CHAPTER THREE

PRINCIPLES OF CONTROL AND ALGORITHMS

3.1 Aircraft Principal Axes

An airplane in flight is free to rotate in three dimensions:

- Pitch, nose up or down.
- Yaw, nose left or right.
- Roll, rotation about an axis running from nose to tail.

The axes are alternatively designated as lateral, vertical, and longitudinal. These axes move with the vehicle, and rotate relative to the Earth along with the plane.

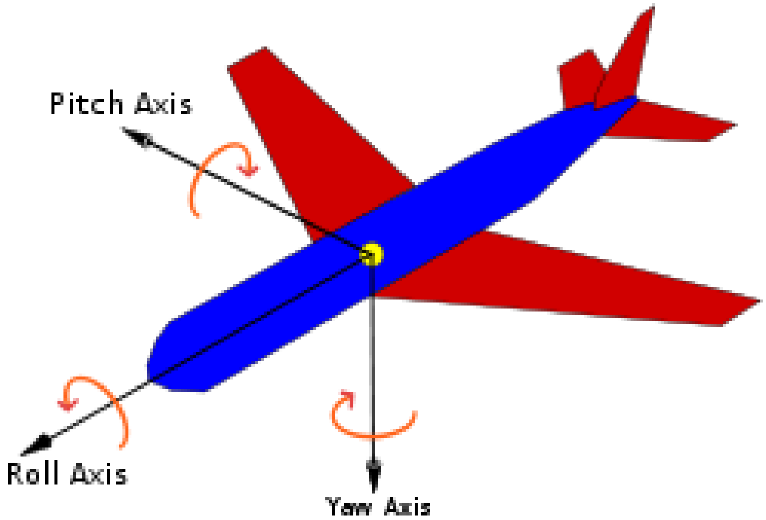

Figure 3.1: Principal Axes.

These rotations are produced by moments about the principal axes. On an airplane, these are produced by means of moving control surfaces, which vary the distribution of the net aerodynamic force about the vehicle's center of gravity. Elevators (moving flaps on the horizontal tail) produce pitch, a rudder on the vertical tail produces yaw, and ailerons (moving flaps on the wings) produce roll. On a spacecraft, the moments are usually produced by a reaction control system consisting of small rocket thrusters used to apply asymmetrical thrust on the vehicle [3].

3.2 Coordinate Frames

Two coordinate frames can be defined in order to describe the motion of the UAV's: Normal Earth-fixed frame F_E and Body frame F_B. Both of them are three dimensional, orthogonal and right-handed [4].

3.2.1 Normal Earth-Fixed Frame:

The origin of the frame is linked to a fixed point O on the Earth and its axes are x_E, y_E, z_E. The x-axis is directed towards the geographical North, the z-axis is directed towards the descending direction of gravitational attraction and the y-axis is the complementing axis.

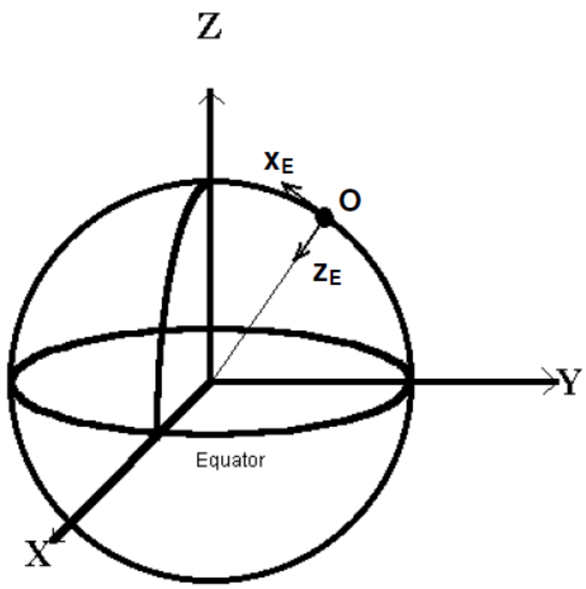

Figure 3.2: Normal Earth-Fixed Coordinate System

3.2.2 Body Frame:

The origin of the body frame is linked to the UAV and the center of mass. Its axes are x_B, y_B, z_B. The x-axis, called the roll axis, points towards the front belonging the symmetrical plane; the y-axis, called the pitch axis, is directed towards the lateral side of the missile; and the z-axis, called the yaw axis, is the complementing axis. G point is the center of mass.

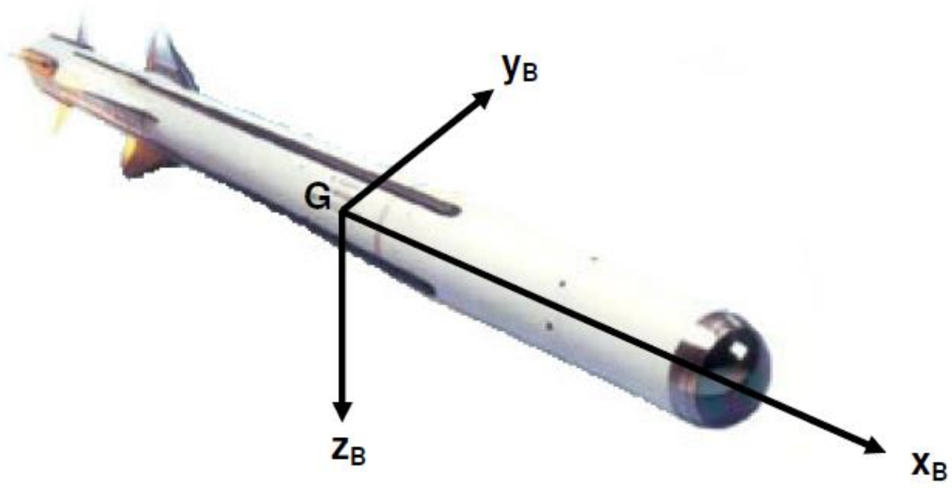

Figure 3.3: Body Coordinate System.

3.2.3 Transformation from Normal Earth-Fixed to Body Frame:

There are three angles in each coordinate system, which allow the transformation from the Normal Earth Fixed Frame (F_E) to the Body Frame (F_B):

- Ψ yaw angle about axis z_E
- Θ pitch angle about axis y_E
- Φ roll angle about axis x_E

Pitch (Θ), Yaw (Ψ) and Roll (Φ) are called Euler's Angles. These three transformations are associated with the transformations below:

$$\boldsymbol{F^E = \left(T_\psi T_\theta T_\Phi\right) . F^B = T_{EB} . F^B} \quad \textbf{(3.1)}$$

Where;

$$\boldsymbol{T_\psi} = \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (3.2)$$

$$\boldsymbol{T_\theta} = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} \quad \textbf{(3.3)}$$

$$\boldsymbol{T_{\Phi}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \Phi & -sin\,\Phi \\ 0 & sin\,\Phi & cos\,\Phi \end{pmatrix} \qquad (3.4)$$

$$\boldsymbol{T_{EB}} = T_{\psi} * T_{\theta} * T_{\Phi} \qquad (3.5)$$

$$= \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\Phi & -sin\,\Phi \\ 0 & sin\,\Phi & cos\,\Phi \end{pmatrix}$$

$$= \begin{pmatrix} \cos\theta\cos\Psi & \sin\theta\sin\Phi\cos\Psi - \sin\Psi\cos\Phi & \cos\Psi\sin\theta\cos\Phi + \sin\Phi\sin\Psi \\ \sin\Psi\cos\theta & \sin\theta\sin\Phi\sin\Psi + \cos\Psi\cos\Phi & \sin\theta\cos\Phi\sin\Psi - \sin\Phi\cos\Psi \\ -\sin\theta & \cos\theta\sin\Phi & \cos\theta\cos\Phi \end{pmatrix}$$

T_{EB} representation describes the transformation from the Normal Earth Fixed Frame to the Body Frame.

3.3 Attitude control

Attitude control is the exercise of control over the orientation of an object with respect to an inertial frame of reference.

Controlling vehicle attitude requires sensors to measure vehicle orientation, actuators to apply the torques needed to re-orient the vehicle to a desired attitude, and algorithms to command the actuators based on:

(1) Sensor measurements of the current attitude.

(2) Specification of a desired attitude.

The integrated field that studies the combination of sensors, actuators and algorithms is "Guidance, Navigation and Control" (GNC) [5].

3.4 Inertial Measurement Unit (IMU)

An inertial measurement unit, or IMU, is an electronic device that measures and reports on a plane's velocity, orientation, and gravitational forces, using a combination of accelerometers and gyroscopes. IMUs are typically used to maneuver aircraft, including UAVs, among many others, and spacecraft, including shuttles, satellites and landers [6].

The IMU is the main component of inertial navigation systems used in aircraft, spacecraft, watercraft, and guided missiles among others.

3.4.1 How IMU works:

An IMU works by detecting the current rate of acceleration using one or more accelerometers, and detects changes in rotational attributes like pitch, roll and yaw using one or more gyroscopes.

3.4.2 Construction:

The term IMU is widely used to refer to a box containing three accelerometers and three gyroscopes. The accelerometers are placed such that their measuring axes are orthogonal to each other. They measure inertial acceleration, also known as G-forces. Three gyroscopes are placed in a similar orthogonal pattern, measuring rotational position in reference to an arbitrarily chosen coordinate system.

3.5 Micro Electro Mechanical Systems

MEMS has been identified as one of the most promising technologies for the 21st Century and has the potential to revolutionize both industrial and consumer products by combining silicon-based microelectronics with micromachining technology. Its techniques and microsystem-based devices have the potential to dramatically affect of all of our lives and the way we live [7].

Micro-electromechanical system (MEM) is a process technology used to create tiny integrated devices or systems that combine mechanical and electrical components. They are fabricated using integrated circuit batch processing techniques and can range in size from a few micrometers to millimeters. These devices (or systems) have the ability to sense, control and actuate on the micro scale, and generate effects on the macro scale.

In the most general form, MEMS consist of mechanical microstructures, micro-sensors, micro-actuators and micro-electronics, all integrated onto the same silicon chip. Micro-sensors detect changes in the system's environment by measuring mechanical, thermal, magnetic, chemical or electromagnetic information or phenomena. Microelectronics processes this information and signal the micro-actuators to react and create some form of changes to the environment.

3.6 Gyroscope

A gyroscope is a device for measuring or maintaining orientation, based on the principles of angular momentum. In essence, a mechanical gyroscope is a spinning wheel or disk whose axle is free to take any orientation. Although this orientation does not remain fixed, it changes in response to an external torque much less and in a different direction than it would without the large angular momentum associated with the disk's high rate of spin and moment of inertia. Since external torque is minimized by mounting the device in gimbals, its orientation remains nearly fixed, regardless of any motion of the platform on which it is mounted [8].

Gyroscopes based on other operating principles also exist, such as the electronic, microchip-packaged MEMS gyroscope devices found in consumer electronic devices, solid-state ring lasers, fiber optic gyroscopes, and the extremely sensitive quantum gyroscope.

Applications of gyroscopes include inertial navigation systems where magnetic compasses would not work (as in the Hubble telescope) or would not be precise enough (as in ICBMs), or for the stabilization of flying vehicles like radio-controlled helicopters or unmanned aerial vehicles. Due to their precision, gyroscopes are also used to maintain direction in tunnel mining.

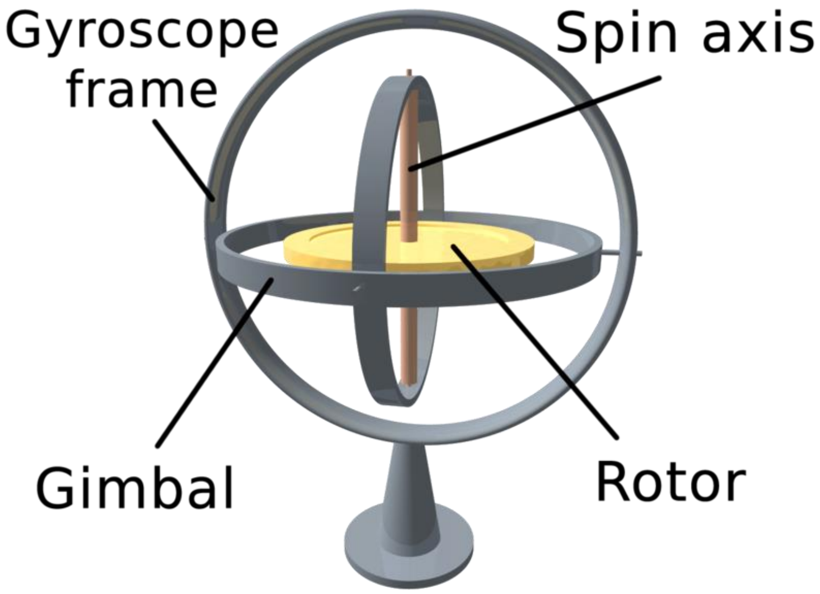

Figure 3.4: Gyroscope demonstration.

A MEMS gyroscope takes the idea of the Foucault pendulum and uses a vibrating element, known as a MEMS (Micro Electro-Mechanical System). The MEMS-based gyro was initially made practical and producible by Systron Donner Inertial (SDI). Today, SDI is a large manufacturer of MEMS gyroscopes.

In addition to being used in compasses, aircraft, computer pointing devices, etc., gyroscopes have been introduced into consumer electronics. Since the gyroscope allows the calculation of orientation and rotation, designers have incorporated them into modern technology. The integration of the gyroscope has allowed for more accurate recognition of movement within a 3D space than the previous lone accelerometer within a number of smart phones.

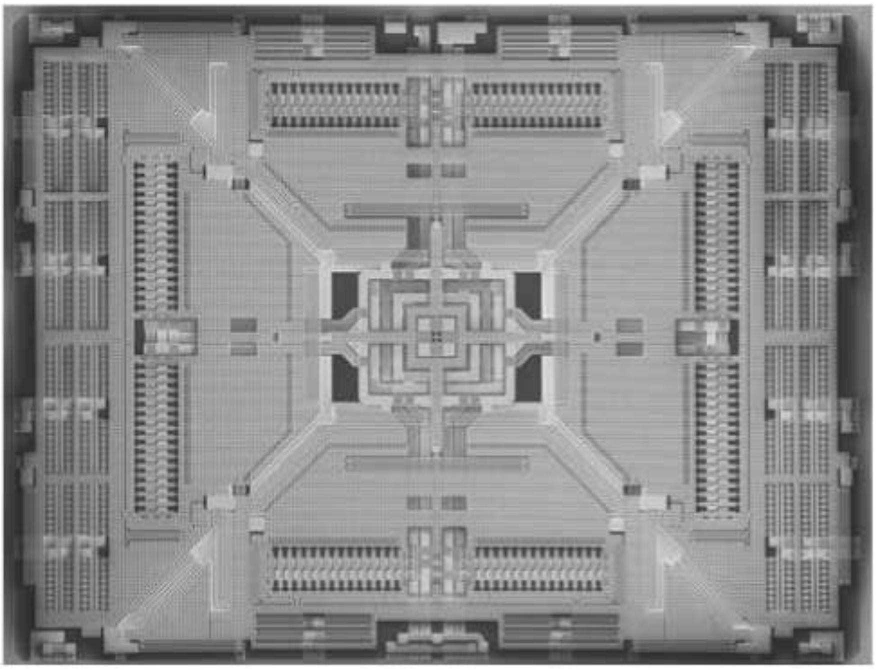

Figure 3.5: MEMS structure of 3-axis digital gyroscopes

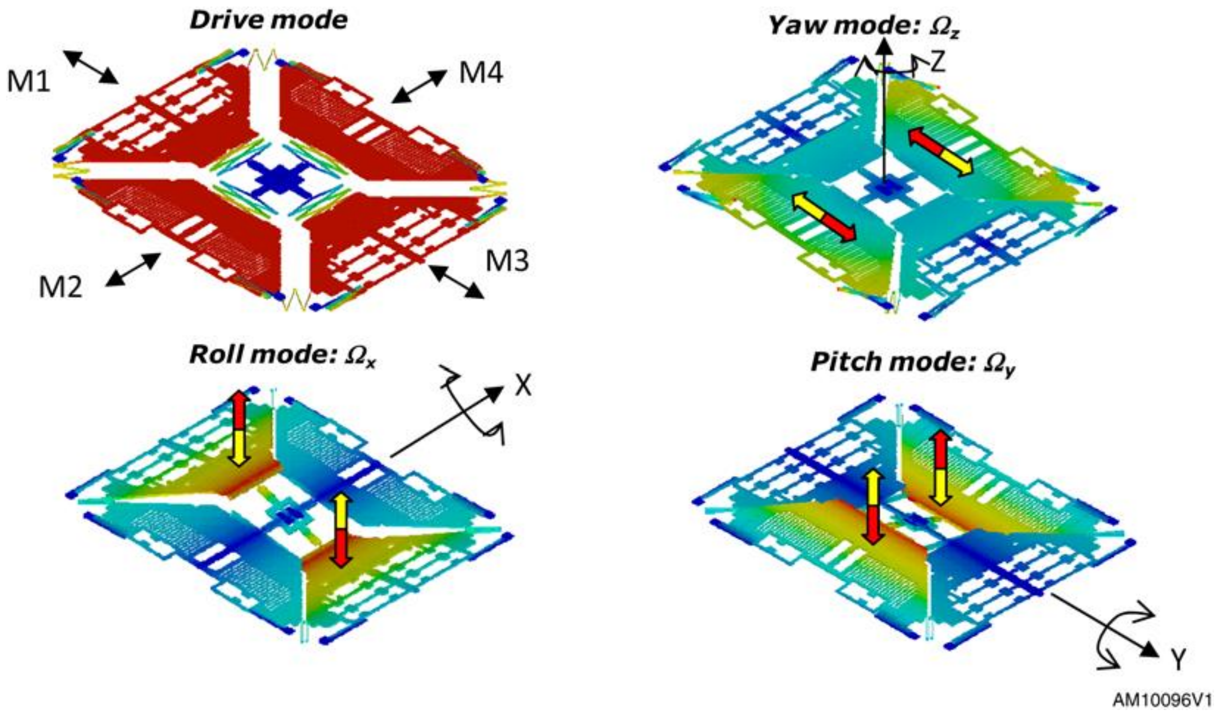

Figure 3.6: Demonstration of single driving mass

3.6.1 Calibrating a MEMS gyroscope:

Gyroscopes are usually factory tested and calibrated in terms of zero-rate level and sensitivity. However, after the gyroscope is assembled on the PCB, due to the stress, the zero-rate level and sensitivity may change slightly from the factory trimmed values.

Gyroscope needs to be calibrated for new zero-rate level and sensitivity values and other important parameters such as:

- Misalignment (or cross-axis sensitivity).
- Long term in-run bias stability.
- Turn-on to turn-on bias stability.
- Bias and sensitivity drift over temperature.
- Getting rid of zero-rate instability.

3.6.2 Gyro sensor output calculations:

MEMS gyroscope output can be expressed as shown in equation:

$$\boldsymbol{R_t = SC * (R_m - R_0)} \qquad (\mathbf{3.6})$$

$\boldsymbol{R_t}$ Is the true angular rate given in dps.

$\boldsymbol{R_m}$ Is the MEMS gyroscope measurement given in signed integer LSBs.

$\boldsymbol{R_0}$ Is the zero-rate level given in signed integer LSBs (the gyroscope output when no angular rate is applied).

SC is the scale factor (or sensitivity) given in dps/LSB.

Applying this equation to the 3-axis digital gyroscope, the true angular on the X-, Y- and Z-axis will be:

$$\begin{bmatrix} \boldsymbol{R_x} \\ \boldsymbol{R_y} \\ \boldsymbol{R_z} \end{bmatrix} = \begin{bmatrix} \boldsymbol{SC_x} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{SC_y} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{SC_z} \end{bmatrix} * \begin{bmatrix} \boldsymbol{R'_x - R_{x0}} \\ \boldsymbol{R'_y - R_{y0}} \\ \boldsymbol{R'_z - R_{z0}} \end{bmatrix} \qquad (\mathbf{3.7})$$

R'_x, R'_y, R'_z, are the raw measurements of the gyroscope.

R_{x0}, R_{y0}, R_{z0}, are the zero-rate level or bias on each axis.

SC_x, SC_y, SC_z, are the scale factor or sensitivity of each axis.

R_x, R_y, R_z, are the final angular velocity information of each axis.

3.7 Accelerometer

An accelerometer is a device that measures proper acceleration. The proper acceleration measured by an accelerometer is not necessarily the coordinate acceleration (rate of change of velocity). Instead, the accelerometer sees the acceleration associated with the phenomenon of weight experienced by any test mass at rest in the frame of reference of the accelerometer device. For example, an accelerometer at rest on the surface of the earth will measure an acceleration g= 9.81 m/s2 straight upwards, due to its weight. By contrast, accelerometers in free fall or at rest in outer space will measure zero. Another term for the type of acceleration that accelerometers can measure is g-force acceleration.

Accelerometers have multiple applications in industry and science. Highly sensitive accelerometers are components of inertial navigation systems for aircraft and missiles. Accelerometers are used to detect and monitor vibration in rotating machinery. Accelerometers are used in tablet computers and digital cameras so that images on screens are always displayed upright.

Single- and multi-axis models of accelerometer are available to detect magnitude and direction of the proper acceleration (or g-force), as a vector quantity, and can be used to sense orientation (because direction of weight changes), coordinate acceleration (so long as it produces g-force or a change in g-force), vibration, shock, and falling in a resistive medium (a case where the proper acceleration changes, since it starts at zero, then increases). Micro-machined accelerometers are increasingly present in portable electronic devices and video game controllers, to detect the position of the device or provide for game input.

3.7.1 Accelerometer sensor output calculations:

Output can be expressed as shown in equation:

Equation 3.8:

$$\begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} = \begin{bmatrix} SC_x & 0 & 0 \\ 0 & SC_y & 0 \\ 0 & 0 & SC_z \end{bmatrix} * \begin{bmatrix} A'_x - A_{x0} \\ A'_y - A_{y0} \\ A'_z - A_{z0} \end{bmatrix} \qquad (3.8)$$

A'_x, A'_y, A'_z, are the raw measurements of the Accelerometer.

A_{x0}, A_{y0}, A_{z0}, are the zero-rate level or bias on each axis.

SC_x, SC_y, SC_z, are the scale factor or sensitivity of each axis.

A_x, A_y, A_z, are the final normalized measurements of each axis.

3.7.2 Calculating tilt angles:

There are two ways to calculate 3 tilt angles in Figure 3.7. The first is use basic trigonometric Equation 3.9, 3.10 and 3.11, where A_x, A_y and A_z are the values obtained after applying accelerometer calibration on raw measurement data.

$$\alpha = \arcsin\left[\frac{A_x}{g}\right] \qquad (3.9)$$

$$\beta = \arcsin\left[\frac{A_y}{g}\right] \qquad (3.10)$$

$$\gamma = \arccos\left[\frac{A_z}{g}\right] \qquad (3.11)$$

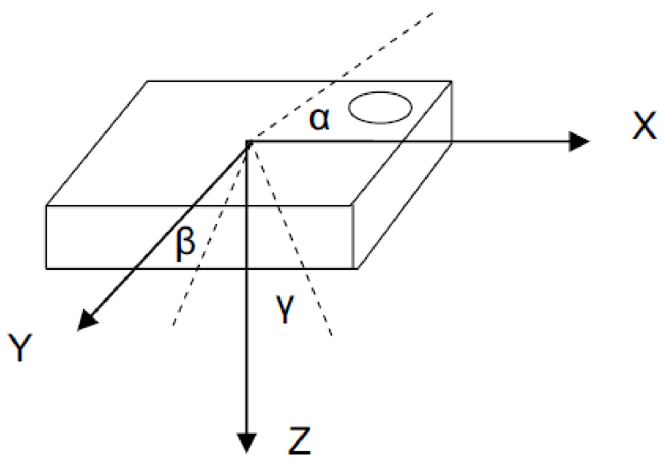

Figure3.7: Tilt angles from a tri-axis accelerometer.

The second way is to use trigonometric Equation 3.12 and 3.13 to calculate pitch and roll tilt angle, which produces constant sensitivity over 360° of rotation:

$$Pitch = \alpha = \arctan\left[\frac{A_x}{\sqrt{\left(A_y\right)^2 + (A_z)^2}}\right] \qquad (3.12)$$

$$\boldsymbol{Roll} = \boldsymbol{\beta} = \mathbf{arctan}\left[\frac{\boldsymbol{A_y}}{\sqrt{(\boldsymbol{A_x})^2 + (\boldsymbol{A_z})^2}}\right] \qquad (3.13)$$

3.8 Magnetometer

The strength of the earth's magnetic field is about 0.5 to 0.6 gauss and has a component parallel to the earth's surface that always points toward the magnetic north pole. In the northern hemisphere, this field points down. At the equator, it points horizontally and in the southern hemisphere, it points up. This angle between the earth’s magnetic field and the horizontal plane is defined as an inclination angle. Another angle between the earth's magnetic north and geographic north is defined as a declination angle in the range of ± 20°depending on the geographic location.

A tilt compensated electronic compass system requires a 3-axis magnetic sensor and a 3-axis accelerometer sensor. The accelerometer is used to measure the tilt angles of pitch and roll for tilt compensation. And the magnetic sensor is used to measure the earth’s magnetic field and then to determine the heading angle with respect to the magnetic north.

If the heading with respect to the geographic north is required, the declination angle at the current geographic location should be compensated to the magnetic heading.

3.8.1 Magnetometer sensor output calculations:

Output can be expressed as shown in equation:

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} SC_x & 0 & 0 \\ 0 & SC_y & 0 \\ 0 & 0 & SC_z \end{bmatrix} * \begin{bmatrix} M'_x - M_{x0} \\ M'_y - M_{y0} \\ M'_z - M_{z0} \end{bmatrix} \qquad (3.14)$$

M'_x, M'_y, M'_z, are the raw measurements of the Magnetometer.

M_{x0}, M_{y0}, M_{z0}, are the zero-rate level or bias on each axis.

SC_x, SC_y, SC_z , are the scale factor or sensitivity of each axis.

M_x, M_y, M_z, are the final measurements of each axis.

3.8.2 Heading calculations:

For the heading calculation, 3-axis magnetic sensor measurements need to be normalized by applying magnetic sensor calibration parameters and then reflected onto the horizontal plane by tilt compensation, as shown in Figure 3.8.

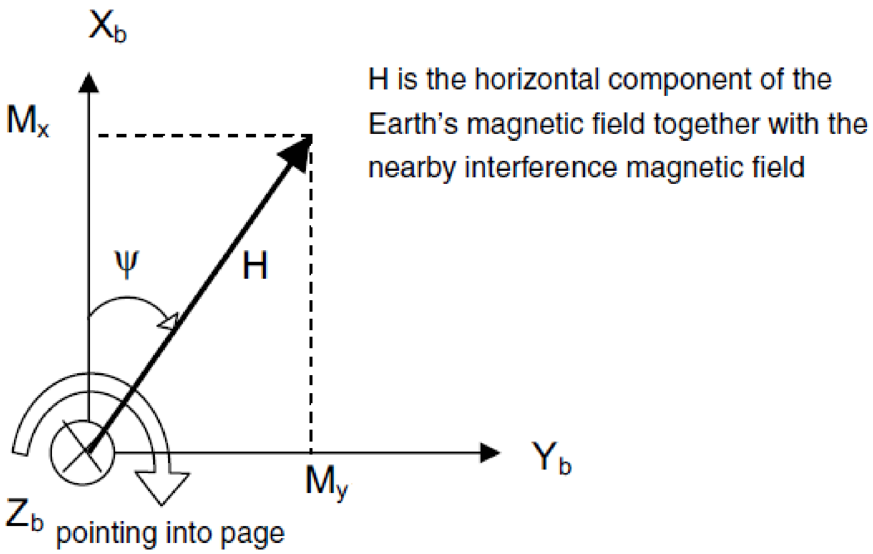

Figure 3.8: Heading calculation.

Tilt compensated magnetic sensor measurements M_{x1}, M_{y1}, and M_{z1} can be obtained as:

$$\boldsymbol{M_{x1} = M_x \cos\rho + M_z \sin\rho} \qquad (\mathbf{3.15})$$

$$\boldsymbol{M_{y1} = M_x \sin\gamma \sin\rho + M_y \cos\gamma - M_z \sin\gamma \cos\rho} \qquad (\mathbf{3.16})$$

$$\boldsymbol{M_{z1} = -M_x \cos\gamma \sin\rho + M_y \sin\gamma - M_z \cos\gamma \cos\rho} \qquad (\mathbf{3.17})$$

From these equations heading can be calculated as:

Heading = Ψ = $\arctan\left(\frac{M_{y1}}{M_{x1}}\right)$ for $M_{x1} > 0$ and $M_{y1} \geq 0$ (3.18)

= $180^\circ + \arctan\left(\frac{M_{y1}}{M_{x1}}\right)$ for $M_{x1} < 0$ (3.19)

= $360^\circ + \arctan\left(\frac{M_{y1}}{M_{x1}}\right)$ for $M_{x1} > 0$ and $M_{y1} \leq 0$ (3.20)

= 90° for $M_{x1} = 0$ and $M_{y1} < 0$ (3.21)

= 270° for $M_{x1} = 0$ and $M_{y1} > 0$ (3.22)

The magnitude $|M| = \sqrt{(M_{x1})^2 + (M_{y1})^2 + (M_{z1})^2}$ (3.23)

The magnitude $|M|$ should also be equal to 1. If not, it means that the external magnetic interference field is detected or a pitch/roll error is present.

3.9 GPS Sensor

The Global Positioning System (GPS) is a space-based satellite navigation system that provides location and time information in all weather conditions, anywhere on or near the Earth where there is an unobstructed line of sight to four or more GPS satellites. The system provides critical capabilities to military, civil and commercial users around the world. It is maintained by the United States government and is freely accessible to anyone with a GPS receiver.

While originally a military project, GPS is considered a dual-use technology, meaning it has significant military and civilian applications. GPS has become a widely deployed and useful tool for commerce, scientific uses, tracking, and surveillance. GPS's accurate time facilitates everyday activities such as banking, mobile phone operations, and even the control of power grids by allowing well synchronized hand-off switching.

GPS Calibration:

The GPS calibration is used to obtain the GPS Home Position. The GPS Home Position is comprised of the latitude, longitude, and altitude of the home position. This is the position that the relative positions of the aircraft (in meters east and meters north) are calculated from. The following formula is used for this calculation:

$$X = (longit - h\_longit) \cdot \cos\left(\frac{h - latitude}{60min/deg} \cdot \frac{\pi}{180deg}\right) \cdot 1853.2\ min/meter \quad (3.24)$$

$$\boldsymbol{Y = (latitude - h\_latitude) \cdot 1853.2\ min/meter} \quad (\mathbf{3.25})$$

The longitude and latitude used in the equation are in minutes. The X and Y position are in meters east and north of GPS Home Position, respectively. The GPS altitude is also referenced from the altitude stored in the GPS Home Position. The home position is also the set of coordinates to which the aircraft will fly, should it lose communication with the ground station.

3.10 Pressure Sensor

Pressure sensor is used to measure Altitude and airspeed. Absolute pressure sensor is used to measure altitude and differential pressure sensor to measure airspeed. The pressure sensor has internal signal conditioning as well as internal temperature compensation.

GPS measure’s altitude but due to high latency and low sensitivity to small changes in altitude; it is used to calibrate and correct the pressure sensor.

3.11 Control strategy

In order to achieve stable autonomous flight, some instability must be addressed. This section discusses the PID control structure developed to stabilize and control the aircraft. To fly the aircraft autonomously, the autopilot must be capable of navigating waypoints. This requires that the autopilot be able to control the heading, altitude, and airspeed of the aircraft. For manual control, it is desirable that the autopilot also accepts pitch and roll angle commands. To accomplish this, a controller constructed of nested PID loops has been developed. The aileron, elevator, and throttle commands are controlled via inner PID loops that stabilize the roll, pitch and throttle. The altitude and heading are controlled with outer loops, which produce commanded values for the inner loops. The autopilot control is divided into two controllers: the lateral controller and the longitudinal controller [9].

3.11.1 Lateral control: [10]

The lateral controller is responsible for controlling the yaw rate, roll angle, and heading. This is accomplished with three inner servo loops and one outer loop. The inner loops produce efforts that drive the aileron and rudder. The outer loops produce commanded values for the inner loops. The inner lateral loops are as follows:

- Aileron from Roll: This loop generates an aileron deflection from the roll error. This loop is responsible for holding the roll attitude of the aircraft. This loop is shown in Figure 3.9.

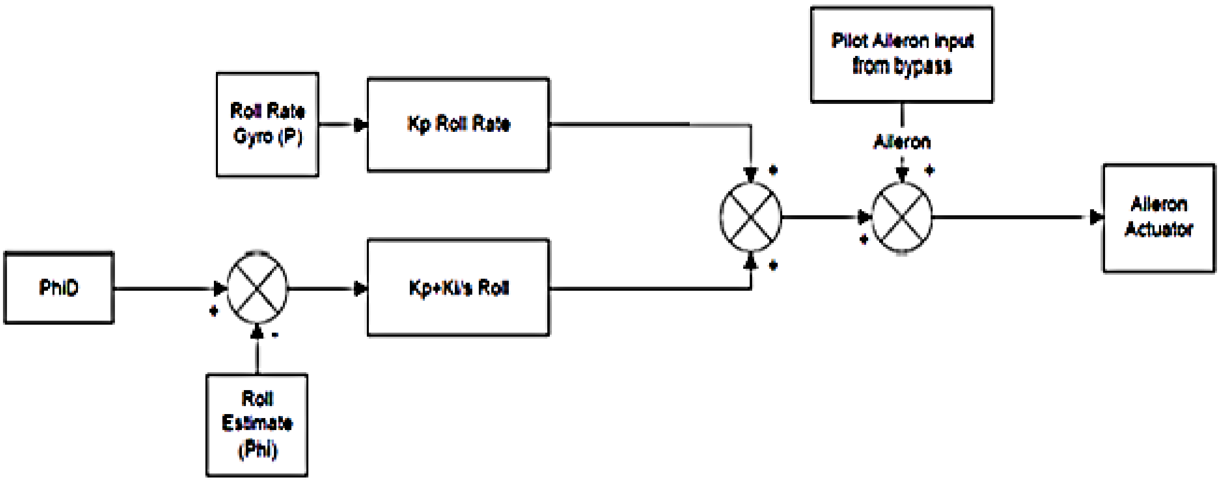

Figure 3.9: Inner lateral roll and roll rate controller [10]

- Aileron from Roll Rate: This loop generates an aileron deflection from the roll rate. It is responsible for damping the roll rate of the aircraft. The control effort for this loop is summed with the effort from the Aileron from Roll loop and sent to the aileron servo actuator. See Figure 3.9.
- Rudder from Yaw Rate: The purpose of this loop is to control yaw rate of the aircraft. This loop drives the rudder servo. This loop is shown in Figure 3.10.

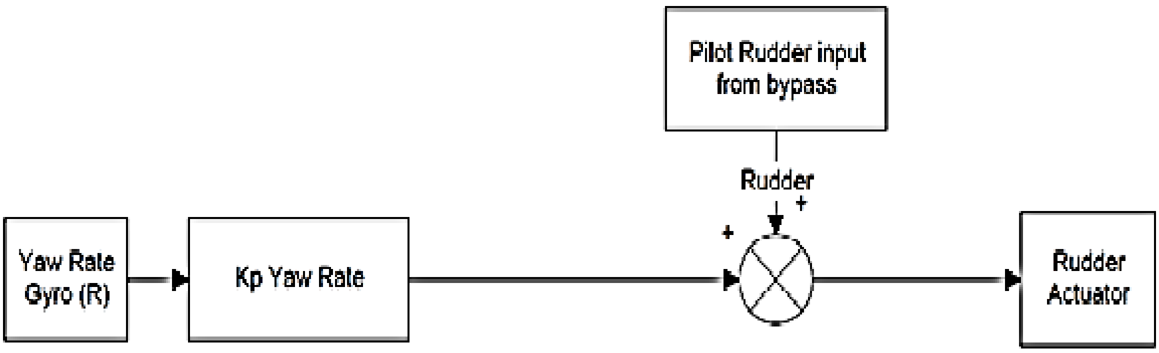

Figure 3.10: Inner lateral yaw rate controller.

The outer lateral control loop is the following:

- Roll from Heading: This is the loop responsible for controlling the heading of the aircraft. It generates a roll angle from the heading error. This roll angle serves as the commanded roll angle for the Aileron from Roll loop. This loop is shown in Figure 3.11.

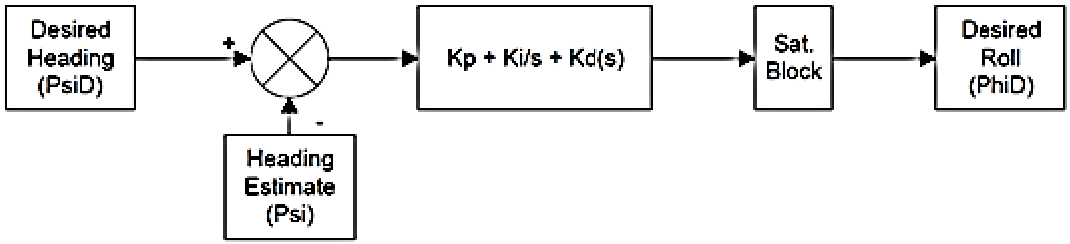

Figure 3.11: Outer lateral heading angle controller.

3.11.2 Longitudinal Control:

The longitudinal controller is responsible for controlling the velocity, pitch angle, and altitude. This is accomplished with 3 inner servo loops and 2 outer loops. The inner loops produce efforts that drive the elevator and throttle. The outer loops produce commanded values for the inner loops. The inner lateral loops are as follows:

- Elevator from Pitch: This loop generates an elevator deflection from the pitch error. This loop is responsible for holding the pitch attitude of the aircraft. This loop is shown in Figure 3.12.
- Elevator from Pitch Rate: This loop generates an elevator deflection from the pitch rate. It is responsible for damping the pitch rate of the aircraft. This loop's control effort is summed with the Elevator from Pitch loop and sent to the elevator servo actuator. See Figure 3.12.

- Throttle from Airspeed: The purpose of this loop is to control the aircraft's airspeed by adjusting the throttle. This loop drives the throttle servo. This loop is shown in Figure 3.13.

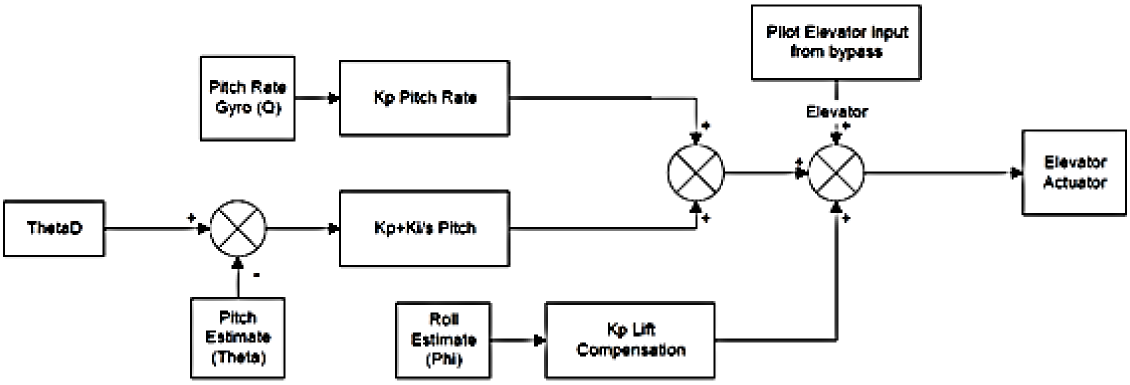

Figure 3.12: Inner longitudinal pitch and pitch rate controller

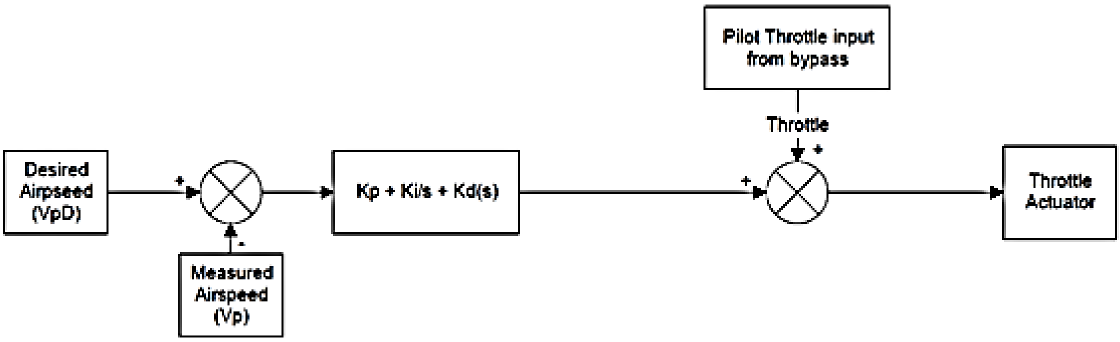

Figure 3.13: Inner longitudinal airspeed controller.

The outer lateral control loops are as follows:

- Pitch from Altitude: This loop generates a commanded pitch angle from the altitude error. The output of this loop connects directly to the Elevator from Pitch loop. This loop is ideal for controlling the aircraft's altitude when the altitude error is small. For large altitude errors, the

Pitch from Airspeed loop should be used. This loop is shown in Figure 3.14.

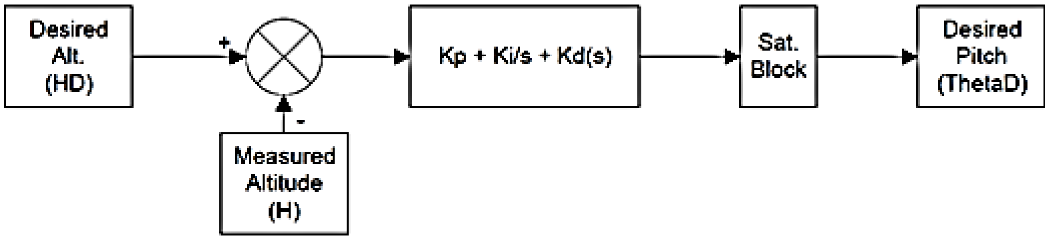

Figure 3.14: Outer longitudinal altitude controller.

3.12 Control Algorithm:

There are two algorithms on the autopilot. The first is the Altitude Tracker. The purpose of the altitude tracker is to enable the correct PID loops to maintain the commanded altitude in an efficient manner. The second control algorithm is the Waypoint Navigation script. The Waypoint Navigation script executes the set of navigation commands uploaded to the autopilot by the user.

3.11.1 Altitude Tracker:

The purpose of the Altitude Tracker is to maintain the aircraft's commanded altitude in an efficient and safe manner. At the heart of the Altitude Tracker are the Throttle from Airspeed and Pitch from Altitude PID loops. When the aircraft is near its commanded altitude, the aircraft's altitude can be controlled easily with small changes in pitch. The altitude error is small in this region; therefore, the commanded pitch angles will also be small and within the maximum angle of attack of the airframe. However, if altitude error is large, the Pitch from Altitude loop will saturate and possibly produce a pitch angle that exceeds the maximum angle of attack of the airframe. A stall will result.

The Throttle from Airspeed loop may also have difficulty maintaining airspeed at these high pitch angles, depending on the thrust available from the motor. In the case where the commanded altitude is significantly below the actual altitude, the Pitch from Altitude loop will command a large negative pitch which may cause the aircraft to exceed its maximum structural airspeed of the airframe.

The solution to these problems is to reconfigure the PID loops based on the altitude error. This is a technique used in general aviation aircraft. When the altitude error is large, the aircraft pitch is trimmed for a safe and efficient climb or descent air speed and the throttle is used to control the rate of climb or descend. In the case of a large positive altitude error, the autopilot is configured to use the Pitch from Air speed PID loop, which regulates the airspeed using pitch. The throttle is set to full for maximum climb performance. As the airspeed is regulated, the aircraft will never enter as tall situation. Once the altitude error is reduced to a set threshold, the Pitch from Altitude and Throttle from Airspeed loops are re-enabled and the Pitch from Air speed loop is disabled. In the case of a large negative altitude error, the same technique is used to lower the aircraft at a constant airspeed to the desired altitude. The throttle is held atidle and the aircraft is allowed to descend at a safe airspeed.

3.12.2 Waypoints Navigation:

The Waypoint Navigation script executes a set of navigation commands uploaded to the autopilot by the user. Its purpose is to navigate the airplane based on the specific command being executed. There are 8 different waypoint commands that can be executed. The Waypoint Navigation script uses the low-level control algorithms to navigate the airplane. It does this either by commanding heading, altitude, and velocity or by commanding roll angle, altitude, and velocity. The method used is determined automatically by the waypoint command being executed. Waypoints are executed sequentially in the order they are uploaded by the user. When the autopilot finishes the last command, it will re-execute the first command.

Waypoint Types:

1. Goto XY: The Goto XY waypoint command is used to navigate to a position specified in meters east and meters north of the GPS Home Position.

2. Goto Legal: The Goto Legal waypoint command is used to navigate to a position specified in degrees longitude and latitude.

3. Loiter XY: The Loiter XY waypoint command executes an orbit around a position specified in meters east and meters north of the GPS Home Position for a specified period of time.

4. *Land XY*: The *Land XY* waypoint command executes a landing sequence around a position specified in meters east and meters north of the GPS Home Position.

The landing sequence orbits the aircraft around the landing position while holding airspeed. The autopilot then cuts throttle and allows the aircraft to descend in the orbit while regulating the airspeed using the

Pitch from Airspeed PID loop. When the aircraft descends to the altitude specified by the Flair Height, the autopilot attempts to level the aircraft by commanding a zero roll angle to the Aileron from Roll PID loop. If the flair height is set to zero, the autopilot will not attempt to flair the aircraft.

5. Take Off: The Take Off waypoint command executes a take-off sequence at the current GPS position. The take-off sequence commands the aircraft to hold a constant pitch (specified in the parameter Take Off Pitch) while using the Aileron from Roll PID loop to hold a 0 degree roll angle. The autopilot commands full throttle. Once the aircraft reaches the airspeed specified in the rotate airspeed input field, the autopilot enables the Altitude Tracker and commands an orbit at the current GPS location with the orbit radius specified in the orbit radius input field. If the aircraft does not achieve the rotate velocity within the period of time specified in the parameter Take Off Rotate Time Out, the take-off sequence is aborted and the autopilot commands 0 throttle in an attempt to land the aircraft. If the aircraft reaches the altitude specified in the altitude input field, the Take Off Command is finished, and the Waypoint Navigation script executes the next waypoint command.

6. Repeat: The Repeat waypoint command causes the Waypoint Navigation script to execute the waypoint command specified in the waypoint number input field. This command is used to repeatedly fly sequences of waypoints.