3.2.3 Compass Calibration

Is Magnetic sensors employ resistance that changes with the magnetic field's strength or direction. Non-contact rotation or position detection is possible when used in combination with a magnet. There are two distinct error categories for magnetic sensors. The instrumentation errors are categorized under the first heading. The sensor offsets, the scale factor, and the sensor axes' non-orthogonality are all included. The fabricator's restrictions are the cause of these sensor errors. a magnetic divergence produced by host platform hardware onboard falls under the second category, which is dependent only by the kind of magnetometer. Sensor's magnetometer tri-axis sensor, and instrumentation errors can be regarded as constants [80-81] and [83-85]. The compass has been used for determining direction for many years and is still widely used in all aspects of daily life. The issue of compass calibration has been the subject of numerous studies. Astronomer Nathaniel Bowditch published a Dedicated Guide to Sky Navigation [86], which includes a swinging calibration technique that requires the device to be levelled and rotated in a series of known declinations. [83] By utilizing the maximum and minimum values of the measurements obtained during the sensor's rotation in the horizontal plane, it was possible to accurately predict the scale factors and compass biases. Although this method is practical, it ignores some sensor errors. A more comprehensive strategy has been treated in [84]. As the sensor total, an Least Squares (LS) iterative batch algorithm figures out a scale factors and deviation of the sensor. Where the initial conditions are given by a LS nonlinear two step. This method is assigned to those sensors that sense a constant linear field. The assumptions behind this calibration's limitations are that misalignments can be ignored and that measurements on the sensor's axis that are parallel to the induced magnetic field are the only ones that are negatively impacted by the soft iron. An iterative Maximum Likelihood Estimator-based geometric method is used in [85]. MLE stands for magnetometer measurement ellipsoidal manifold. The misalignment matrix is computed by an additional closed-form optimal algorithm.

3.2.3.1 Magnetometer Errors model and Calibration Process

Magnetic sensors employ resistance that changes with the magnetic field's strength or direction. Non-contact rotation or position detection is possible when used in combination with a magnet. There are two distinct error categories for magnetic sensors. The instrumentation errors are categorized under the first heading. The sensor offsets, the scale factor, and the sensor axes' non-orthogonality are all included. The fabricator's restrictions are the cause of these sensor errors. A magnetic divergence produced by host platform hardware onboard falls under the second category, which is dependent only by the kind of magnetometer sensors. Magnetometer tri-axis sensor, and instrumentation errors can be regarded as constants.

The following can be thought of as the error model for magnetometers:

Complete Error Modeling

$$\widehat{\mathbf{H}} = \mathbf{SM}(\mathbf{A}_s\mathbf{h} + \mathbf{b}_\mathrm{h}) + \mathbf{b}_s + \varepsilon \tag{3.6}$$

Become:

$$\widehat{\mathbf{H}} = \mathbf{Ah} + \mathbf{b} + \boldsymbol{E} \tag{3.7}$$

$\mathbf{A} = \mathrm{S\,M\,A_s}$ Soft iron $\mathrm{A_s}$ and non-orthogonality matrix M and scale factor matrix S.
$\mathbf{b} = \mathrm{S\,M\,b_h} + \mathrm{b_s}$ is a combined biases includes Hard Iron $\mathrm{b_h}$ and the sensor offset $\mathrm{b_s}$
$\mathbf{S} = \mathrm{diag}(s_x \quad s_y \quad s_z)$ is scale factor matrix, $(s_x \quad s_y \quad s_z)$ are ratio constants of between input and output.

$\mathbf{M} = \mathrm{N}^{-1} = [e_x \quad e_y \quad e_z]^{-1}$, M matrix utilized to rectify the effects of non-orthogonality, such as misalignment errors, and $e_x \quad e_y \quad e_z$ are misalignment errors provide the sensor direction of such x, y, and z axis. N is a matrix in which the orientation of each sensor axis is indicated by N column vectors.

Where $\mathrm{h}^\mathrm{T} = [h_x \quad h_y \quad h_z]$ is the sensor magnetic field error-free. $\widehat{\mathrm{H}}^\mathrm{T} = [\widehat{\mathrm{H}}_x \quad \widehat{\mathrm{H}}_y \quad \widehat{\mathrm{H}}_z]$ Are the magnetometers, sensor reading. Misalignments, soft iron errors, and the scale factors, are all combined in matrix A (3x3). the bias when combined b is the total sensor bias. E represents Gaussian white noise.

S is matrix of scale factors or the factor of relationship between the input and the output. M is for no orthogonality error. Where N is a matrix in which each axis in the magnetometer sensor is indicated by a column vector. Non-orthogonality, which includes misalignment errors, can be represented by using the inverse of N. The e_x , e_y and e_z are the no orthogonality error vectors of (3x1) that respectively provides the directions for the sensor with respect to the x, y, and z axes.

Bias, even when there is no movement, there is often a slight offset in the signal output represented by the term "bias b_s".$b_s = [b_{sx} \quad b_{sy} \quad b_{sz}]^{\mathrm{T}}$

Hard Iron, b_h It is a bias caused by permanent magnets or the magnetization of iron materials that are already magnetized. $b_h = [b_{hx} \quad b_{hy} \quad b_{hz}]^{\mathrm{T}}$

Soft iron, ferromagnetic materials interact with an external field to produce magnetism b_s, This modifies both the intensity and direction of the sensed field. The soft iron effect can be represented as matrix A_s which is (3x3) [87].

$$\mathrm{A_s} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{32} & a_{33} \end{bmatrix}$$

In an environment devoid of perturbations, the standard deviation of the magnetometer's vector measurement should match the Earth's magnetic field. Rotating the sensor in space should result in the description of a sphere with a radius equivalent to the Earth's magnetic field [87][84].

The next equation constrains the readings of an ideal magnetometer in surroundings devoid of perturbations:

$$\boldsymbol{H_m^2} - \| \mathbf{h} \|^2 = \boldsymbol{H_m^2} - \mathbf{h}^{\boldsymbol{T}}\mathbf{h} = \mathbf{0} \tag{3.8}$$

Where H_{m} geomagnetic field mode of the international Geomagnetic Reference Field (IGRF) provided by the International Association of Geomagnetism and Aeronomy (IAGA) [88].

By rewriting equation 3.6 to be

$$\mathbf{h} = \mathbf{A}^{-1}(\hat{\mathbf{h}} - \mathbf{b} - \boldsymbol{\varepsilon}). \tag{3.9}$$

Substituting h in equation 3.9 in 3.6 to get

$$(\hat{\mathbf{h}} - \mathbf{b})^{\mathrm{T}}(\mathbf{A}^{-1})^{\mathrm{T}}\mathbf{A}^{-1}(\hat{\mathbf{h}} - \mathbf{b}) - H_m^2 = 0. \tag{3.10}$$

suppose $\mathbf{Q} = (\mathbf{A}^{-1})^{\mathrm{T}}\mathbf{A}^{-1}$, (3.11)

then equation 3.10 become

$$(\hat{\mathbf{h}} - \mathbf{b})^{\mathrm{T}}\mathbf{Q}(\hat{\mathbf{h}} - \mathbf{b}) = H_m^2 \tag{2.12}$$

Re-writing equation 3.12 to be

$$\hat{\mathbf{h}}^T\mathbf{Q}\hat{\mathbf{h}} + (-2\mathbf{Q}^{\mathrm{T}}\mathbf{b})^T\hat{\mathbf{h}} + \mathbf{b}^{\mathrm{T}}\mathbf{Q}\mathbf{b} - H_m^2 = 0 \tag{3.13}$$

Suppose $\mathbf{u} = -2\mathbf{Q}^{\mathrm{T}}\mathbf{b}$ and $k = \mathbf{b}^{\mathrm{T}}\mathbf{Q}\mathbf{b} - H_m^2$. Then equation 3.13 become

$$\hat{\mathbf{h}}^T\mathbf{Q}\hat{\mathbf{h}} + \mathbf{u}^T\hat{\mathbf{h}} + \boldsymbol{k} = \mathbf{0} \tag{3.14}$$

Since the magnetic field of the Earth is positive, consequently, the general formula of an ellipsoid is in equation 3.14, [89] the calibration process is the estimation of unknown parameters in equation 3.14. Along numerous orientations that best characterize the ellipsoid, it is feasible to calibrate magnetometers using the restriction on the norm of the field vector equation 3.14.

The calibration algorithm in this paper is inspired by the work in [87] and consists of main two steps. Where in the initial step involves locating the parameters “u" and "k” by finding of "b" and "Q" of the equation 3.14 which a fitting problem involving the fitting of an ellipsoid to a magnetic field measurement collected in random paths or along different orientations. The last step is the calibration of "b" and "A".

Numerous approaches have been devised. By using the least squares method, algebraic fitting techniques attempt to solve optimization issues. In this study, however, the calibration method employs an adaptive least squares estimation to resolve the ellipsoid-fitting issue, which manages the measurements' excessive noise, the details of the used calibration process are in [87].

5.4.2 Compass Calibration Results

The results of calibration in Figure 5.39 after and before calibration, demonstrate a considerable improvement in orientation accuracy. exhibits the readings of the calibrated HMC5883l magnetometer. As expected after calibration, the combined bias "A" and scale factors "b", soft-iron, and misalignments have been accurately predicted on the sphere manifold whose radius matches the local Earth's magnetic field norm. As expected, the combined bias is a bit high, and this is because the magnetometer used in this experiment is located close to some metal screws and bolts and some rods used to fix the quadrotor body, which affected the magnetometer reading by introducing "larger variations in the magnetic field and due to metal magnetization currents, causing a hard iron effect in the local magnetic field" [72].

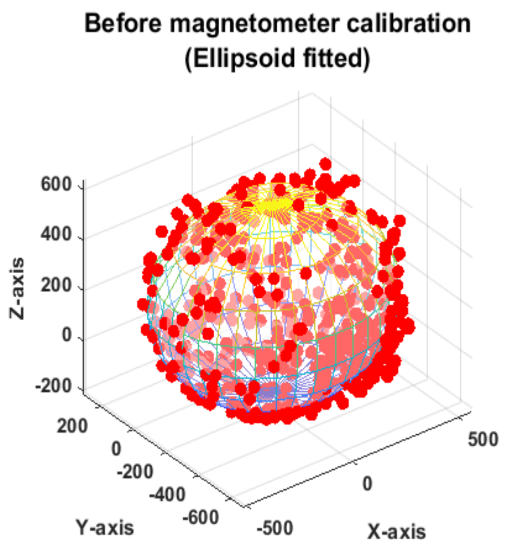

Figure 5.39: HMC5883l Magnetometer-calibrated measurements were plotted on the sphere manifold with normalized radius after calibration.

$$A = \begin{pmatrix} 0.0020 & 0 & 0 \\ 0 & 0.0020 & 0.0003 \\ 0 & 0.0003 & 0.0020 \end{pmatrix} \text{(n.u.)}. \quad \text{Combined bias} \quad b = \begin{pmatrix} -84.4699 \\ -37.8363 \\ -7.3886 \end{pmatrix} (\mu \text{ Tesla})$$

The results of the compass calibration indicate a marked improvement in orientation accuracy after determining the SEM parameters, including combined bias and scale factors, for the HMC5883l magnetometer.