Camera Offset Calibration

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1 Overview

The goal of the camera offset calibration algorithm is to determine the orientation of a mounted camera with respect to the body-fixed frame of the UAV. The outputs of the algorithm are the roll, pitch, and yaw offsets of the camera with respect to the body-fixed frame of the UAV.

In order to record the necessary data, a UAV is placed on an ArUco marker at a known orientation w.r.t. the ArUco marker. Using measurements from the UAV's IMU, the orientation of the ArUco marker with respect to a world inertial frame is calculated. The UAV is then flown over the ArUco marker such that the marker is in the field of view of the camera. For best results, the UAV should orbit around the marker at a relatively low altitude. Each image with the ArUco marker fully in view is referred to as a detection. The UAV flies around the ArUco marker until many detections are recorded (in our data sets, about 250 detections). The roll, pitch, and yaw offsets of the camera are then determined by minimizing the sum of the norm squared error between measured offset and estimated offset.

2 Notation

Throughout the paper, many rotation matricies are defined. The notation, $R_{\text{ArUco}}^{\text{World}}$, is used to refer to the orientation of the ArUco frame with respect to the World frame.

Other parameters referred to are defined as follows:

ϕ_g−roll offset of camera frame in UAV body frame

θ_g−pitch offset of camera frame in UAV body frame

ψ_g−yaw offset of camera frame in UAV body frame

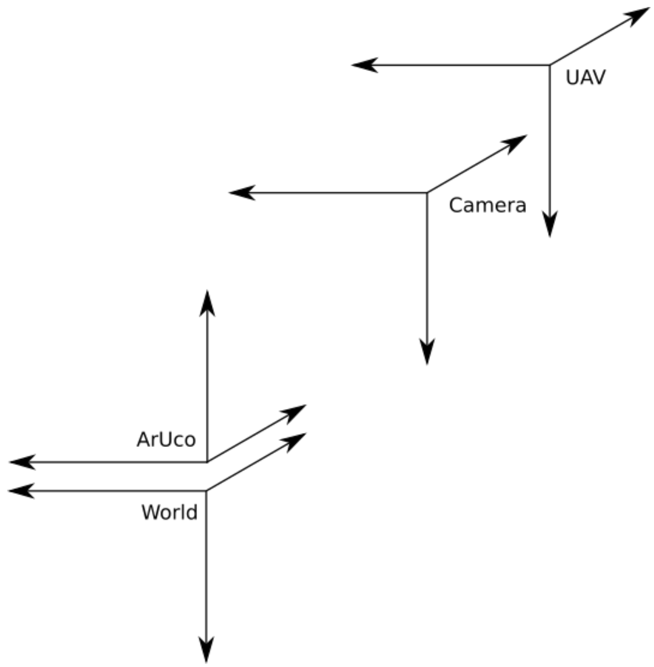

Figure 1: Coordinate frames used in the camera offset calibration.

3 Coordinate Frames

The principal coordinate frames used are depicted in Figure 1.

Since we can not assume that the ArUco marker is placed on level ground, we must measure the orientation of the ArUco marker w.r.t. the inertial world frame. This is done when the UAV is placed on the ArUco marker before takeoff. An average of several IMU measurements is used to compute $R^{\text{World}}_{\text{UAV\_init}}$. Since we assume to know how the UAV is placed on the ArUco maker, we know $R^{\text{UAV\_init}}_{\text{ArUco}}$. These rotations are then multiplied

$$R^{\text{World}}_{\text{ArUco}} = R^{\text{World}}_{\text{UAV\_init}} R^{\text{UAV\_init}}_{\text{ArUco}} \tag{1}$$

and the result is the deisred orientation of the ArUco marker w.r.t. the inertial world frame.

4 Rotation-based Optimization

The rotation-based optimization problem is formulated as

$$\min_{\phi_g,\theta_g} \sum \| R^{\text{UAV}}_{\text{Cam}}(\phi_g, \theta_g, \psi_g) - R^{\text{UAV}}_{\substack{\text{Cam}\\ \text{meas}}} \|^2 \tag{2}$$

where the matrix norm used is defined as the Frobenius norm.

The measured rotation matrix is a result of the ArUco and IMU measurments as well as known rotation matricies:

$$R^{\text{UAV}}_{\underset{\text{meas}}{\text{Cam}}} = R^{\text{UAV}}_{\underset{\text{meas}}{\text{World}}} R^{\text{World}}_{\text{ArUco}} R^{\text{ArUco}}_{\underset{\text{meas}}{\text{Cam\_Ar}}} R^{\text{Cam\_Ar}}_{\text{Cam}}. \tag{3}$$

Here it is important to note that the measurements from the ArUco algorithm yield the rotation of the camera frame in the ArUco frame. However, the camera frame defined by the ArUco algorithm (Cam_Ar) is different than the camera frame we have defined. The last rotation, $R^{\text{Cam\_Ar}}_{\text{Cam}}$, accounts for this difference. In our camera frame, the origin is defined as a NED frame with the camera pointing straight down, along the z-axis, the x-axis up through the top of the camera, and the y-axis out the right.

In the above equation, $R^{\text{UAV}}_{\text{World}}$ and $R^{\text{ArUco}}_{\text{Cam\_Ar}}$ are the results of measurements at each detection of the ArUco marker. The rotation matrix, $R^{\text{Cam\_Ar}}_{\text{Cam}}$, is constant and accounts for the difference in definition between the NED camera frame and ArUco's camera frame. The rotation matrix $R^{\text{World}}_{\text{ArUco}}$ is not assumed to be known, but is calculated from measurements before takeoff as shown in Equation 1.

5 Flight Path Anaylsis

As shown above, the rotation-based optimization is only dependent on two measurements $R^{\text{UAV}}_{\text{World}}$ and $R^{\text{ArUco}}_{\text{Cam\_Ar}}$ which result from the IMU and the ArUco detections respectively. In order to minimize the error in the optimization results, we must simply minimize the error in these measurements. An analysis of the noise for these two measurments provides some insight on the optimal flight path for the camera calibration routine.

IMU Measurements

UAV orientation measurements are most accurate when movement is minimized. Accelerations on the IMU that are not gravity can cause significant errors in estimated attitude.

ArUco Measurements

For Planck, the noise on the Planck tag measurements depends wholly on the Planck tag detection algorithm, however I believe a few general principles apply.%

- Accuracy of measurements decreases with increase of altitude of the camera

- Accuracy of measurements decreases with extreme closeness due to imperfectly calibrated camera intrinsic parameters (edge pixels more sensitive to these imperfections)

- Lighting can cause a bias at any one viewpoint of the tag. A variety of viewpoints is desired to minimize the effects of biases.

Optimal Flight Path

Following the logic of the above analysis, I believe the optimal flight path for the camera calibration routine to be a slow, low altitude orbit around the ArUco marker. Such a flight path would incur only small accelerations (to minimize noise in IMU measurements) and address lighting/bias concerns from Planck tag measurements.