

Autonomous Quadrotor Landing on a Moving Platform

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2 Introduction

Over the years there has been at least some interest in the problem of landing a quadrotor on a moving platform and there have been at least 5 academic publications on the topic [1, 2, 3, 4, 5, 6]. The problem has been explored from a fairly wide range of approaches.

Possible applications for this work include autonomous landing on a boat in high wind conditions, landing on a charging platform and more.

The major challenge with autonomous precision landing is the difficulty of obtaining a reliable estimate of the landing target relative to the quadrotor, the landing target can often go out of the camera's field of view causing the quadrotor to lose track of the target, other vision based artifacts that include lighting, lens distortion, color, etc.

The autonomous landing problem can be thought of as a set of three separate control problems or

stages. First the quadrotor must detect the relative position and velocity of the landing target using either GPS or visual methods. Next the quadrotor must determine a rendezvous location with the landing target and plan the required flight trajectory. Once the quad has rendezvoused a final landing trajectory must be calculated between quadrotor and the landing pad.

In this project we focus developing a set of controllers that produce the final landing trajectory and using a fiducial marker called an AprilTag *CITE APRILTAGS* to provide the estimated state of the quadrotor relative to the landing pad.

3 Related Work

(Needs love but might also just be cut.)

For perception existing solutions use a variety of simple to complex techniques. In [2] a basic color threshold technique was to identify the landing target, while [6] used optical flow in images captured on board the quadrotor to obtain necessary relative information for control.

A comparison between a PID and Linear Quadratic Control (LQC) was explored in [4]. However the authors admit, even though LQC performed slightly better than the PID controller the difference was minor and may be attributed to the additional time spent tuning the LQC. In [6] a PID controller was developed to land on an oscillating platform in the vertical direction with no lateral movement. While interesting, the solution took over 1 minute to transition from hovering over the landing pad to landing. Additionally the experiments did not seem to account for pitch or roll of the platform.

4 Methodology

The majority of effort in this project so far can be separated into two individual but complementary pieces. First, a significant effort was spent on ensuring the quadrotor's state was updated at a rate of at least 20 Hz. Next, using the information

in the state a set of PID controllers were developed that along with a state machine monitors the current relative position of the quadrotor and either initiates a landing procedure or attempts to minimize the relative displacement and velocity between the quadrotor and the landing pad in the horizontal plane.

4.1 Measurement and State Estimation using AprilTags

One of the major challenges when using AprilTags on a robot that has limited computational power, such as a quadrotor, is the rate at which the AprilTag library can compute the state. This problem is exacerbated when using larger image sizes as the computational time of the AprilTag software appears to grow at least exponentially as shown in (add a figure here). This problem was also noted in the work of [5] and he addressed the issue by reducing the brightness of the image so that majority of the image is black except for the AprilTag. An example of this implementation is shown in figure (Kevins image). This allowed Ling [1] to calculate states at a rate of approximately 10 - 15 fps but it came at the cost of requiring the brightness parameters to be set ahead of time and also removed a lot of the robustification that is provided in the standard AprilTag library.

In this work, the slow rate of state estimation was addressed using a novel method where the image size and calibration parameters are set depending on the current distance between the quadrotors position relative to the landing pad.

4.1.1 Adaptive Image Preprocessing

As discussed previously, the low rate of the AprilTag library when processing images of 640 by 480 pixels results in an update rate of approximately 3 to 5 fps on a Snapdragon 8 core processor, which is too low to be used effectively in a PID control loop. Building on the work of Ling, who noted that higher update rates were possible using AprilTags when the majority of the image is filled with black pixels, a set of image preprocessing methods were developed to maximize the update rate of the AprilTag library.

4.1.2 Adaptive Image Windowing

If one assumes that the quadrotor does not move too fast, there is relatively low rotation between image captures, and that the image update rate is quite fast (60 fps in this implementation), then the lo-

cation the AprilTag in the following image can be estimated based off of the location it was last observed in the previous image. Therefore whenever an AprilTag is measured in an image, a bounding box around the AprilTag is calculated and then used in the following image to black out the portions of the image where the AprilTag is unlikely to be. An example of this implementation is highlighted in Figure (Adaptive windowing).

While the adaptive windowing procedure works well for when the AprilTag is observed at a distance, where they do not take up a significant portion of the image, it begins to fail when the quadrotor approaches the landing pad as the observed size of AprilTag begins to become larger and larger in the image. This leads to the processing time of the AprilTags to increase as the quadrotor gets closer, which is a major issue as in these cases a higher update rate is actually required. In cases where the AprilTag is not observed in the expected location (bounding box), the size of the bounding box is set to the size of the image and the entire image is processed.

4.1.3 AprilTag Inception

In order to be used for landing, the AprilTag attached to the landing pad must be relatively larger so that it can be detected from a distance of at least 15 meters which from our experience means the AprilTag must be at least 50 cm by 50 cm in size. The large size of the AprilTag becomes a major issue during the final portion of the landing procedure as the AprilTag image will both appear quite large in the captured image which causes the Adaptive Windowing Procedure outlined above to become ineffective. Furthermore close proximity to the AprilTag also greatly increases the chance that a portion of the AprilTag will be located outside of the captured image, causing no state estimation to be provided at the critical stages of landing.

To address both the decreasing state update rate as a function of proximity and reduce the probability of losing sight of the AprilTag during landing a secondary AprilTag is embedded in the larger AprilTag. This secondary AprilTag is assigned a different family id, and is placed in the center of a primary AprilTag. Whenever the secondary AprilTag is captured in the image, the adaptive windowing method is set to track only the secondary AprilTag rather than the larger one, which reduces the portion of the image that must be processed in with each im-

age capture. An example of this procedure is highlighted in Figure 1.

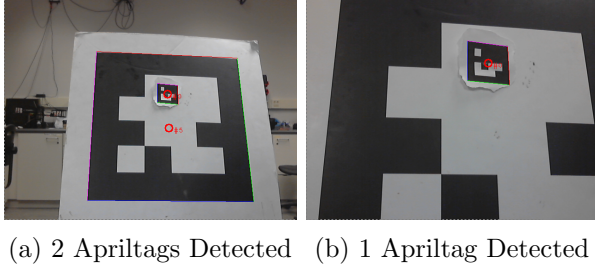


Figure 1: Apriltag Inception - To mitigate the FOV problem associated with

4.1.4 Adaptive Image Down-sampling

It was also noted that the image could be greatly down sampled as well if the quadrotor approaches the landing pad as not as many pixels are required to calculate the location and state of the AprilTag in the image. Therefore 3 image sampling sizes were also introduced into the code which sub-sample the image to 160 by 140 pixels and 320 by 280 (half and quarter resolution) when the distance between the camera and the AprilTag is less than 1.5 and 3 meters respectively. If the camera is further than 3 meters from the AprilTag the native resolution of 640 by 480 is used. This change only affected the image processing time when the quadrotor is within 3 meters of the quad and has the desired effect of increasing the rate of AprilTag process.

In order to use this down sampling effectively without corrupting the AprilTag estimations, 3 camera calibration files were also computed at the normal, half and quarter camera resolutions. The calibration file passed to the AprilTag library during the state estimation procedure is selected based on what the current camera resolution is set at.

4.2 Controller and State Monitoring

5 Experimental Hardware

The quadrotor used in this experiment assembled from a DJI F450 quadrotor frame, 4 Emax 2213-935KV motors with complementary DJI E310 420S 20A electronic speed controllers. The flight controller selected for the project was a Pixhawk v2.4 running the PX4 firmware stack. An Odroid XU4 was selected as the onboard computer to process captured images from a video stream and sends attitude commands via usb to the Pixhawk based on the PID controllers and current state as outlined

above. Communication between the Odroid and the Pixhawk is handled by the mavros package which is a wrapper around the popular Mavlink communication protocol for UAVs. Video was captured using a PointGrey Firefly 2.0 camera operating 60 frames per second (fps) with a resolution of 640 by 480 pixels along with a FujiFilm 135 degree FOV lens. The quadrotor and camera are highlighted in Figure 2



Figure 2: DJI F450 with Pixhawk v1.5

6 Results

- Results of the image stuff
 - Plot of FPS vs distance
 - Plot of true state vs mocap state?
- PID/Control results
 - Plot XY for the controller loop
 - Optimal PID settings
 - How we got there
 - Decent plot (V as a function of Z)
 - Decent planner
 - Video?

6.0.1 Detection Delay

$$t_{\text{capture}} = t - \delta t_{\text{camera}} + \delta t_{\text{detection}} \quad (1)$$

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