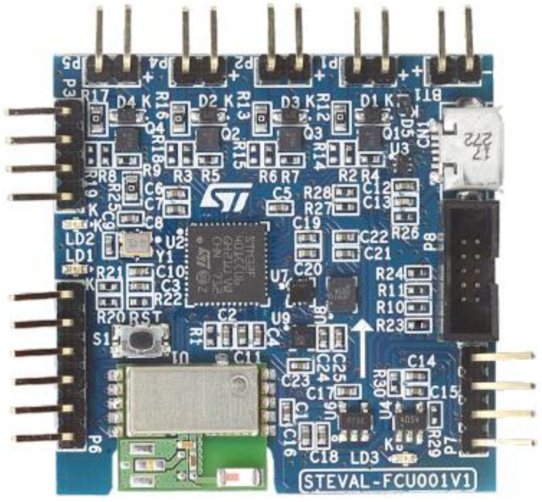
Embedded systems with drones – Hands-on lecture 4

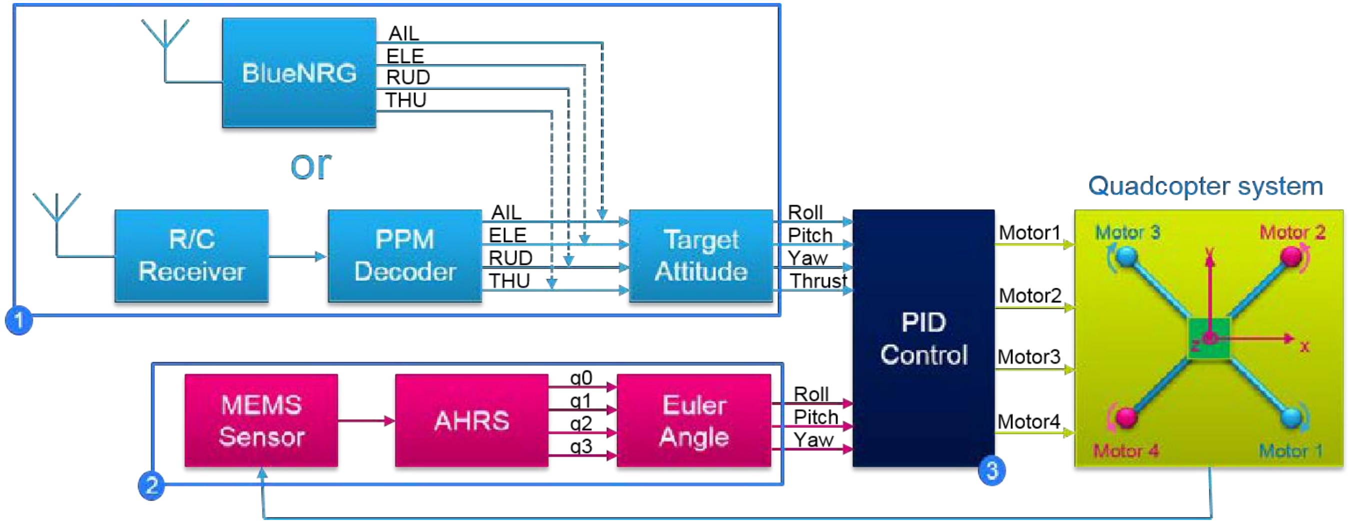
Project-based Learning Center | ETH Zurich
Michele Magno michele.magno@pbl.ee.ethz.ch
Tommso Polonelli tommaso.polonelli@pbl.ee.ethz.ch
Vlad Niculescu vladn@iis.ee.ethz.ch

STEVAL – State Estimator

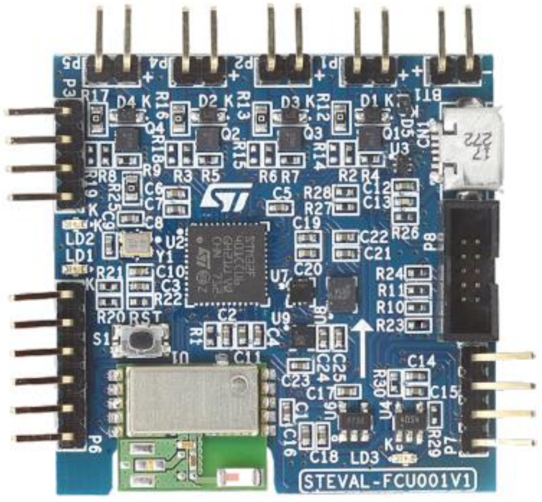


Exercise goals

- Understand how the estimator (Mahony filter) of the STEVAL's firmware works
- Understanding how the orientation of an object can be mathematically represented and calculated using accelerometer and gyroscope data
- Understand the differences between this estimator and the EKF

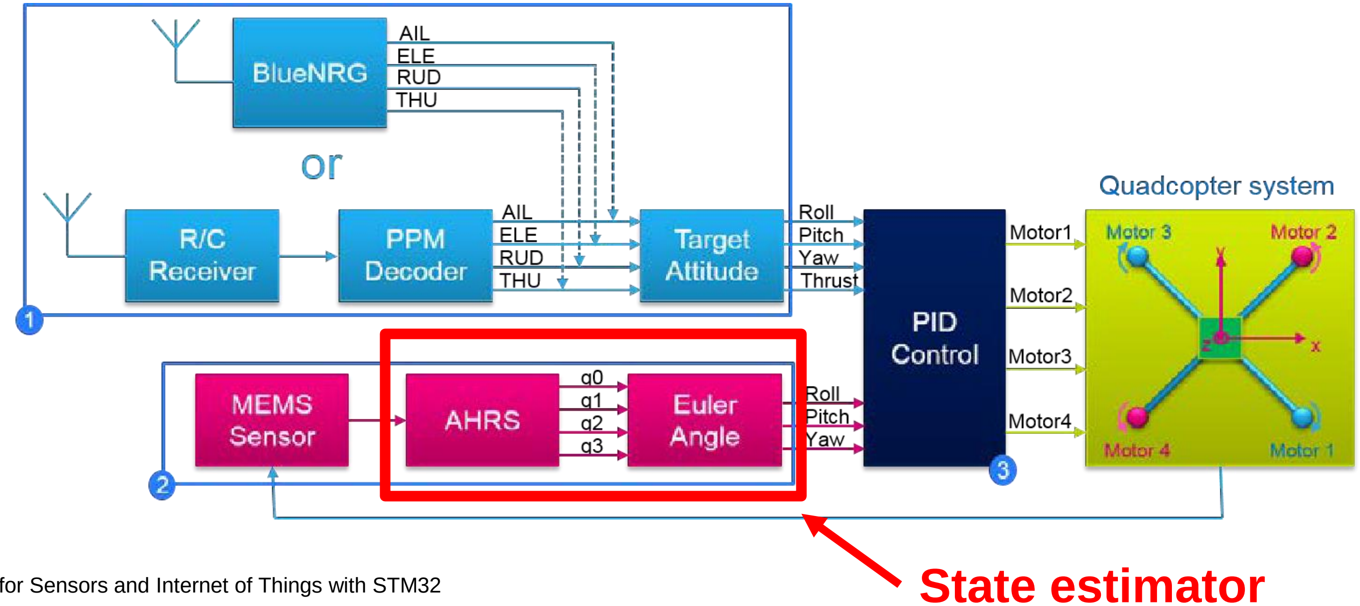


STEVAL – State Estimator



Exercise goals

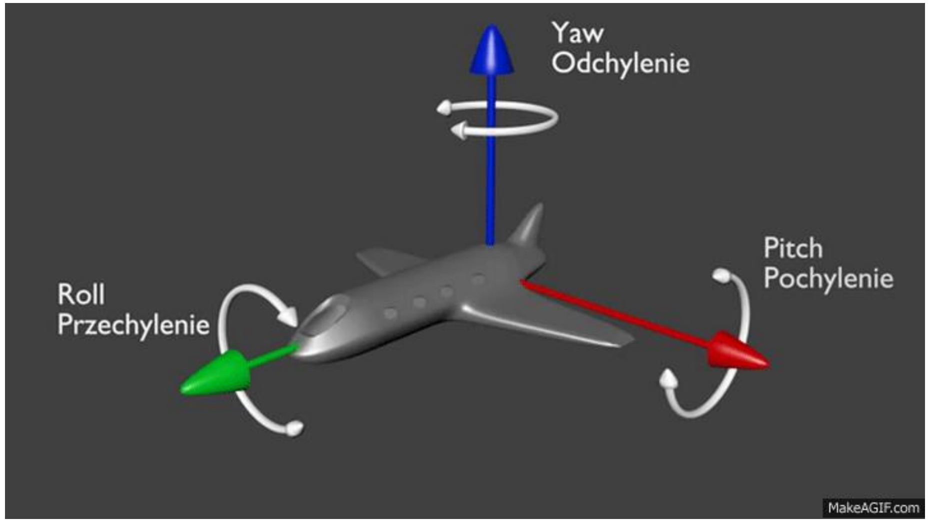
- Understand how the estimator (Mahony filter) of the STEVAL's firmware works
- Understanding how the orientation of an object can be mathematically represented and calculated using accelerometer and gyroscope data
- Understand the differences between this estimator and the EKF



Attitude Representation

STEVAL's firmware only implements an attitude estimator
System state:

$$\boldsymbol{x} = \begin{pmatrix} \Phi \\ \theta \\ \psi \end{pmatrix} \quad \begin{matrix} \text{Yaw} \\ \text{Pitch} \\ \text{Roll} \end{matrix}$$

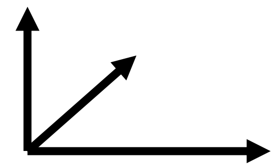


- The representation used by the AHRS module is the Euler angle system.
- They are a series of three angles (ψ, θ, Φ) representing rotation around three axes, in sequence.
- A variety of Euler angle systems exist, the difference being the rotations order
- Our system rotates first about the z axis by the angle ψ, about the y axis by θ, and about the x axis by Φ.

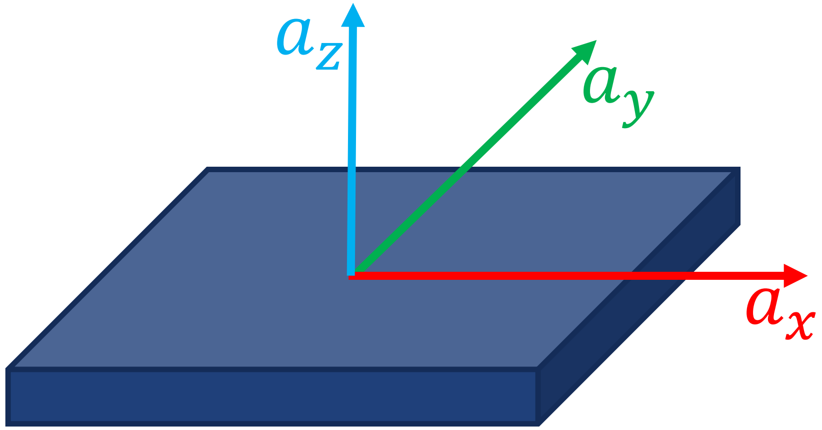
Sensor Output

STEVAL uses Accelerometer and Gyroscope for attitude estimation.

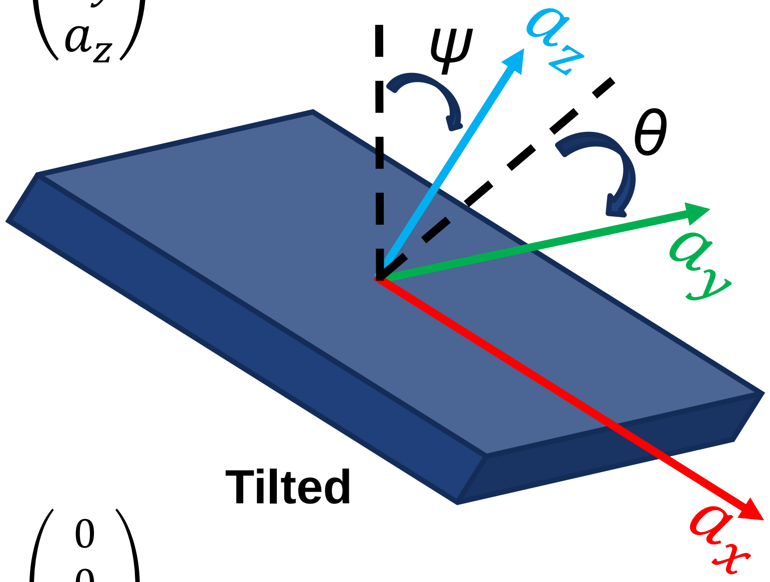
Accelerometer: provides the 3D acceleration vector *in the body frame* $\begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix}$



Earth frame



Aligned



Tilted

- When stationary and aligned to the earth frame, the accelerometer's output is $\begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix}$
- Knowing the acceleration at *Φ=θ=0*, by geometry we calculate roll (*Φ*) and pitch (*θ*) from the misalignment with the gravity

$$\theta = \tan^{-1} \frac{-a_x}{\sqrt{a_y^2 + a_z^2}} \qquad \psi = \tan^{-1} \frac{a_y}{a_z}$$

Sensor Output

STEVAL uses Accelerometer and Gyroscope for attitude estimation.

Gyroscope: provides the 3D angular velocity vector *in the body frame* $\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix}$

Euler angles are obtained by integration

$$\begin{pmatrix} \Phi \\ \theta \\ \psi \end{pmatrix} \leftarrow \begin{pmatrix} \Phi + \Delta_t \cdot \omega_x \\ \theta + \Delta_t \cdot \omega_y \\ \psi + \Delta_t \cdot \omega_z \end{pmatrix}$$

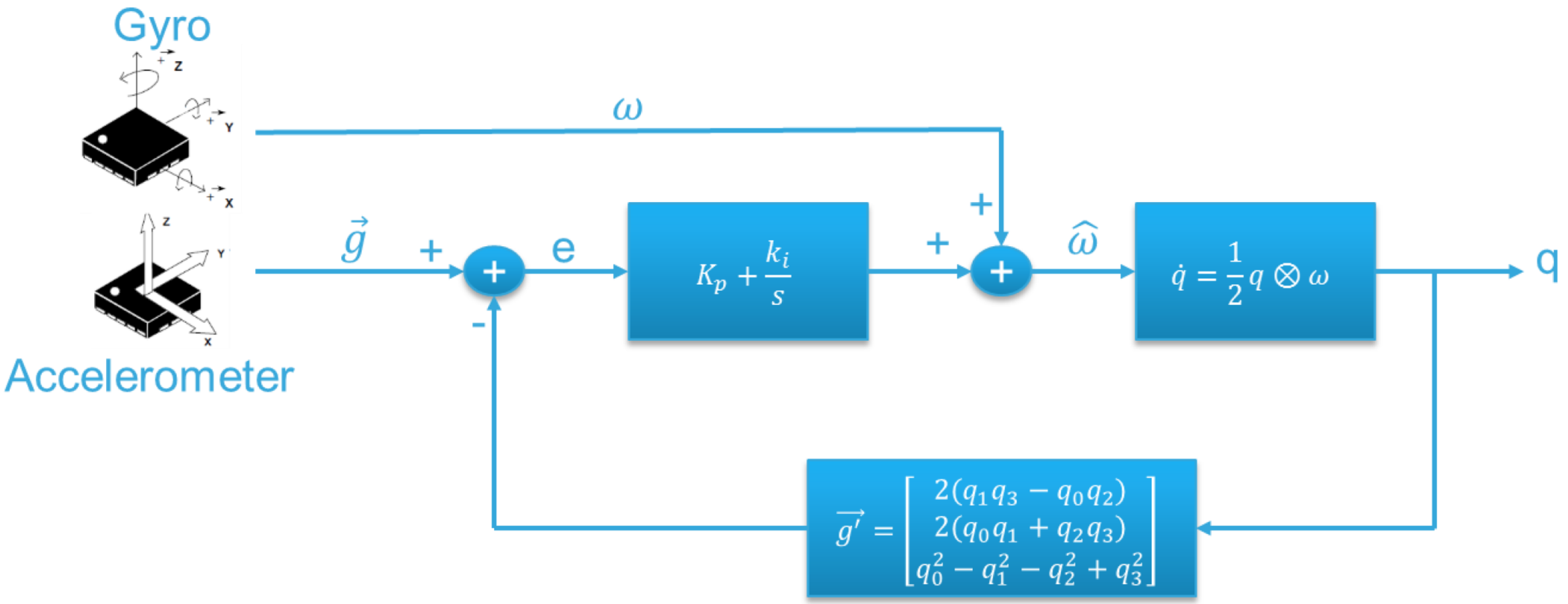
Accelerometer $\left\{ \begin{array}{l} \text{Roll} \\ \text{Pitch} \end{array} \right.$

Magnetometer $\left\{ \text{Yaw} \right.$

Gyroscope $\left\{ \begin{array}{l} \text{Roll (derivative)} \\ \text{Pitch (derivative)} \\ \text{Yaw (derivative)} \end{array} \right.$

Sensor Output

- STEVAL does not use EKF because it has higher complexity
- It uses a more lightweight state estimator, called Mahony filter



- Accelerometer is always influenced by high-frequency noise, and gyroscope has a low-frequency offset.
- Gyroscope results are accurate in short-term, but generate an offset over time.
- Accelerometer is not accurate in short-term because of noise, but is reliable over time.

Evaluation board – STEVAL-FCU001V1

$$\begin{matrix} \boldsymbol{a(k)} \\ \boldsymbol{g(k)} \end{matrix} \rightarrow \boxed{\text{AHRS}} \rightarrow \boldsymbol{\hat{q}\,(k)} \rightarrow \boldsymbol{\hat{x}\,(k)}$$

Quaternion vector | Euler angles vector

Raw data from accelerometer and gyro

$$\boldsymbol{a(k)} = \begin{pmatrix} a_x(k) \\ a_y(k) \\ a_z(k) \end{pmatrix} \quad \boldsymbol{g(k)} = \begin{pmatrix} g_x(k) \\ g_y(k) \\ g_z(k) \end{pmatrix}$$

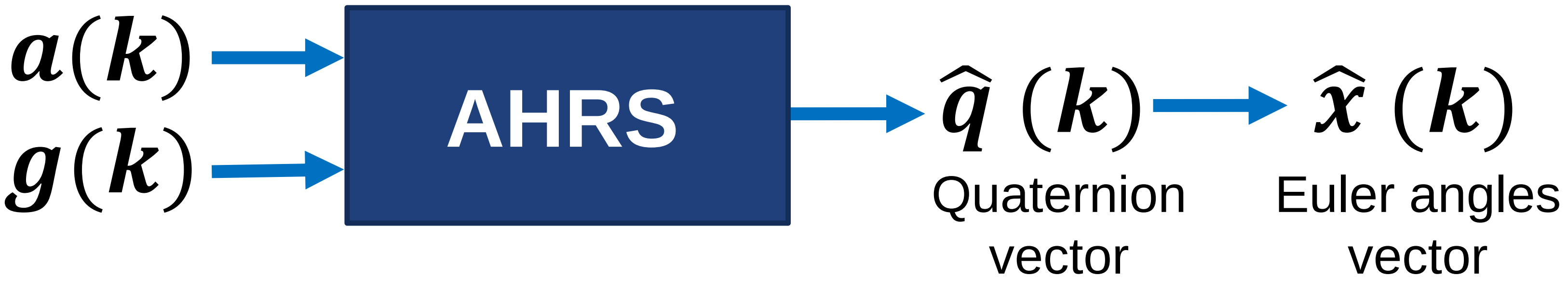
Quaternion estimate

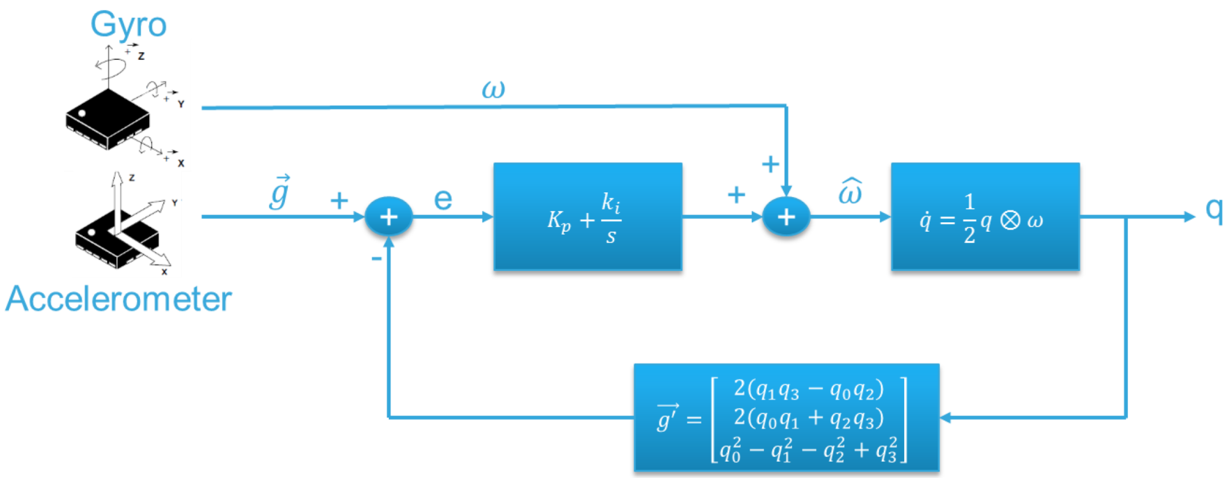
$$\boldsymbol{\hat{q}\,(k)} = \begin{pmatrix} q_x(k) \\ q_y(k) \\ q_z(k) \\ q_w(k) \end{pmatrix}$$

Algorithm steps (Mahony Filter)**:**

1. Collect $\boldsymbol{a(k)},\ \boldsymbol{g(k)}$
2. Estimate gravity vector $\boldsymbol{G}$ from $\boldsymbol{\hat{q}\,(k-1)}$
3. Calculate error vector $\boldsymbol{e} = G \times \boldsymbol{a(k)}$
4. $\boldsymbol{e_{INT}} = \boldsymbol{e_{INT}} + \boldsymbol{k_I} \cdot \boldsymbol{e} \cdot \Delta_{\boldsymbol{t}}$
5. $\boldsymbol{g^*(k)} \leftarrow \boldsymbol{g(k)} + \boldsymbol{k_P} \cdot \boldsymbol{e} + \boldsymbol{e_{INT}}$
6. Update $\boldsymbol{\hat{q}\,(k)}$ knowing $\boldsymbol{g^*(k)} \cdot \Delta_{\boldsymbol{t}}$

Evaluation board – STEVAL-FCU001V1

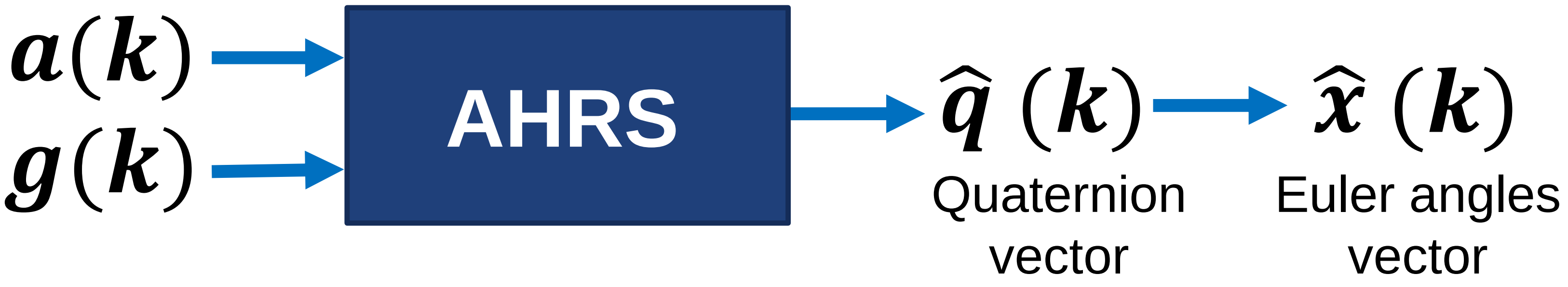




Algorithm steps (Mahony Filter)**:**

1. Collect $\boldsymbol{a}(\boldsymbol{k}),\ \boldsymbol{g}(\boldsymbol{k})$
2. Estimate gravity vector $\boldsymbol{G}$ from $\hat{\boldsymbol{q}}\ (\boldsymbol{k}-\mathbf{1})$
3. Calculate error vector $\boldsymbol{e} = G \times \boldsymbol{a}(\boldsymbol{k})$
4. $\boldsymbol{e_{INT}} = \boldsymbol{e_{INT}} + \boldsymbol{k_I} \cdot \boldsymbol{e} \cdot \Delta_{\boldsymbol{t}}$
5. $\boldsymbol{g}^*(\boldsymbol{k}) \leftarrow \boldsymbol{g}(\boldsymbol{k}) + \boldsymbol{k_P} \cdot \boldsymbol{e} + \boldsymbol{e_{INT}}$
6. Update $\hat{\boldsymbol{q}}\ (\boldsymbol{k})$ knowing $\boldsymbol{g}^*(\boldsymbol{k}) \cdot \Delta_{\boldsymbol{t}}$

Evaluation board – STEVAL-FCU001V1



Algorithm steps (Mahony Filter)**:**

1. Collect $a(k),\ g(k)$
2. Estimate gravity vector G from $\hat{q}\ (k-1)$
3. Calculate error vector $e = G \times a(k)$
4. $e_{INT} = e_{INT} + k_I \cdot e \cdot \Delta_t$
5. $g^*(k) \leftarrow g(k) + k_P \cdot e + e_{INT}$
6. Update $\hat{q}\ (k)$ knowing $g^*(k) \cdot \Delta_t$

Algorithm steps (EKF)**:**

1. Collect $a(k),\ g(k)$
2. Prediction step:

   $\hat{q}_p(k)$ from $\hat{q}_m(k-1)$ and $g(k) \cdot \Delta_t$
3. Update step:

   $\hat{q}_m(k)$ from $\hat{q}_p(k)$ and $a(k)$

Project proposal

Student Project:

Implement an alternative version for the drone based on the EKF:

- you will have to implement the 3-state attitude estimator
- compare the performance with the existing Mahoney filter

LAB4: Exercise overview

Template can be found in your Polybox folder LAB4

Exercise	Assignment	Concept
Exercise 1	In the file *main.c*, identify the functions that update the quaternion and convert it to Euler angles.	Understanding the code
Exercise 2	In the same file, print the Euler angles in the serial console right after they are updated.	AHRS, State estimator
Exercise 3	Analyze the implementation of the attitude estimator in *ahrs.c* and identify the code associated to each step of the algorithm in Slide 8.	Understanding the code
Exercise 4	Modify the variable AHRS_KI found in *ahrs.h* to 1.0f. What do you observe in the printed attitude?	AHRS, State estimator
Exercise 5	Comment out the correction steps (2-5 in Slide 8) of the gyroscope data. What do you observe? Hint: you can simply replace $\boldsymbol{g}^*(\boldsymbol{k})$ with $\boldsymbol{g}(\boldsymbol{k})$ in Step 6.	AHRS, State estimator

LAB4: Exercise overview

Template can be found in your Polybox folder LAB4

Exercise	Assignment	Concept
Exercise 6 (advanced)	Evaluate the computation time and the number of cycles necessary to run one iteration of the AHRS.	
Exercise 7 (advanced)	Use the print procedure learned in the LAB3 to log the output of the AHRS over time.	
Exercise 8 (advanced)	Log the roll and pitch as in Lab 3 and compare the results with the ones provided by the AHRS. What do you observe?	
Exercise 9 (advanced)	Using Python, plot the information acquired before (roll and pitch) on the same plot for a better visualization.	

Hint: Getting the elapsed number of cycles

```
// Defining the counter register address. Add this in the beginning of the main.c

#define  ARM_CM_DEMCR      (*(uint32_t *)0xE000EDFC)
#define  ARM_CM_DWT_CTRL   (*(uint32_t *)0xE0001000)
#define  ARM_CM_DWT_CYCCNT (*(uint32_t *)0xE0001004)
```

```
// Enable the counter. Add this in the main() function before the "while" loop

if (ARM_CM_DWT_CTRL != 0) {        // See if DWT is available
    ARM_CM_DEMCR      |= 1 << 24;  // Set bit 24
    ARM_CM_DWT_CYCCNT  = 0;
    ARM_CM_DWT_CTRL   |= 1 << 0;   // Set bit 0   }
```

```
// Count the number of cycles

ARM_CM_DWT_CYCCNT = 0;
t1 = ARM_CM_DWT_CYCCNT;
run_your_function();
t2 = ARM_CM_DWT_CYCCNT;
delta = t2 – t1;
```