ASI-CAIF Fellowship 2020 Report

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This report summarizes the work done during the months of November and December of 2021 spent at NYU's Agile Robotics and Perception Laboratory (ARPL). The Lab is lead by Prof. Giuseppe Loianno and most of the research is performed on quadrotor platforms. In particular, the effort consisted in modifying a quadrotor's low level attitude controller from a PID (Proportional, Integral and Derivative) controller to a geometric controller.

Review

The experimental platform is shown of Fig. 1, it weighs 850 grams, uses four propellers to provide thrust and its mounted on a 3D printed structure.

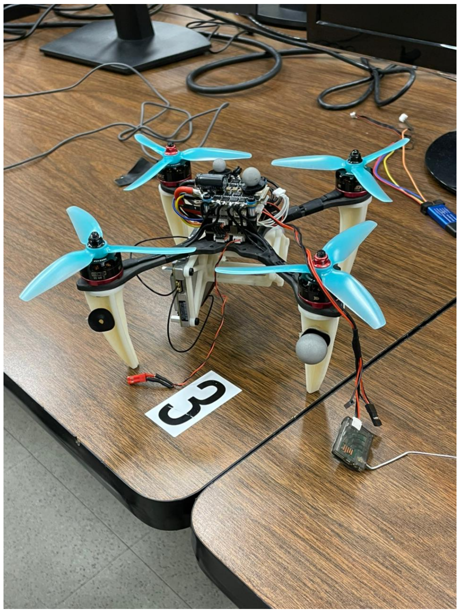

Figure 1: Quadrotor used for experiments.

The drone carries the Pixhawk XRacer board with the Open Source PX4 autopilot. The board carries two Inertial Measurement Units, two magnetometers and a barometer. The outputs of these sensors are fused with an Extended Kalman Filter to estimate the vehicle's states. For the low level attitude controller, we focus on the filtered Quaternion that defines the rotation from NED local earth frame to X, Y, Z body frame [5]. Furthermore the controller requires current measurements of angular velocity, these are obtained with the Gyroscopes integrated in the IMU's. The Gyroscope measurements provide a noisy measurement of the angular velocity [3]:

$$\boldsymbol{\Omega}_m = \boldsymbol{\Omega} + \mathbf{b}_g + \mathbf{n}_g, \tag{1}$$

where $\boldsymbol{\Omega}_m$ is the measured angular velocity, $\boldsymbol{\Omega}$ is the vehicles angular velocity, $\mathbf{b}_g$ is the tri-axial Gyro bias and $\mathbf{n}_g$ is Gaussian white noise. The bias is estimated with the implemented Extended Kalman Filter, to estimate the vehicles angular velocity the bias is subtracted from the measurement and both a notch and low pass filter are used.

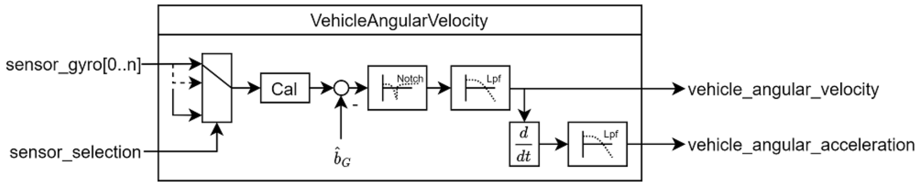

Figure 2: Angular velocity estimation in PX4, courtesy of [1]

The attitude controller implemented in the PX4 autopilot uses a cascaded architecture, the first block uses the current orientation and the desired orientation to obtain an error quaternion. In turn, this error quaternion is used to obtain angular rates set points in the body frame as described in [2]. Summarizing, the set point angular velocity can be found as:

$$\boldsymbol{\Omega}_{sp} = \frac{2}{\tau}\operatorname{sgn}(q_{e,0})\boldsymbol{q}_{e,1:3}, \tag{2}$$

where $\boldsymbol{q}_e = \boldsymbol{q}^{-1}\boldsymbol{q}_{sp}$ is the error measure, representing the rotation from $\boldsymbol{q}$ to $\boldsymbol{q}_{sp}$. Practically the control law is implemented as shown in Fig. 3.

The input desired orientation comes either from the position controller or from the Radio Controller. The complete architecture of the controller is shown in Fig. 4.

In the implemented architecture the calculated $\boldsymbol{\Omega}_{sp}$ is used along with the current angular velocity $\boldsymbol{\Omega}$ in a PID loop to obtain normalized control torques, shown in Fig 5.

The implemented low level geometric controller is that described by Lee et. al. on [4], where the body torques are obtained as:

$$\boldsymbol{M} = -\boldsymbol{k}_R\boldsymbol{e}_R - \boldsymbol{k}_\Omega\boldsymbol{e}_\Omega + \Omega \times J\Omega, \tag{3}$$

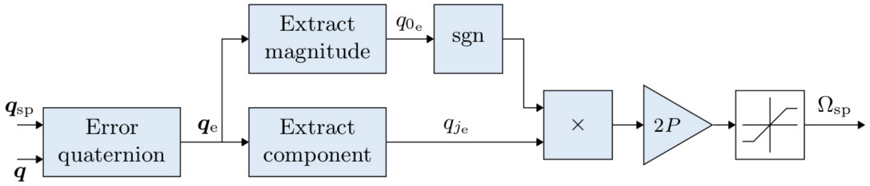

Figure 3: Block diagram for the desired angular rates as implemented in the PX4 autopilot, courtesy of [1]

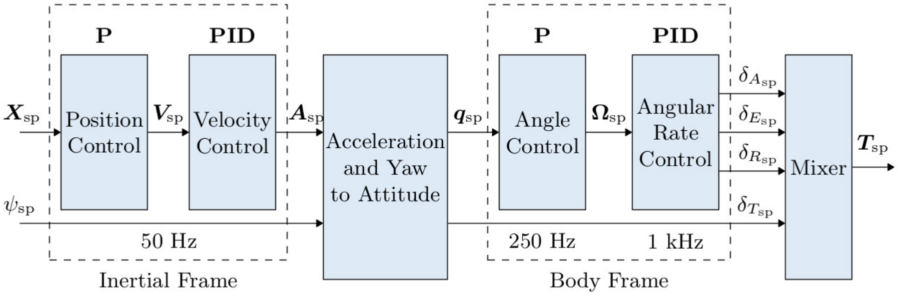

Figure 4: Control architecture, courtesy of [1]

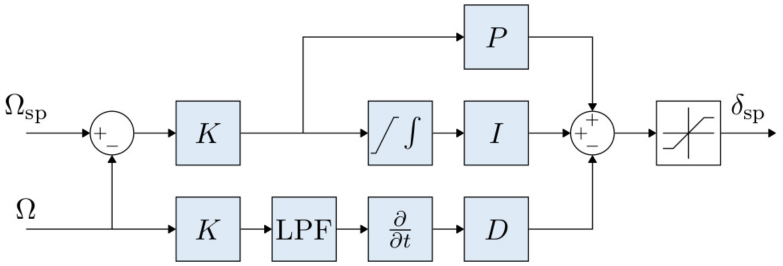

Figure 5: Angular rate control PID, courtesy of [1]

where k_R, k_Ω are gains for the orientation error $\boldsymbol{e}_R$ and the angular rate error $\boldsymbol{e}_\Omega$. The control moment corresponds to a tracking controller on SO(3), this controller exponentially stabilizes the zero equilibrium of the attitude tracking errors. Since this controller implements both the angle and angular rates control in the same operation, the originally implemented cascaded architecture (where the $\boldsymbol{\Omega}_{sp}$ is obtained) gets bypassed as shown in Fig 6.

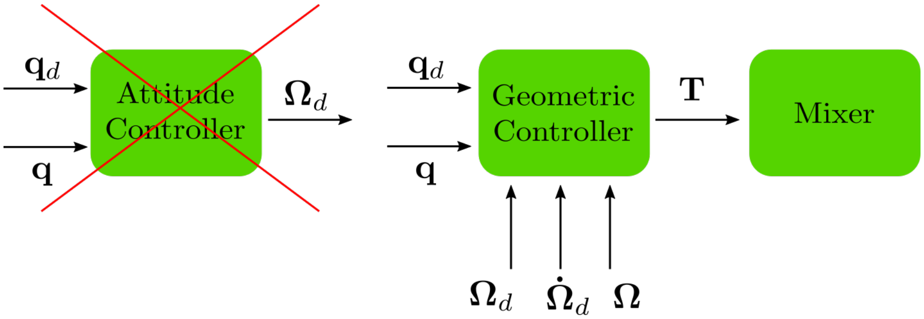

Figure 6: Control architecture with geometric controller.

The implementation of the controller consisted on modyfiing the C/C++ autopilot firmware, the code is outside the scope of this report.

After careful tuning of the gains, attitude tracking results on manual flight are reported in Figs. 7, 8 and 9.

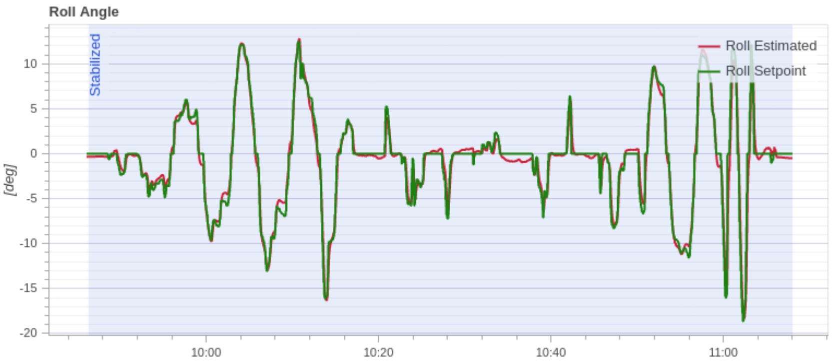

Figure 7: Roll angle tracking with implemented attitude controller.

Comments

The work here developed is currently being continued with a formal appintment as an Assistant Research Scientist at NYU ARPL.

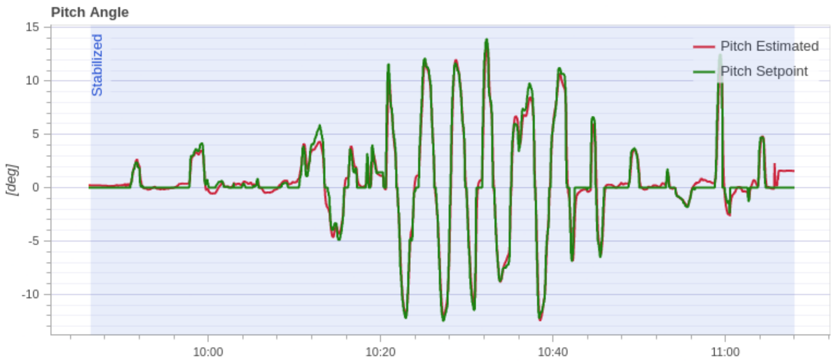

Figure 8: Pitch angle tracking with implemented attitude controller.

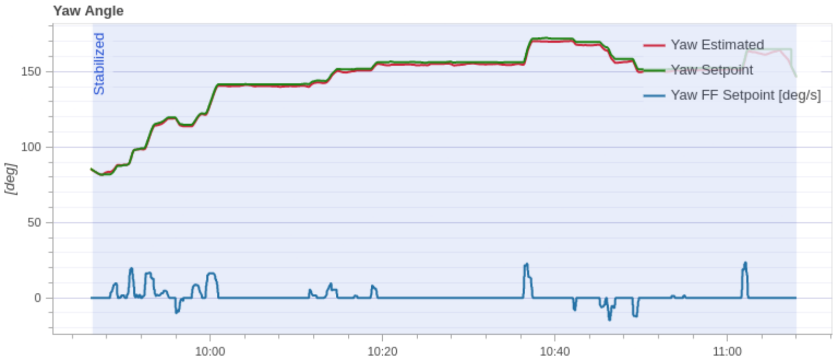

Figure 9: Yaw angle tracking with implemented attitude controller.

References

[1] Controller Diagrams | PX4 User Guide.

[2] Dario Brescianini, Markus Hehn, and Raffaello D'Andrea. Nonlinear Quadrocopter Attitude Control: Technical Report. Technical report, ETH Zurich, 2013.

[3] Giuseppe Loianno. Robot Localization & Navigation Lectures, 2022.

[4] Taeyoung Lee, Melvin Leok, and N. Harris McClamroch. Geometric tracking control of a quadrotor UAV on SE(3). In *49th IEEE Conference on Decision and Control (CDC)*, pages 5420–5425, Atlanta, GA, December 2010. IEEE.

[5] PX4. Using the ECL EKF | PX4 User Guide.