Precise Unmanned Aerial Vehicle (UAV) Flight Control

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***Abstract*—The aim of the project is to develop a system to control the motion of a UAV (Unmanned Aerial vehicle) to precisely advance to a desired location based on certain fine-grained input displacements. In other words, the over aching goal is to achieve fine-grained (centimeter-level) translation-control of the drone. The overall system diagram of the project and the scope is portrayed in figure 12. The INS (Inertial Navigation system) and the GNSS (Global Navigation Satellite System) data is considered the essential data for the flight processor in order to control the motion of the UAV. The control in outdoor environments primarily exploits localized differential GNSS information, termed as RTK (Real-time Kinematics). Indoor control (control in GPS denied environments) exploits INS data, where the location and the displacement of the UAV is estimated by adequate post-processing of the accelerometer, gyroscope and magnetometer sensor measurements (typically referred to as IMU (Inertial Measurement Unit) data). The disparity between the estimated location of the UAV and the desired location is used to drive the actuators controlling the motion of the UAV. These input displacements are translated to rotational torque used to drive the motors of the UAV based on a PID (Proportional IntegralDerivative) controller. The goal of this project is three fold: 1. To determine how to extract precise displacement and position information of the UAV based on sensor data, 2. To achieve fine-grained translation-movement of the UAV, and 3. To evaluate and tune the PID controller parameters to achieve accurate positioning of the UAV. Here the term UAV and drone is used interchangeably to refer to a Quadrotor.**

I. Introduction

A. Aim

The goal of this project are two fold,

- **Achieve precise PID control of the drone:** This involves modifying and tweaking the PID controller of the drone to improve the flight quality (translation, attitude and altitude stability) while concentrating primarily on the translation controller. The aim of this project is to determine how to tune the different parameters of the controller to achieve the best performance. This requires a complete overhaul of the control architecture of the drone.
- **Design a fine grained positioning system for the drone:** This defines the ability of the drone to navigate to a desired location with high accuracy (cm level accuracy) in both indoor and outdoor settings. This involves the design and implementation of precise fine grained displacement sensing techniques/ algorithms and a displacement based PID controller.

B. Motivation

PID Control for drones: Drones are complex systems including a variety of controllers for rate, attitude, altitude, position & velocity control. Typically, drones have pre-configured control parameters that can be manually tuned based on experiments. We performed cause and effect experiments and theoretical analysis to modify the PID controllers and to tune the parameters to improve the flight quality, by making the drone resilient to wind and other external disturbances, noise and other imperfections of the drone.

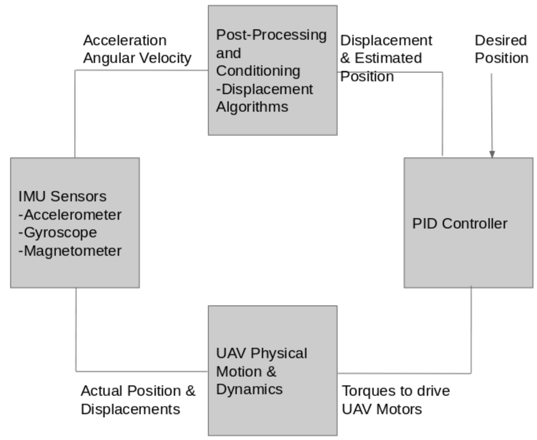


Fig. 1: High-level System Diagram: Containing the typical blocks of a CPS.

Positioning systems for Drones: Modern drones come equipped with GNSS (Global Navigation Satellite System) based positioning which is suited for outdoor coarse navigation. This is not suited for indoor navigation or fine grained navigation or control of the drone. Existing indoor navigation systems for drones rely on additional heavy infrastructure. Hence, we require precise position sensors and control of the drone that are adequate for both indoor and outdoor environments.

C. Problem Statement

The problem of achieving fine-grained motion-control of the drone is formalized via the following example problem. The goal is to move the drone in a 2D-grid with 5 cm way-points as shown in figure 2, in both indoor and outdoor environments. The challenge lies in implementing fine-gained position sensors, fine-grained actuation, and PID controllers to facilitate this motion.

II. System Design

Drones, are cyberphysical systems that consist of three major components: sensors, controllers and actuators. These components are indicated in figure 12. Optimization of the dynamics of the drone, demands the individual optimization,

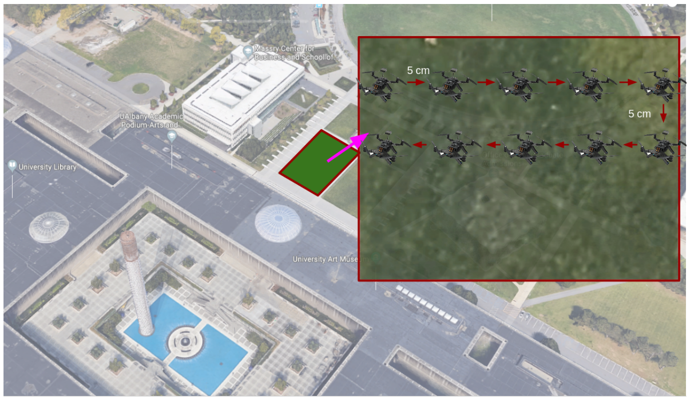


Fig. 2: Fine-grained motion plan for Drone in Collin's Circle, Ualbany.

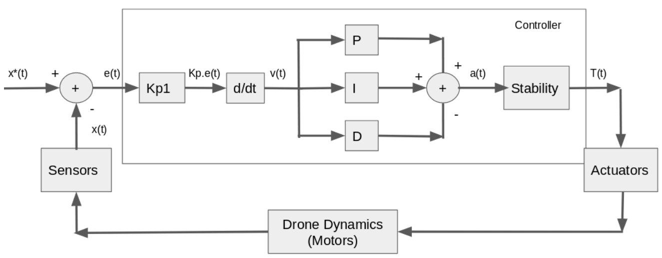


Fig. 3: System Diagram including the PID Controller

proper integration and joint optimization of these components. Figure 3 shows the system diagram with the PID controllers to maintain the stability and positioning of the drone. Figure 4 shows the system diagram for the fine-grained positioning of the drone from sensor to controller.

III. Implementation

For the purpose of this project, we employed the Intel Aero Ready-to-fly drone, due to the multitude of available sensors, programming flexibility and high-computational capabilities. It is to be noted that this project was primarily envisioned, to aid the research on "Localization using UAVs". Thus, the drone was equipped with radio resources (USRP B210). For enhanced outdoor sensing, the UAV was equipped with a RTK-GPS module and a raspberry pi. This additional payload and its impact on the dynamics of the drone, served as a secondary motivation for this project. The drone uses the Ardicopter firmware built on-top of the PX4 framework to promote hardware and software flexibility. The software framework for sensing, control and the evaluation of PID controllers were implemented primarily via python-dronekit. The fine actuation of the drone was achieved by specifying the required rotational

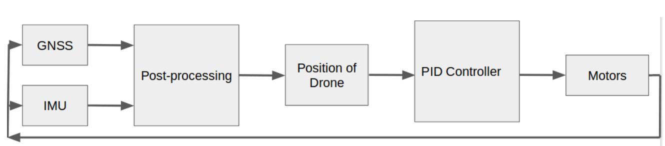
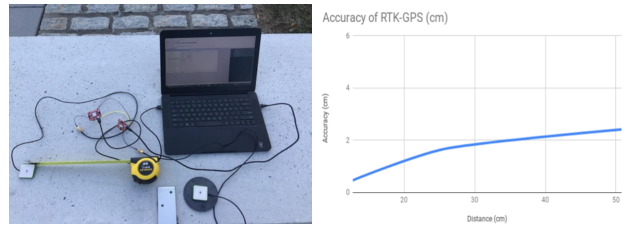


Fig. 4: Positioning System Design: From Sensing to Controlling in indoor and outdoor environments.



(a) Setup to test the accuracy of the RTK module.
(b) Accuracy with displacement of the Rover, in cm

Fig. 5: Bench-marking the accuracy of RTK-GPS.

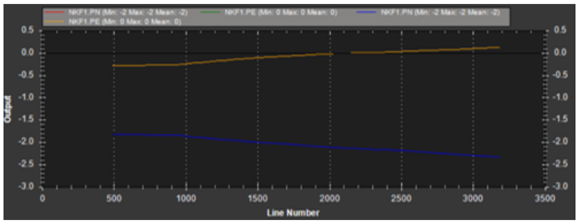
torques to drive the motors of the drone, to achieve a fine control of roll, pitch and yaw of the drone. The movement of the drone was terminated, when the disparity between the desired position and the actual position was less than a threshold (5 cm).

IV. Sensors

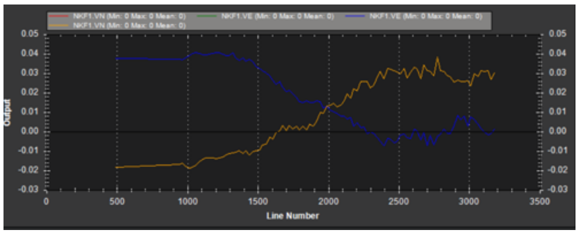
The drone includes a variety of sensors for advanced flight control. The sensors in the context of this work provide measurements required to drive the feedback loops of the various PID controllers. The translation controller of the drone relies on accurate positioning of the drone. The sensors and the techniques applied for fine-grained sensing of the drone is summarized below.

1. Outdoor Positioning (GNSS based sensing and Guided control of the drone): In essence, a GNSS receiver measures the transmitting time of GNSS signals emitted from four or more GNSS satellites and these measurements are used to obtain its position (i.e., spatial coordinates- latitude and longitude) and reception time. Pure GNSS based positioning has a resolution of 2.5 m. Most communication equipment (smartphones, drones etc...) rely on the GNSS data for positioning. There are two major issues with such positioning, 1. The resolution of 2.5 m is insufficient for precise localization of devices, 2. GNSS based localization is limited to outdoor positioning with strict requirements on the sanity of GNSS data (visibility of satellites and the atmospheric conditions) which may be affected on cloudy days. Hence, we envision employing Real Time Kinematics (RTK) [1], to improve the resolution of GNSS based positioning to about 2.5 cm, which enables precise localization of the drone. A GNSS receiver ('Drone', referred to as the Rover) capable of RTK (Intel Aero, equipped with external RTK module) takes in the typical signals received from the GNSS along with a correction stream (in real-time) to achieve 2.5cm positional accuracy. Additionally, an RTK receiver (a laptop equipped with another RTK module, called the 'Base') takes in an RTCM correction stream and then calculates the location of the drone with 2.5cm accuracy in real time. This achieves the required cm-level location sensing of the drone in outdoor settings. The fine-grained motion of the drone exploits the disparity between the current RTK position estimation and the desired position to navigate the drone. Figure 5 shows the bench-marking of the accuracy of the RTK-GPS.

2. Indoor Positioning (INS based sensing and Unguided but controlled navigation): The IMU data consists of data



(a) North, East displacement Estimates from EKF.



(b) North, East velocity Estimates from EKF.

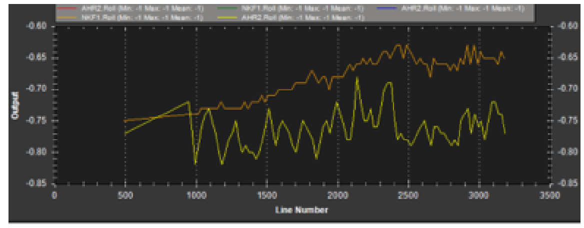
Fig. 6: Translation Performance of EKF.

from the accelerometer, gyroscope and the magnetometer. In theory we can convert the tilt-corrected linear acceleration of the drone to linear displacement. This localization scheme is very attractive for indoor localization (or in GPS-denied environments). However, the precise localization using IMU data is heavily impaired by the: a. (double integral) noise drift (of the accelerometer data), b. inaccuracies in the tilt estimation (of the gyroscope data), and c. the imperfect compass offset correction (of the magnetometer data) of the drone. We developed conditioning, smoothing and event-detection algorithms to alleviate these inaccuracies to achieve a median +/- 5 cm accuracy with constrained (planned) motions of the drone (moving the drone as in Figure 2, by hand (no wind)). The controlled motion of the drone, allows us to alleviate the drift in the IMU based displacement estimation. This accuracy can be improved by exploiting Extended Kalman Filter techniques (EKF) to estimate the position. The advantage of the EKF over the simpler complementary filter algorithms, is that by fusing all available measurements (from different sensors) it is further able to reject measurements with significant errors [2]. The EKF also corrects for the IMU drifts by using known position measurements (e.g., GPS or known movement of drone), when available. This makes the drone less susceptible to faults that affect a single sensor. We use the 2 IMUs available on the drone to improve the location estimate, by complementing the readings and alleviating the inaccuracies. The performance of EKF sensor fusion is demonstrated in figures 6 and 7 for the linear (1-D) part of the motion of the drone as indicated in figure 2

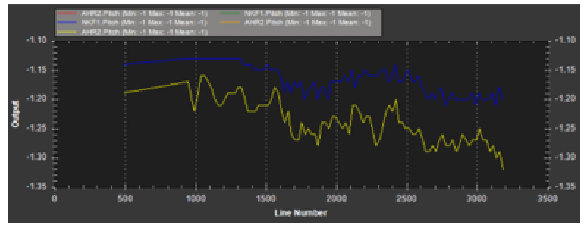
Other techniques exist that use Ultra Wideband (UWB) radio waves or Optical signals (Optitrack) to estimate the location of the drone. However, these techniques rely on significant additional hardware to facilitate positioning. Hence, we rely on the GNSS and IMU data to localize the drone with high accuracy.

V. Calibration

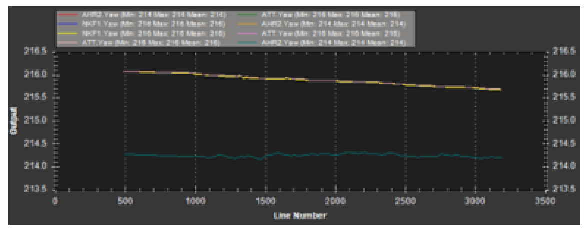
The external battery mounted on the drone, and the additional payload (radio and RTK module) severely affects the dynamics of the drone and the sensor data. Hence, the sensors



(a) Roll angle Estimates from EKF.



(b) Pitch angle Estimates from EKF.



(c) Yaw angle Estimates from EKF.

Fig. 7: Tilt Performance of EKF.

required calibration of the Electronic Speed Control System (ESC), Accelerometers and the Compass (Magnetometer). The accelerometer was calibrated by holding the drone for a short duration in each of the local reference planes of the drone. The compass was calibrated by performing random rotations of the drone, to estimate and correct for the offset in the compass measurements along the local reference plane. The ESC calibration could not be performed as the battery was external to the drone, and provided no control over the battery.

VI. Modeling the Physical Dynamics

The drone consists of four rotors, which are placed equidistant from the center of mass of the drone. The combination of the torques produced from the rotors are control to drone to move in roll, pitch and yaw direction.

As shown in figure 8, each two neighbour rotors are rotating counter to each other to cancel the gyroscopic effects and aerodynamics torques generated by each of them. Each motor produces a force f_i which proportion with the angular velocity by

$$f_i = kw^2 \qquad (1)$$

The torque required for the motion of the drone is function in the difference of the forces generated from the for rotors. The pitch torque is function in the difference of $f_1 - f_3$, the roll torque is function of $f_2 - f_4$, the yaw torque is the sum of all torques which are generated by the rotors. In other words, if we need to increase the yaw axis, we have to increase the

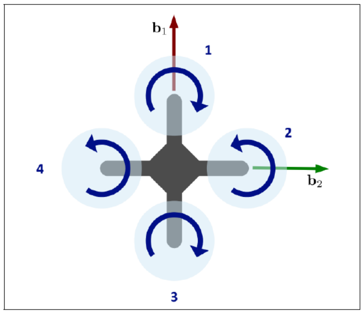


Fig. 8: Quad copter setup [3]

velocity of the rotor 1 and 3 and decrease the velocity of the rotors 2 and 4 simultaneously.

VII. PID Controller

Here we describe the behavior of the PID controller in the UAV, and describe the parameters that will be tuned. Typically drones have four different PID controllers which are altitude, attitude (row, yaw, pitch) and translation PID controllers. These controllers work with each other simultaneously and with the actuators in order to provide the stability and the reliability for missions of the drone. The row, yaw and pitch PID controllers try to maintain the stability of the drone to be resilient to wind and other external forces. However the translation PID controller is tasked with moving the drone to a desired location based on the current location estimated from the GNSS data. The tuning of the translation PID controller is critical to ensure that the drone moves to the precise desired location. In this work, we focus primarily on tuning the translation PID controller, and to some extent the stability PID controller (i.e row, yaw and pitch PID).

The translation PID controller consists of two controllers in cascade. The first is proportional controller which uses the error in the position (i.e the difference between the desired and current locations) and and converts it to desired speed. The desired speed is the input for the second PID controller which converts it to desired desired acceleration. The resulting desired acceleration becomes a lean angle which is then passed to the stability PID controller to regulate the angles. The output from the stability PID controllers is the torques to drive the actuators (motors).

In our project we concern on the fine movement of the drone in centimeter accuracy, which differ than the movement of the drone based on the GNSS data with has from 2 to 3 meters accuracy. So we need to tune the PID controller in such a way to maintain the stability for these short distance accuracy.

Before we describe the strategy that will be used in the PID tuning, let us analyze the system model. As we mentioned before that the translation PID controller takes the error between the current position and the desired position and converts it to desired acceleration to fed the stability PID controller. So we can model the whole drone plant as a second order system that takes the acceleration and converts it to current displacement as shown in figure 9. From this model, the transfer function

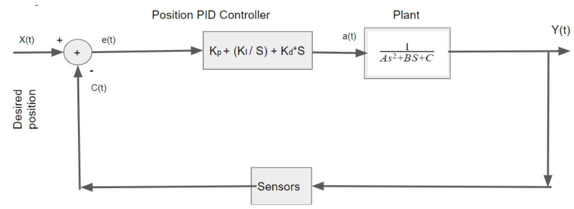


Fig. 9: System Model

of the model can be given by

$$\frac{Y(s)}{X(s)} = \frac{K_d s^2 + K_p s + K_I}{As^3 + (B + K_d)s^2 + (C + K_p)s + K_I} \tag{2}$$

where K_p,K_I and K_d are the proportional, integral and derivative constant of the PID controller, and A,B and C are general coefficients of a general second order system. We can get the system coefficients through experiments, however it is not easy to do that. The other way is to try to analyze this general transfer function to have a staring point to tune the PID controller.From control theory, there is a trade off between the stability and the responsiveness of a system. In our project we concern on stability in order to reach a certain limit of centimeter accuracy movement of the drone.

For second order system, if we added more poles, the system will be more stable in the sense that it will have a finite number of oscillation, however adding more zeroes will led to more oscillation for the step response of the system. Therefore we can say that K_d will tends to be zero to reduce the number of zeros in the transfer function which will lead to more stable step response for the system.

Also the proportional gain K_P leads to high response rate for the system, however the system may suffer from overshooting, which make the system unstable in case of large errors.

Another way of analysis we use in order to find a starting point for PID tuning. As shown in figure 10, The typical step response for PID controller. From the control theory, we can conclude that the proportional gain K_P makes the system more responsiveness of the system through decreasing the raise time, however the system can suffer from overshooting. this can be overcome by adding more derivative component K_d, because the derivative component role is to predict the future error through the rate of the change of the current error, while this can lead to increase the setting time and the system may reach to unsuitability and it is noise sensitive. Moreover the integral part K_I is considered the most important part to achieve the stability, but it may leads to make the system over damped (i.e the system has slow response.).

In our work, we concern on the stability of the system rather than the responsiveness. This stability allows the drone to achieve the fine grid movement. So from the previous analysis, we try to eliminate the derivative component K_d, and start by small values of K_P to avoid overshooting.

After we define the criteria that we used to tune the PID controller, We need to verify this criteria through experimental results. We set $K_d = 0$, $K_I = 1$ and $K_I = 0.5$, then we

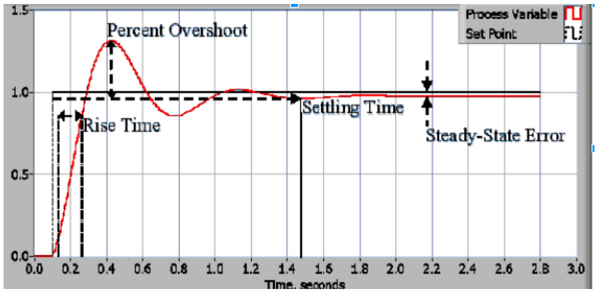


Fig. 10: Typical PID response

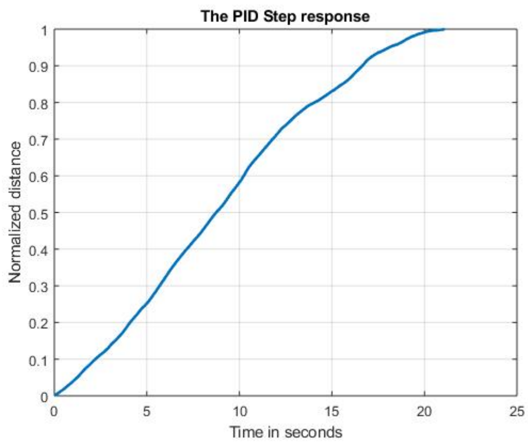


Fig. 11: PID step response for the first experiment

made two measurements to analyze these values as shown in figure 10 and 11. We can see that the step response of the PID controller is very smooth due to eliminating the derivative component and make the proportional component relatively small. In other words, we increase the number of poles in the transfer function given in (2) while reduce number of zeros at the same time.

VIII. Communication Architecture

In this section, we try to give an overview about the communication architecture of intel aero compute board [4]. The board consists of two main boards, the first called Intel aero flight controller, while the second called Intel aero compute board. The Flight controller consists of STM32 micro controller in addition of some sensing modules which are gyroscope MPU-6500, Altitude pressure sensor M55611 and Magnetometer HMC5883L. All these sensing modules help the controller and especially the implemented PID controllers to adjust the drone transitional motion, altitude and stability. These sensing modules communicate with the controller using different communication protocols such as I^2C and SPI. The flight controller board send the commands to the actuators through the processor in the compute board using UART protocol. The second board consists of Intel Atom x7-Z8750 processor and Altera MAX 10 FBGA which gives huge computation power for the board. This board is communicating directly with the drone peripherals through five analog channels and four GPIO.

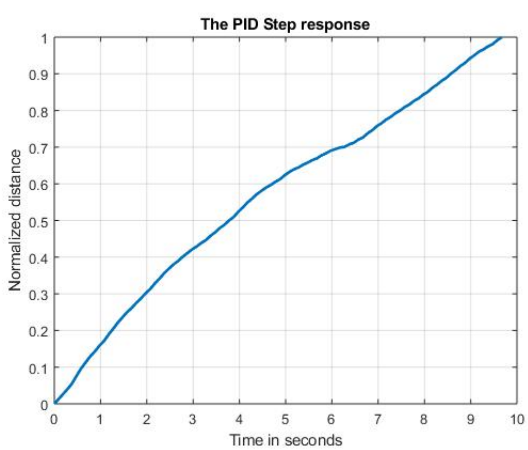


Fig. 12: PID step response for the second experiment

IX. Conclusion and Future Work

In this work, we try to acheive a fine grained translation of the drone in centimeter level. We try to perform our algorithm in outdoor and Indoor environment where it is considered as GPS denied environment. The IMU data are Post processed in order to determine the current position of the drone in indoor environments to achieve decimeter level accuracy. In outdoor environments, we use real time RTK-GPS data to achieve centimeter level accuracy. These demonstrates our ability to achieve fine-gained sensing of the location / displacement of the drone.

Also we tune the transitional PID controller with a specific methodology to serve this high accuracy. However we solve some obstacles like extracting the log files from the drone and perform the proper formatting so that we could extract the necessary information needed for analysis in order to tune the drone controller properly. Also how to reference the drone location in centimeter level however all the positioning data are referenced to the GPS has from two to three meter accuracy which is not suitable to analyze our algorithm, so we make post processing for the sensor data to have the accurate positioning of the drone.

However we faced some limitation in our experiments due to the weather, so that the accuracy of the algorithm affects by the external force of the weather (i.e wind) and also the battery life affects us so that we could not do two or three measurements at a time.

Our future work will be focused on the effect of adding more proportional component k_P in order to find the optimal K_P with the fastest responsive time and also the higher accuracy that could be acheived.

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