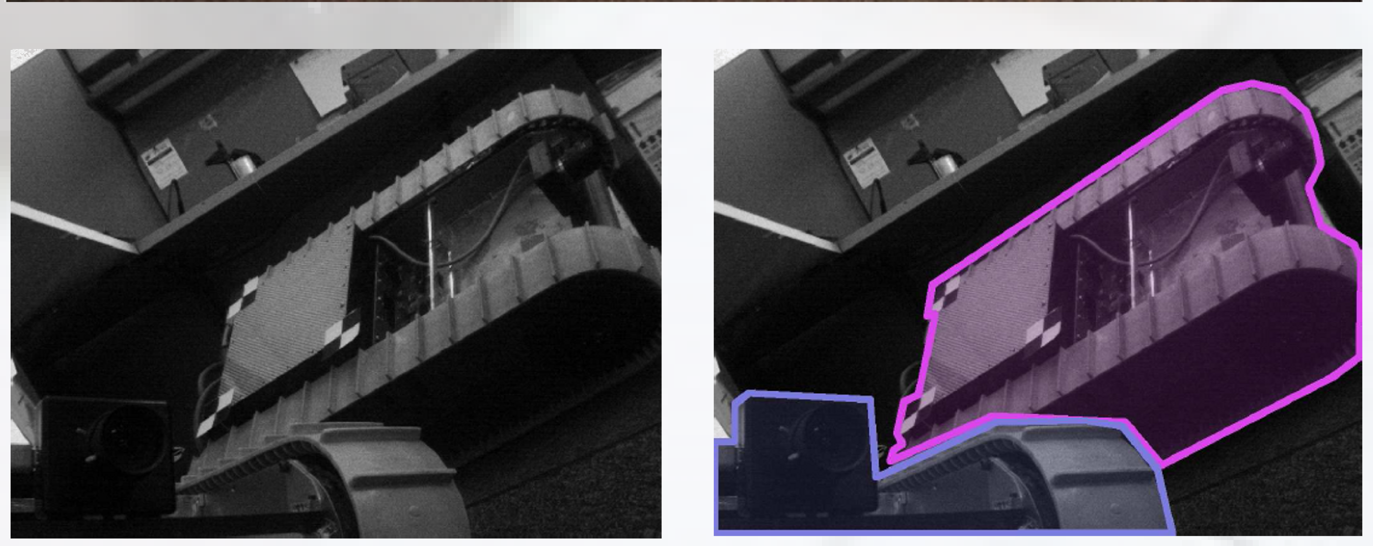
Simulation: Sensitivity analysis

- Analytical & MLE accuracy decrease with:
  - Increased pixel noise / mirror distances
  - Additional mirrors in the system

Experimental Validation

- Calibrate camera to robot-body transformation
- 3 points in 900 images (1024 x 768 px)
- Mirror distances between 30 and 50 cm
- **Results:** estimation error (3 sigma): 9 mm, 0.6 deg per axis





Above: A robot calibrates its camera-to-body transformation using reflections in two mirrors. Below: Image recorded during experimentation (left), and the corresponding annotated image (right).

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