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Study on attitude heading reference system for an Unmanned Aerial Vehicle in an aerial surveillance scenario

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***Abstract*— Nowadays Unmanned Aircraft Systems (UAS) have an integrated and collaborative framework that is used in many applications such as military, security and surveillance, service delivery, disaster rescue, and much more due to its flexibility and accessibility of flying. The Unmanned Arial Vehicle (UAV) or drone is useful to perform a task without a pilot on it and it also has features like path planning. The system contains a computing and communication system onboard that allows communication with the physical drone and ground stations. The control and navigation of the UAS involve the gathering of sensor data and fuse using the Attitude Heading Reference System (AHRS). This can be realized using the SITL simulator of the drone by using python API which can send Mavlink messages to the autopilot. We can increase the precession of automation in our UAV's using SITL to send Mavlink messages on flight gear 3D virtual environment. This paper performs the study of the AHRS by deploying the standard surveillance mission by a quadrotor UAV which performs actions on the software in the loop simulator.**

Keywords*— UAS, AHRS, Mavlink, Autonomous flight, SITL, Flight Gear

I. Introduction

In this study of indoor and outdoor air quality are a popular topic and a major determinant in such a way Unmanned Aerial Vehicle (UAV's) depend on these environments. The small (UAVs) with new design architectures and configurations are being developed to meet the higher requirements for various professional fields such as parcel delivery, remote sensing, mapping, surveillance, and dangerous missions. Kang, et al. proposed [1]. An Unmanned Aerial Vehicle (UAV) or drone is only an aircraft that can fly autonomously or remotely without any human pilot, crew or passengers on it. Although the term "UAS" (Unmanned Aerial System) is the system of UAV, Mary, et al. proposed[2]. UAS provide the necessary modules that makes a UAV work including its GPS and ground control module, transmission systems, camera, all the software, and the user can control the drone from the ground. UAV is one of the components of a UAS. We can also say that all UAVs are drones. Muhammad, et al. proposed [3]. Nowadays the "UAV" and "UAS" are commonly can trace to the military but are also can be used by more technically oriented drone mapping plots, as well as in drone-related policy. Remotely piloted aircraft (RPA) is an unmanned aircraft that is real-time piloting. Ali, et al. proposed [4]. It is a communication, command, and control system that includes data links and other system elements that connect human-operated remote pilot station(s) to the Remotely-piloted aircraft system (RPAS). The remote pilot-in-command (PIC) and the small remote control aircraft (RA) must operate in a direct visual line of sight (VLOS) and also alternatively the small RA with PIC's designated. Nicoletta, et al. proposed [5].

An AHRS (Attitude and Heading Reference System) is simply a combination of sensors and the processing system that can provide heading and three axes that provide attitudes such as roll, pitch, and yaw and also orientation information for small unmanned aerial vehicles and other unmanned vehicles as well as for gimbals, reflector, and aperture antennas and other sensor platforms. B, et al. proposed [6]. AHRS will be utilized to detect sensor fusion and state estimation attitude algorithms such as extended Kalman filters to compute attitude and heading from the multiple sources of data, in another way it may form part of a larger inertial navigation system (INS) and also Inertial measurement units (IMUs) are mostly used in attitude estimation in aeronautics, navigation system and also in robotics [7]. It is widely used for measuring accelerations and angular velocities with the use of accelerometer and gyroscope. AHRS estimation is one of the important processes for small-scale (UAV) control due to its smaller sensors and the limitation of space and power.

It is also designed to replace the traditional mechanical gyroscopic flight measuring instruments. It is also utilized in Autonomous Control Systems Laboratory (ACSL) for usage in various applications such as industrial and infrastructure inspection, logistics, radiation monitoring, aerial photography, precision agriculture, and disaster investigation and management. Accuracy estimation also uses to reduce the sensor's noises by using a low-pass or highpass filter system for noise filtering. AHRS can also use an Extended Kalman filter (EKF) to obtain better accuracy than filter systems. However, the complexity of (EKF) able to prevents the implementation of real-time attitude estimation at typically embedded microprocessors on small UAV systems. Mie, et al. proposed [8].

The controlling of the quadcopter in the way of takeoff, fly to specific locations and positions, and landing to done perfectly and successfully we need to implement the same algorithms on a real drone. The quadcopter simulation was done successfully and it gives the same behavior as the (software in the loop) SITL simulator (Fig.1) gives the access to us to run Plane, Copter or Rover without any hardware physical drone, at the simulation time prior when it is in the same autopilot software which is Ardupilot. Qays, et al. proposed [9].

Implementation in real-life processing, digital signal processors (DSP) integrated with CPU that is used in several small UAVs. Hentati, et al. proposed [10]. Field-Programmable Gate Array (FPGA) has used image processing for self-localization of the UAV and also to adapt small UAVs problem. We can develop EKF circuit for FPGA since it faster and efficient processing is needed to implement real-life processing. Mie, et al. proposed [11].

2 Related Research

2.1 Attitude Representations

Attitude is one of the needed value inputs, in order to control an aerial platform correctly, by the autopilot control system [12].

Attitude is generally a representation of 3 unit rotations of the aerial platform. These rotations are roll, pitch, and yaw [13]. There are also several different rotations representations used. Among them are the Cbn matrix, Euler angle, and quaternion angle representation. In Cbn transformation matrix is a representation of the 3X3 matrix,that is sequential rotation of (roll φ, pitch θ, and yaw ψ). Where bn represents the rotation of a vector from the body frame to the navigation frame. Here is the representation of the Cbn matrix that represents 9 values of attitude. A, et al. proposed [14].

$$C_{bm}(\phi,\theta,\psi) = \begin{bmatrix} \cos\theta\cos\psi & -\cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi \\ \cos\theta\sin\psi & \cos\phi\cos\psi + \cos\phi\sin\theta\sin\psi & -\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix} \ldots(1)$$

2.2 Euler Angles Representation

The Euler angles (Fig. 2) are introduced by Leonard Euler, which is designed to describe the attitude of reference frame relative frame to inertial frame by three successive rotation (Euler) angles about the body axes [15].

The Euler angle (roll φ, pitch θ, and yaw ψ) is widely used in the aerospace field.

1.1 Roll rotation (φ): this rotation represents the wingtips up/down. When roll angle φ = 0, the wings are in a horizontal position. Here roll angle φ = 30 degrees.

$$R(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \ldots(2)$$

1.2 Pitch rotation (θ): this rotation represents the nose of the airframe up/down. When pitch angle θ =0, the vehicle is in a horizontal position. Here pitch angle θ = 30 degrees.

$$R(\theta) = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \ldots(3)$$

1.3 Yaw rotation (ψ): this rotation represents the nose of the airframe left/right. This is the rotation of the airframes gravity vector. When the yaw angle ψ =0, the airframe start pointing north. Here yaw angle ψ =30 degrees [16].

$$R(\psi) = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \ldots(4)$$

2.3 Quaternion Angle Representation

The system with quaternions is valid for all attitudes. (Fig 3) The [p, q, r] rotation rates are to update the quaternion angle. Wang, et al. proposed[17]. The viewed quaternion angles are: E = [e0 e1 e2 e3] The quaternion angle vector E elements are:

2.4

$$e_0 = \cos\left(\frac{\mu}{2}\right)$$
$$e_1 = \alpha\sin\left(\frac{\mu}{2}\right)$$
$$e_2 = \beta\sin\left(\frac{\mu}{2}\right)$$
$$e_3 = \gamma\sin\left(\frac{\mu}{2}\right)$$

Geometric Dynamics Model and control of quadrotor

The dynamic quadrotor model is defined using a geometric representation, it is also a coordinate-free model that is represented by a rotation matrix to show the rotation from body-frame to the inertial frame, R, in the Special Orthogonal group of dimension 3(SO(3)) := {R ∈ R3×3 | RT R = I, det(R) = +1}. The center of mass position of the quadrotor is denoted by x, This table representing the dynamics of the quadrotor on the Special Euclidean group of dimension 3 (SE(3)). Lee, et al. proposed [18].

m∈ R Mass of the quadrotor

J ∈ R3×3

Matrix Inertia with respect on body-fixed frame of the quadrotor

R∈SO(3) It is the matrix rotation of the quadrotor from body fixed frame to the inertial frame

Ω ∈ R3 Body-frame angular velocity

x∈ R3 Position vector of the quadrotor's center-of-mass in the inertial frame

v∈ R3 Velocity vector of the quadrotor's center-of-mass in the inertial frame

f∈ R Thrust and Magnitude of the quadrotor and moves in the –b3 direction

M ∈ R3 Moment vector of the quadrotor in the body-fixed frame

e1, e2, e3 ∈ R3 These are the unit vectors which move along the x,y,z directions of the inertial-frame

b1, b2, b3 ∈ R3 Body fixed axis of the quadrotor represented

b3 is the inertial-frame which is orthogonal to the plane of the quadrotor

g∈ R Acceleration due to gravity, is along the direction e3

The configuration space of this system with 6 degree-of-freedom and 4 inputs corresponding to the 4 rotors is Q := SE(3). Equations of motion for the quadrotors is discussed given below.

$$x^{\cdot} = v, (1)$$
$$mv^{\cdot} = mge3 - fRe3, (2)$$
$$R^{\cdot} = R\Omega \qquad \ldots(5)$$
$$\times, (3)$$
$$J\Omega =^{\cdot} M - (\Omega \times J\Omega),$$

2.5 Geometric Tracking Control for Quadrotor

The geometric tracking control is tracks the record of the desired quadrotor trajectory xd(t). The thrust f and orientation Rd are calculated by the position controller,while the attitude control calculates moment M to track the orientation Rd. Lee, et al. proposed[19].

The attitude tracking error is defined as, $e_R = 1\ 2\ (R^{T}{}_{d}\ R - R^{T}\ R_d)^{\vee}$

The angular velocity tracking error on TRSO(3) as, eΩ = Ω − R T RdΩd.

The configuration error between the system and desired attitude is defined as,

$\Psi = 1\ 2\ T$ race[I − R T d R]. Here, Ψ is defined positive and upper bounded by 2.

The dynamics of the attitude error are then given as,

$$J e^{\cdot} \Omega = J\Omega +^{\cdot} J(\Omega \times R\ T\ R d \Omega d - R\ T\ R d \Omega^{\cdot}\ d)$$

$$J e^{\cdot} \Omega = M - (\Omega \times J\Omega) + J(\Omega \times R\ T\ R d \Omega d - R\ T\ R d \Omega^{\cdot}\ d) \ldots (6)$$

2.6 Effects of Model Uncertainties and Disturbances on the Dynamics Attitude

Determine the external disturbances can be captured in the attitude dynamics of the quadrotor and the external disturbances are defined as, $R^{\cdot} = R\Omega\ \times$, (17) $J^{-}\Omega =^{\cdot} M - \Omega \times J^{-}\Omega + \theta e$,

Where the model properties, like in mass, m and in inertia J, and θe represents the unknown external disturbance and J^{-} is the true (unknown) inertia of the quadrotor. The attitude error dynamics.

Liang, .et al. proposed [20].

$$e^{\cdot} R = C(R\ T\ d\ R) e \Omega, \ldots (7)$$

$$J^{-} e^{\cdot} \Omega = M - (\Omega \times J^{-}\Omega) + J^{-}(\Omega \times R\ T\ R d \Omega d - R\ T\ R d \Omega^{\cdot}\ d) + \theta e \ldots (8)$$

Therefore, the closed-loop attitude error dynamics of the quadrotor along with the model uncertainties and disturbances can be given as, $e^{\cdot} R = C(R\ T\ d\ R) e\Omega$, $J e^{\cdot} \Omega = \mu + \theta$

2.7 Kalman and Information Filters

In a nonlinear system the transition matrix is using of nonlinear functions as trigonometric function, and f model is denoted as vehicle system. Song, .et al. proposed [21].

$$\begin{aligned} \dot{x}(t) &= f(x(t), u(t), t) \\ z_n(t) &= h_n(x(t), t) + \epsilon_{z_{n(t)}} \end{aligned} \ldots (9)$$

2.8.1 Control Architecture

The control technique used to track the trajectory using Geometric Attitude controller along with a reference model for dynamics position and attitude controller [22]. The desired trajectory, positions and its higher derivatives are calculated and used to calculate forward feed inputs (Fig. 4) [23].

2.8.2 IMU measurement of the Quadrotor Implementation

The cascaded controllers have a lower level, higher-level bandwidth that is used to control four-rotor angular velocities, we can control this into three steps. Firstly, the desired attitude and thrust (Td) are provided from the PPM signal [24], [25]. Then, the attitude control torque can design using the IMU measurement. Finally, the motor can control the torque and thrust using get that PCM signals can be generated in ESCs (Fig. 5).

2.8.1 Control Architecture

The control technique used to track the trajectory using Geometric Attitude controller along with a reference model for dynamics position and attitude controller [22].

2.9 Attitude Stabilization Control Design

The quadrotor UAV design a controller to stabilize the attitude of the considered quadrotor that has six degrees of freedom while it has only four inputs. The sum of the thrusts of each motor can be defined as the collective input or throttle input [26], [27].

3 System Model

3.1 Architecture

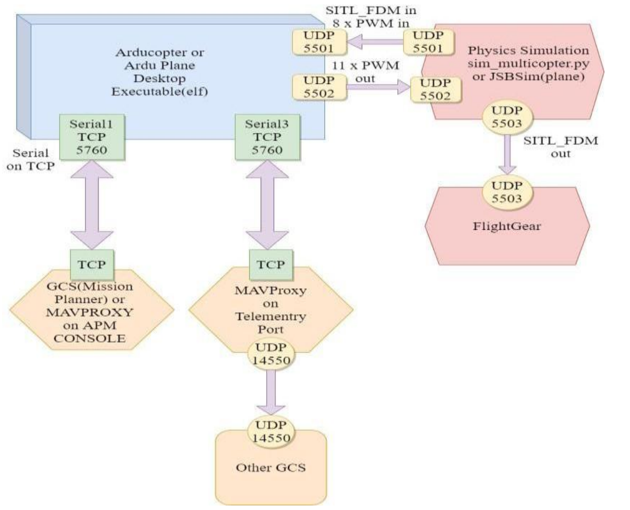

Fig. 1. Ardupilot (Software in the loop) architecture, port number may vary depending on the environment

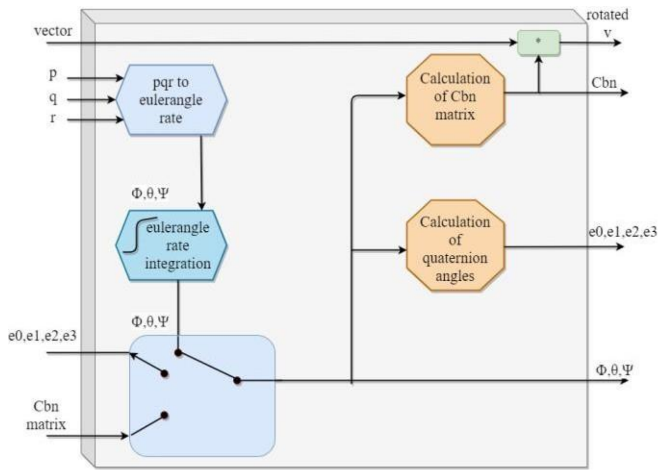

Fig. 2: Block schematics of Euler Angles Representation

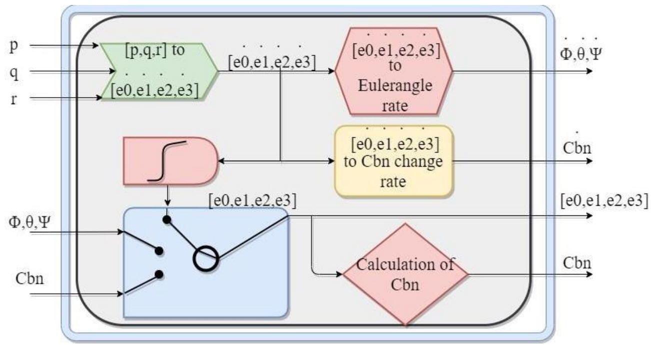

Fig. 3: Block schematics of Quaternion Angle Representation

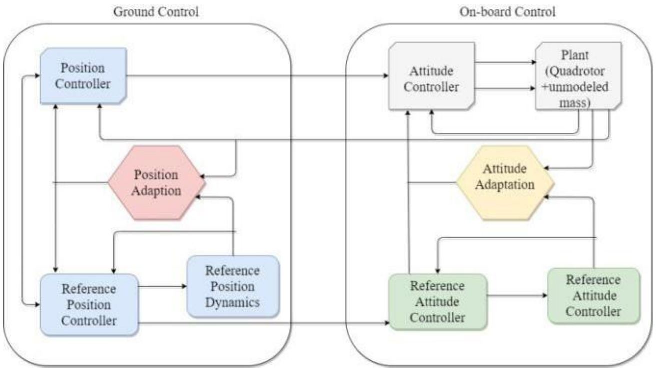

Fig. 4: Attitude Stabilization Control Architecture

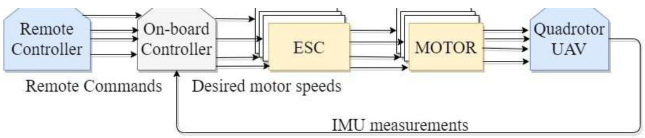

Fig. 5: Quadrotor Cascaded Control Loop Architecture

3.2 Mathematical model

1. The rotation matrix is call the C_{bn} matrix and is defined in the above equation [28].

$$C_{bn} = R(\phi, \theta, \psi) = R_\phi R_i R_\psi \quad \dots (10)$$

The C_{bn} matrix is 3x3 original matrix with 9 elements.

$$C_{bn} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \dots (11)$$

$$\det C_{bn} = 1$$

The row and columns of C_{bn} orthogonal matrix.

$$C_{bn} C_{bn}^T = I^{3x3} \dots (12)$$

The C_{bn}3x3 matrix is possible to all inverted angles.

$$C_{bm}(\phi, \theta, \psi) = \begin{bmatrix} \cos\theta\cos\psi & -\cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi \\ \cos\theta\sin\psi & \cos\phi\cos\psi + \cos\phi\sin\theta\sin\psi & -\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix} \dots (13)$$

Taylor expansion of the trigonometric function in C_{bn} matrix and small angles where cos α ~ 1 and sin α ~ α . This is the following skew symmetric rotation matrix.

$$C_{bn}(\phi, \theta, \psi) = I^{3x3} + I^{3x3} \times \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} 1 & -\phi & \theta \\ \phi & 1 & -\psi \\ -\theta & \psi & 1 \end{bmatrix} \dots (14)$$

2. Non-linear system (f) model function

$$\begin{gathered} \dot{x}(t) = f(x(t), u(t), t) \\ z_n(t) = h_n(x(t), t) + \epsilon_{z_n(t)} \end{gathered} \dots (15)$$

The sensor models are describe the function h_n

$$E\left|\epsilon_{u(i)} \epsilon_{u(j)}^{T'}\right| = \delta_{ij} Q(i) \dots (16)$$

The noise control signal covariance matrix is denoted as Q.

$$\mathbf{F} = \nabla \mathbf{f} = \frac{\partial \mathbf{f}}{\partial \mathbf{x}} = \begin{bmatrix} \frac{\partial f_1}{\partial z_1} & \frac{\partial f_1}{\partial z_2} & \cdots & \frac{\partial f_1}{\partial z_n} \\ \frac{\partial f_2}{\partial z_1} & \frac{\partial f_2}{\partial z_2} & \cdots & \frac{\partial f_2}{\partial z_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial z_2} & \cdots & \frac{\partial f_3}{\partial z_n} \end{bmatrix} \dots (17)$$

This is the linearization of the state transition function.

4

Results

In this Mavproxy paper for the simulation scenario, we have to use Ardupilot mission planer SITL [29], to deploy a map on it to get UAV trajectory and use Mavlink to find out the resultant attitude error (Fig.8) from the desired roll, pitch, yaw attitude angles (Fig. 7) and determine the massage data speed rate and the quadrotor vibration [30], [31], in respect to x, y, z-axis. (Fig. 9) and also determine message rate of data streaming of UAV (Fig. 10). Here we show the resultant graphs of APM SITL and also show the map plot of UAV flying path in KSFO airbase using flight gear and pointing out the full flying path with the blue (the time of UAV flying Mavlink, Azza, et al. proposed [32], remote instruction to get all the environment variables) and yellow (the timing of UAV autopilot on the given commends to follow the path) marked path (Fig. 6).

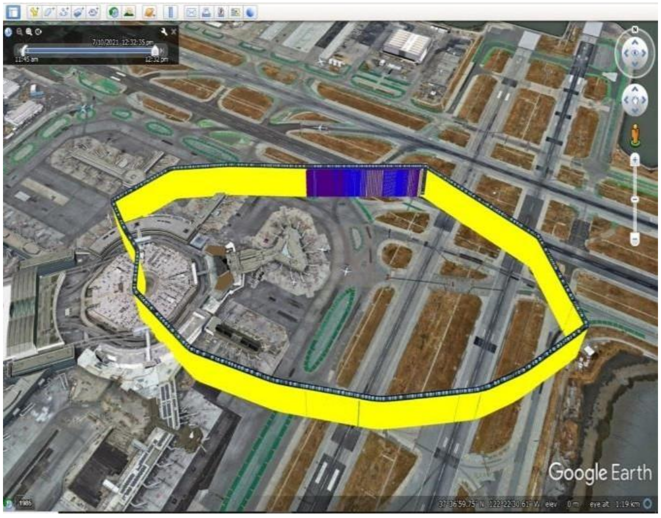

Fig. 6: The UAV flying path in Flight gear to showing in Google Earth platform (KSFO Airbase)

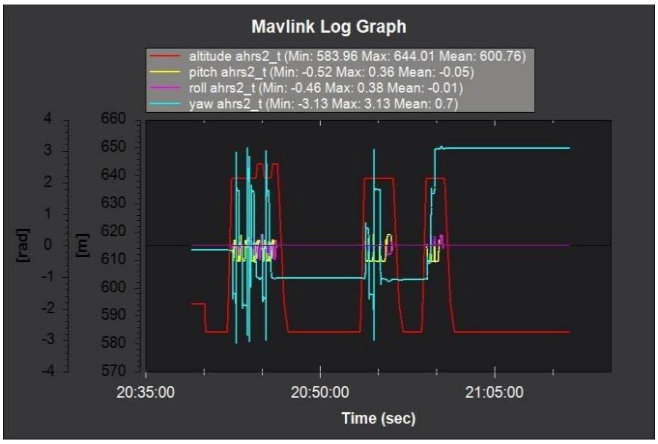

Fig. 7: Mavlink Log Graph showing altitudes AHRS (roll φ, pitch θ and yaw ψ) Respect to Time (sec) and amplitude (m/rad)

Here we can determine the pitch, roll, yaw AHRS Mean value from its Min and Man values in the following Mavlink graph respective of x-axis time (sec) and y-axis amplitude (m/rad) graph.

Pitch Mean = -0.05; [Min=-0.52, Max=0.36]

Roll Mean= -0.01; [Min=-0.46, Max=0.38]

Yaw Mean= 0.7; [Min=-3.13, Max=3.13]

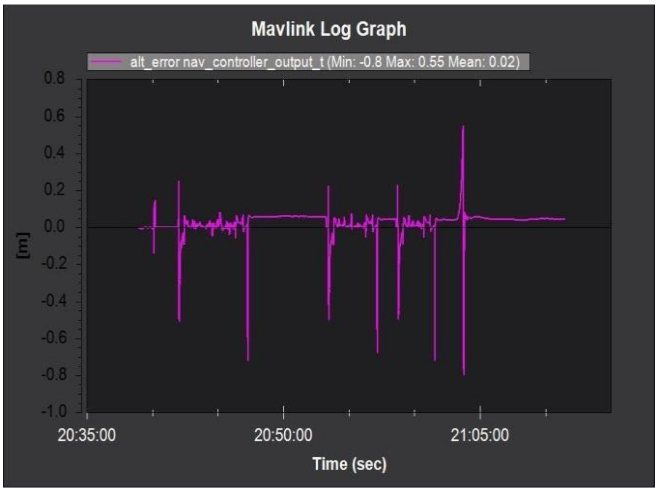

Fig. 8: Mavlink log graph to determine the attitude error in respect to Time (sec) and amplitude(m/rad)

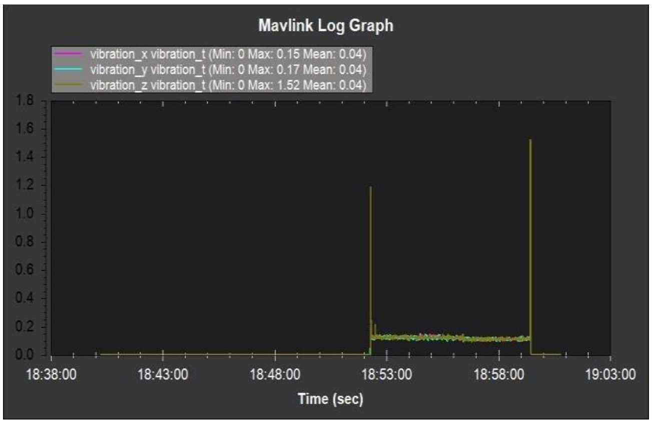

Fig. 9: Mavlink log graph to determine UAV vibration respect to X, Y, Z-axis

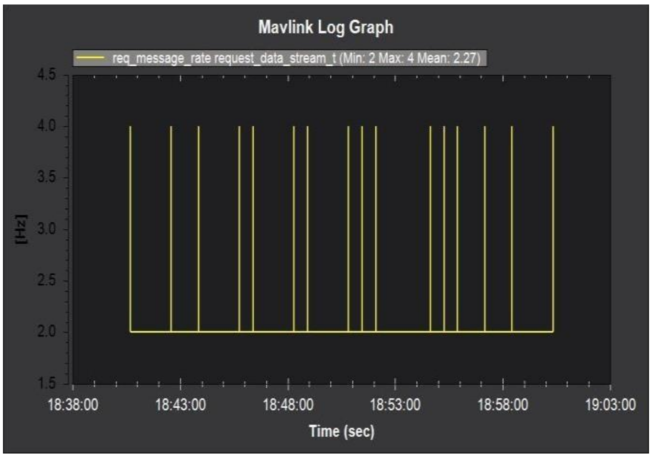

Fig. 10: Mavlink log graph to determine message rate of data streaming in UAV Respect to Time (sec) and amplitude (Hz) scale

5 Conclusion

In this paper, we convey a quadrotor UAV attitude stabilization controller. In the loop system considering external disturbance torque, the attitude and the angular velocity of the quadrotor were to be uniformly ultimately bounded by the proposed controller. UAV's performance depends on the attitude of the environment and the angels of moments and flips to control the attitude of the UAV may regulate. Future work will emphasize the position or path following control of the quadrotor with the use of methods of Position control and Trajectory tracking with the help of GPS and/or vision system that efficient individual quadrotor control methods even in the presence of external disturbance.

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