Chapter 1

Demonstration setup introduction

This chapter will serve as an explanation and a user manual for the demonstration setup. The demonstration setup consists of a wooden setup, a quadcopter, and a software. The tutorial has three parts:

1. Digital signal processing: manipulation of the signal with filters as to have the best representation of reality.
2. PID regulation: Regulating the P, I and D values to have a quadcopter that flies in a stable manner.
3. Making the quadcopter fly a small trajectory in the x, y, and z-axis autonomously, where the displacement inputs come from the software. This part of the tutorial takes 2-3 minutes.

1.1 Demonstration setup

Figure 1.1 shows the demonstration setup. It consists of a quadcopter attached with rubber bands to a wooden setup. The quadcopter does not touch the ground as is shown in figure 1.2. The reasons for choosing a rubber band for attachment instead of a hard material, is to limit the vibrations caused by the motors and propellers as much as possible. Note also that only the two unattached motors will be used during the PID testing phase.

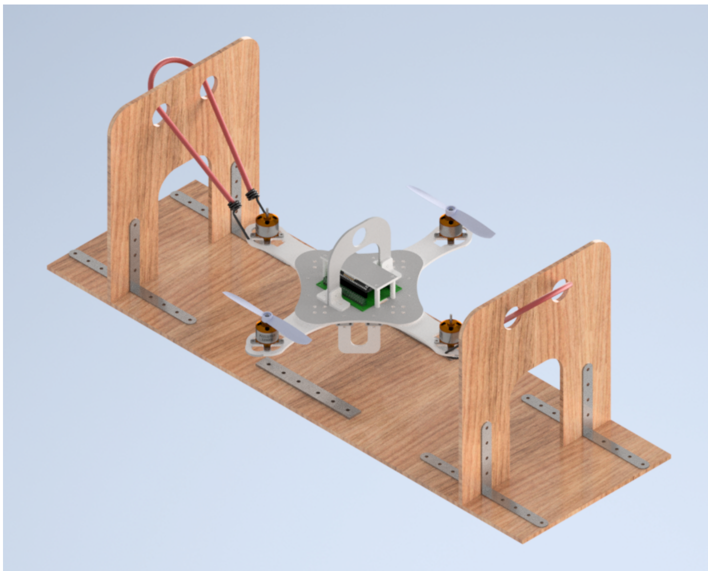

Figure 1.1: Perspective view of the demonstration setup.

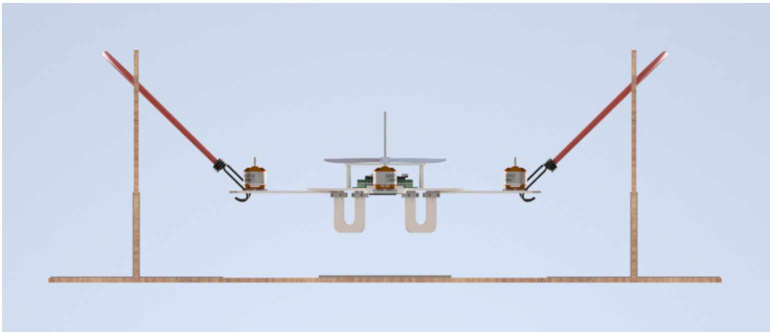

Figure 1.2: Side view of the demonstration setup: the quadcopter is elevated in the air by the band attachments.

1.1.1 Wooden setup parts

The wooden setup consists of two vertical, and two horizontal wooden plates, made of 6mm birch, fixed together with metal assembly brackets.

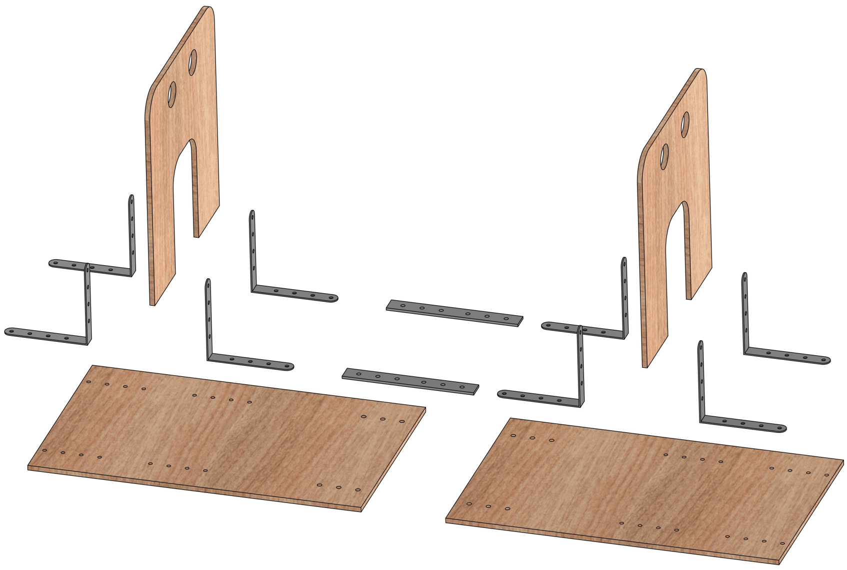

Figure 1.3: Exploded view of the wooden setup.

1.1.2 Quacopter parts

The quadcopter parts are shown in figure 1.4. The quadcopter consists of the following parts and components:

1. main microcontroller: ESP32 (1x)
2. IMU sensor (accelerometer + gyroscope): MPU6050 (1x)
3. Terminal adapter for ESP32 (1x)
4. Main base plate (1x)
5. Arm (4x)
6. Brushless motor: A2212/13T 2200KV (4x)
7. Propeller: double blade 6040 (4x)
8. Motor fixator (4x)
9. LiPo carrier (1x)
10. Handhold (1x)
11. ESC: 4-in-1 (1x)

12. Foot (4x)

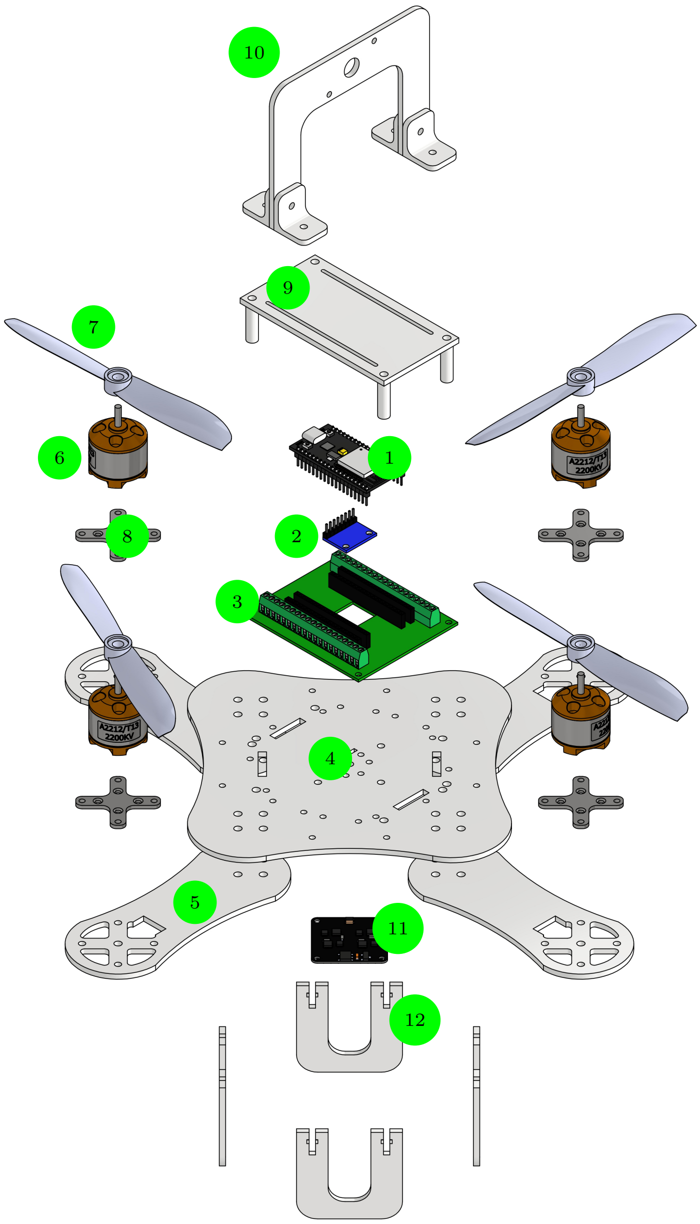

Figure 1.4: Exploded view of the quadcopter with numbered parts.

1.2 User manual for GUI

Along with the physical demonstration setup, there is the software part of the tutorial, i.e., the graphical user interface (GUI). The GUI is made with a virtual machine called "processing IDE", which works on the Java programmin language. The goal of the GUI is signal processing and PID regulation. Following will be a short manual explaining how to use the GUI. A more detailed explanation will be give in section 1.3. The GUI is used with the following steps:

1. Write your name and press 'enter'.

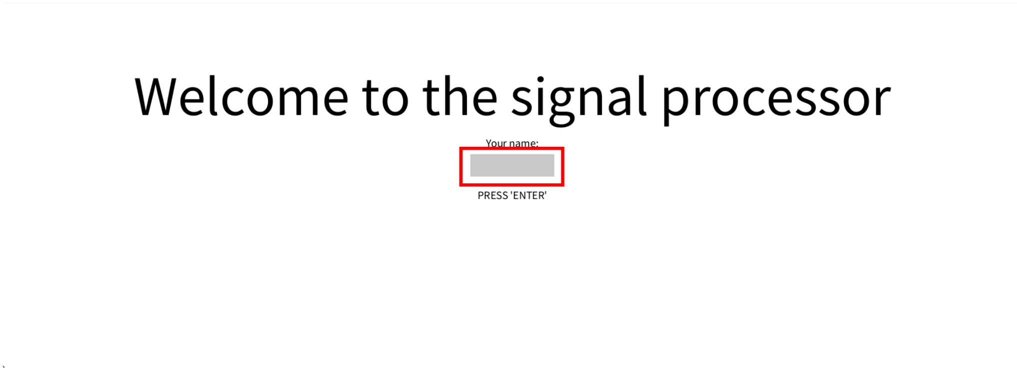

Figure 1.5: Step 1.

2. Your name will appear in the background. Click on the 'COMLIST' button in the upper-left corner.

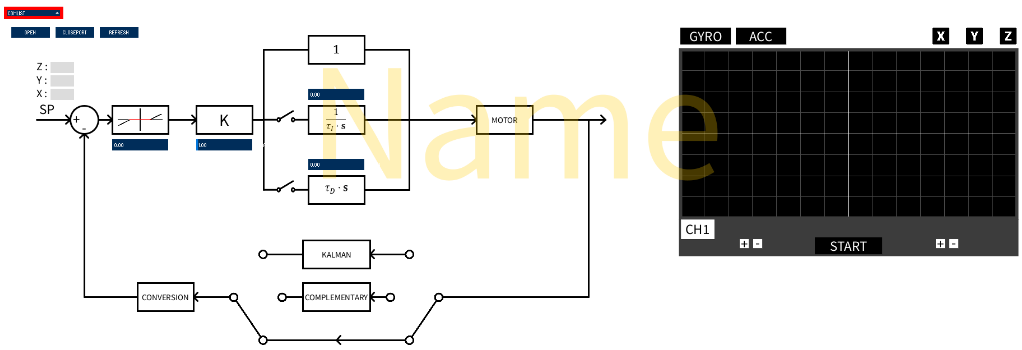

Figure 1.6: Step 2.

3. Look for the appropriate bluetooth COM port and click on it. Then, click on 'OPEN'.

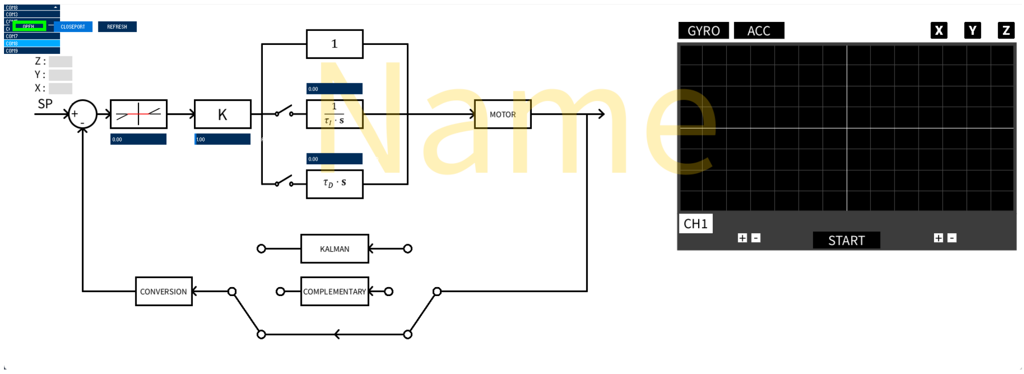

Figure 1.7: Step 3.

4. Click on "GYRO", then on "X", and then on "START".

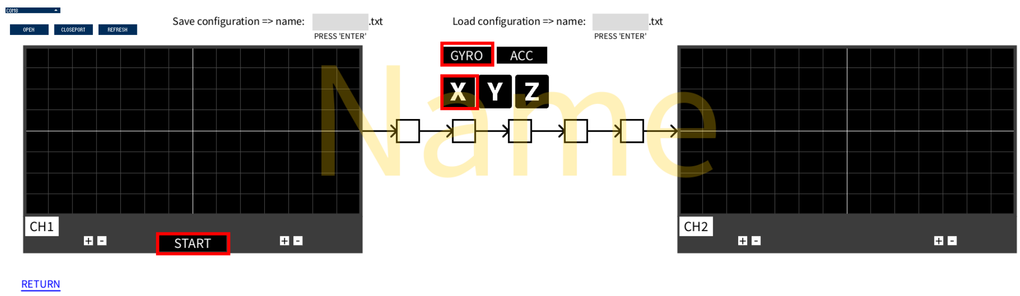

Figure 1.8: Step 4.

5. The x-axis readings of the gyroscope will appear on the left oscilloscope. You can press the +/- buttons beneath "DPS" or "ms" to zoom out/in the signal in the vertical or horizontal direction, respectively.

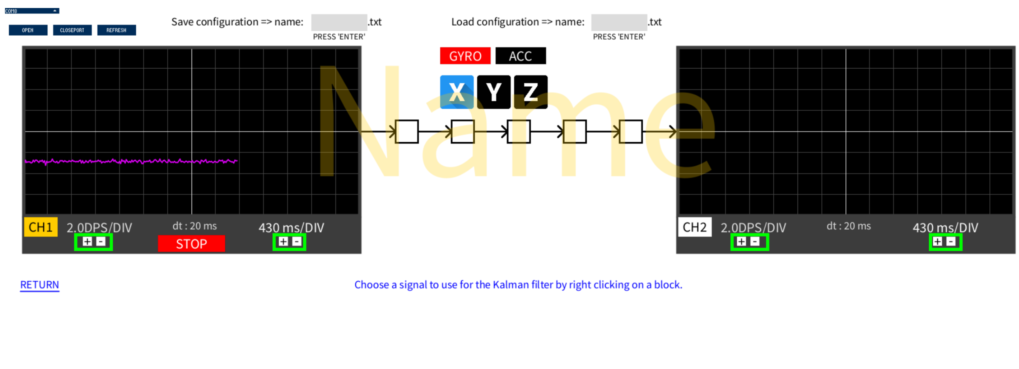

Figure 1.9: Step 5.

6. Click on the first block to the right of the working oscilloscope. The following filters will appear: HP (highpass filter), LP (lowpass filter), BC (bias compensation), INT (integration), DR (derivation), and OP (mathematical operation). Choose one of these, and enter a number, if needed. The HP and LP will ask for a cut-off frequency, BC will ask for a to-be-removed bias, if 'auto' is selected, or the amount of measurements to calculate an average, if 'manual' is selected. INT and DR will not ask any input. OP provides the four basic mathematical operations: $+, -, \times$, and $/$, and will ask a number to enter.

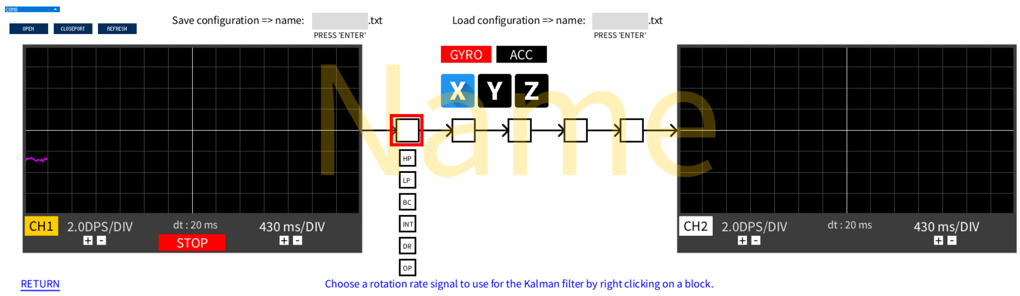

Figure 1.10: Step 6.

7. You can choose up to five filters. Each chosen filter will take the signal manipulated by the previous filter, and will manipulate it in turn. The resulting signal will appear in the right oscilloscope. **Note that the chosen filters and operations will operate on the three axes.**

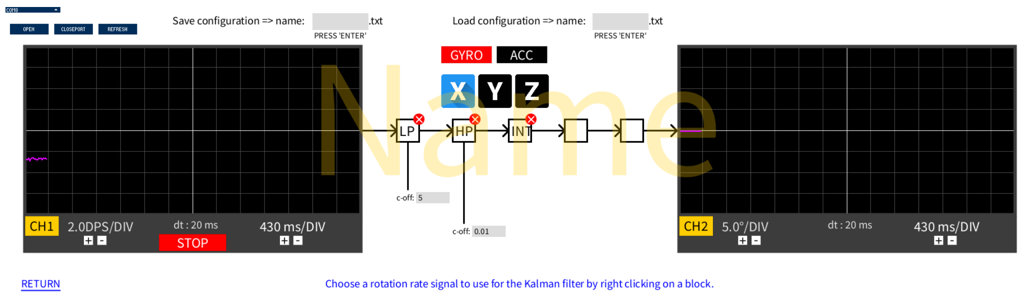

Figure 1.11: Step 7.

8. Choose a rotation rate signal, i.e., an angular velocity signal, by right clicking on the respective block. This signal will be used by the Kalman filter.

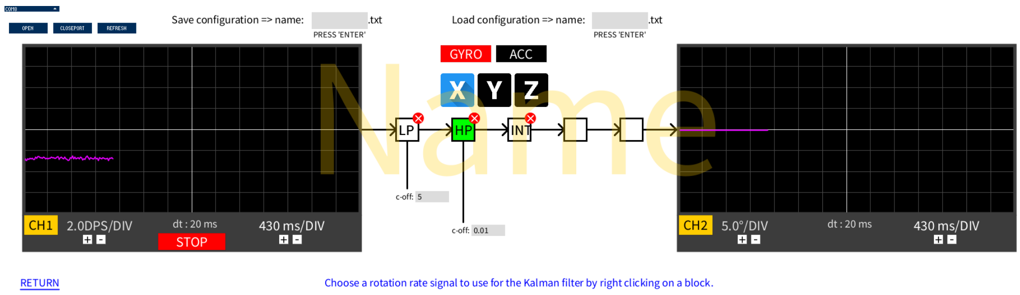

Figure 1.12: Step 8.

9. Now, choose the accelerometer, and manipulate the signal as desired. When dealing with the accelerometer, it is better to choose the z-axis, because it has the highest bias-offset.

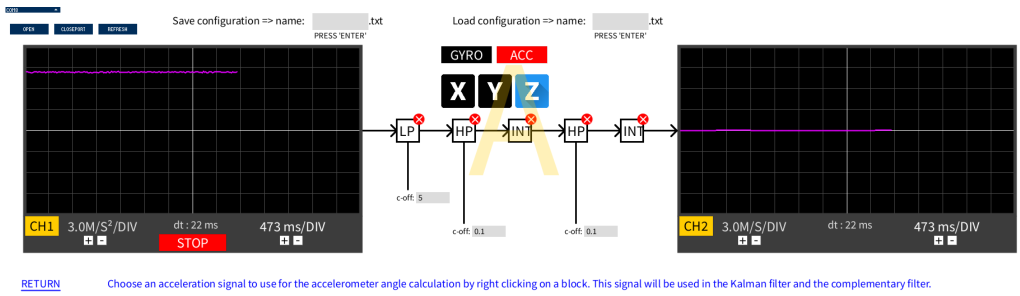

Figure 1.13: Step 9.

10. Choose an acceleration signal to use for the accelerometer angle calculation by right clicking on a block. This signal will be used in the Kalman filter and the complementary filter.

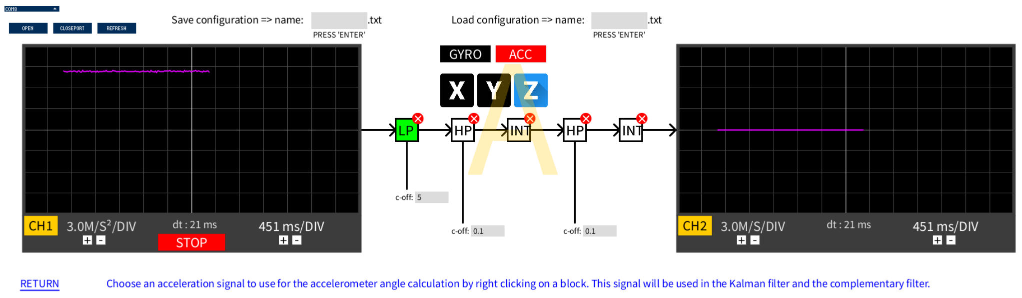

Figure 1.14: Step 10.

11. Click on 'RETURN' to come back to the control system panel.

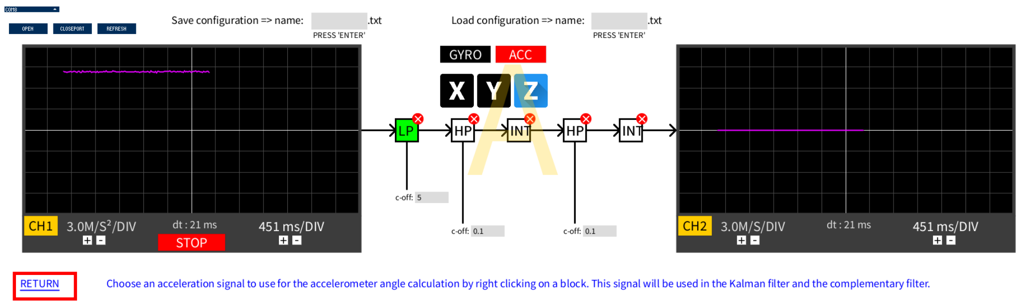

Figure 1.15: Step 11

12. Choose between the Kalman filter, the complementary filter, or none of these. The respective signal will appear on the right oscilloscope.

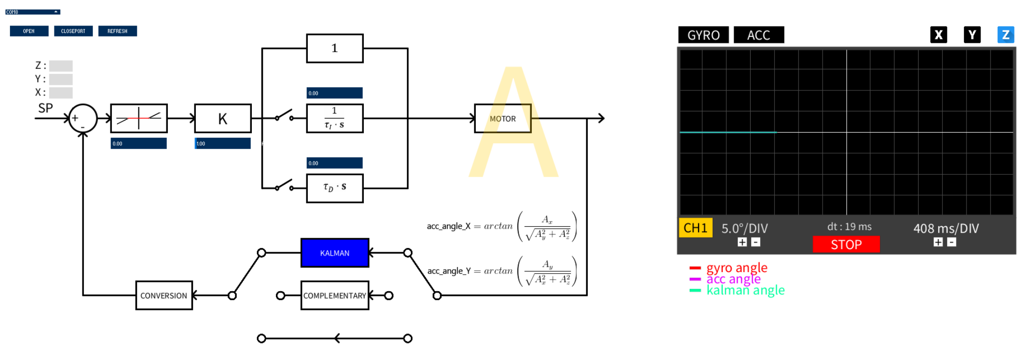

Figure 1.16: Step 12: Kalman filter selected.

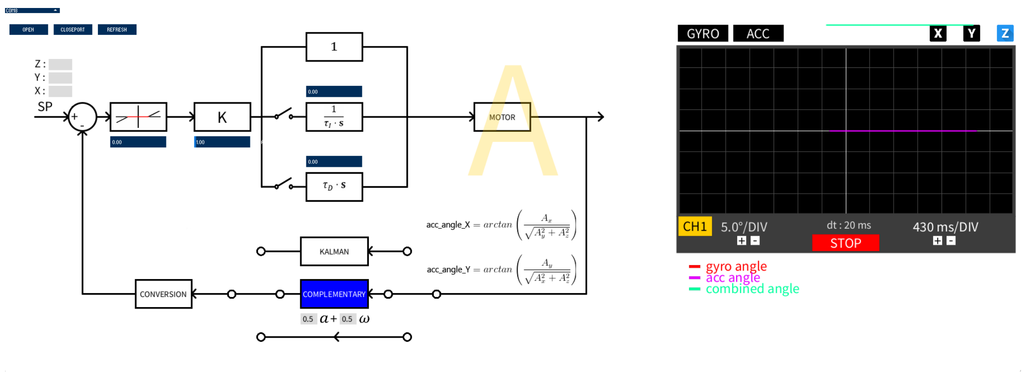

Figure 1.17: Step 12: complementary filter selected.

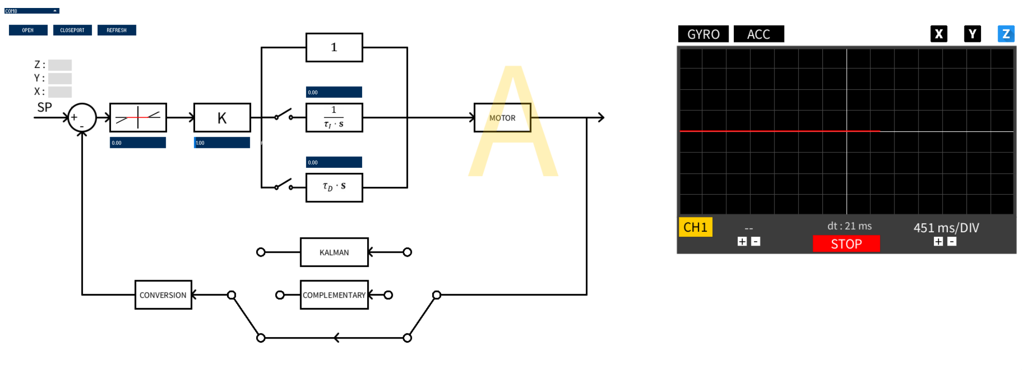

Figure 1.18: Step 12: No Kalman or complementary filter selected.

13. Activate and adjust the deadband, if necessary.

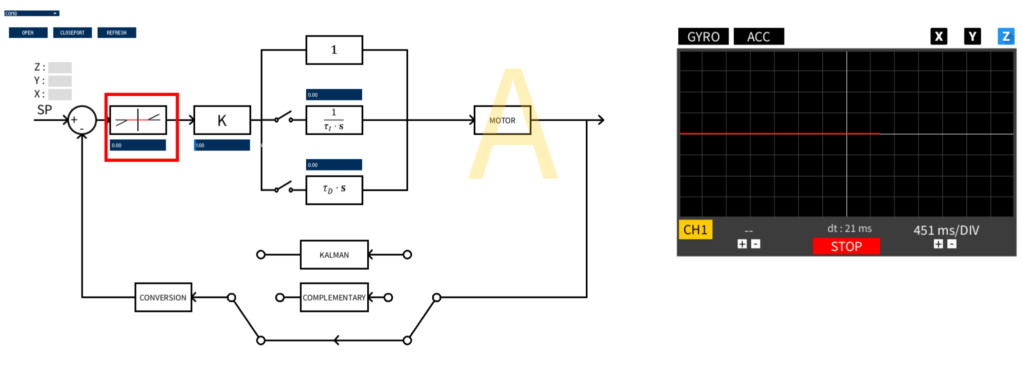

Figure 1.19: Step 13.

14. Activate the motors and press the 'up' key on the keyboard multiple times until a satisfactory motor speed level is reached.

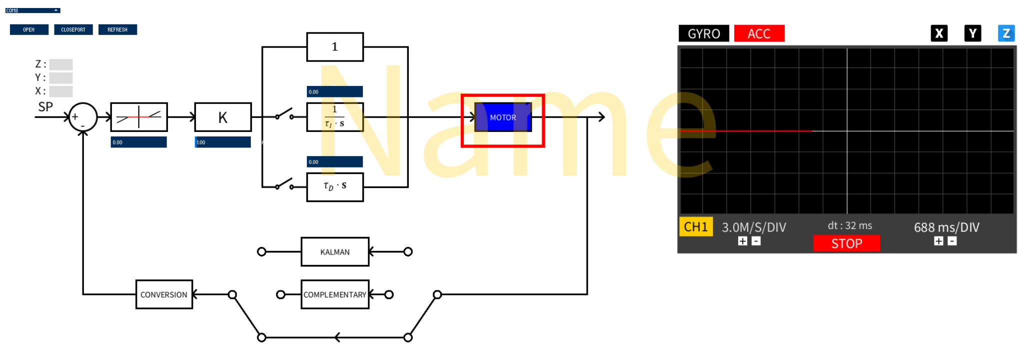

Figure 1.20: Step 14.

15. Regulate the PID settings by activating the controllers you want, and making adjustments for the main gain, and the integral and derivative time constants, if the controllers of these two are activated.

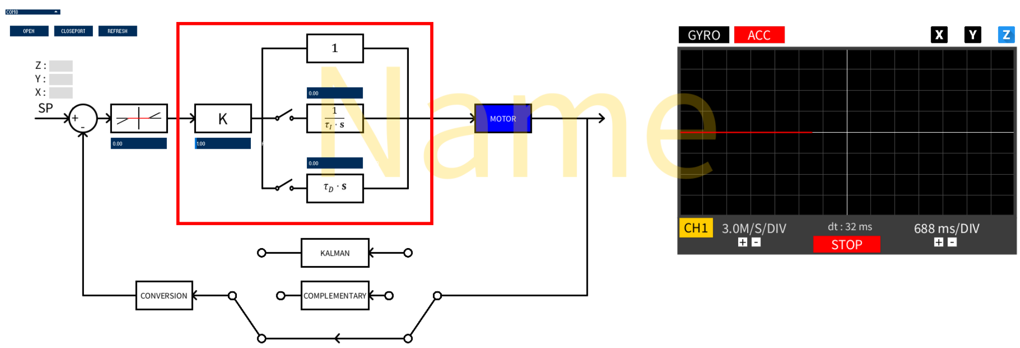

Figure 1.21: Step 15.

1.3 GUI: Signal processing recommendations

The first part of the tutorial is signal processing. For this part, the quadcopter should not be attached to the elastic band and must be laid down on the flat surface of the wooden setup. As a matter of fact, the measurements of the sensor have to be filtered while in rest position. Following will be an explanation on which filters have to be chosen for both the gyroscope and the accelerometer sensors, along with their respective input values (cut-off frequencies etc.).

1.3.1 Gyroscope

First block: low-pass filter (LP)

As mentioned in section **??**, a low-pass filter blocks high frequencies, such as noise and vibrations, and passes low frequencies. Even though we have established that the gyroscope is much more insensitive to vibrations than the accelerometer, there will still be some vibrations when the motors start spinning. This will translate in some fluctuations in the angle measurements, and then in the angle error term, and finally in the PID behaviour. Apart from that, even when the motors are not turning, applying a differentiator, as is done by the D-controller, will tremendously amplify the already existing noise in the signal, as is illustrated in figure 1.22. Thus, it is mandatory to apply a LP-filter to the gyroscope measurements to void these fluctuations. The LP-filter can be the first filter to be selected, as shown in figure 1.23. In a frequency spectrum, noise lies after the maximum usable frequency of the device, in this case the MPU6050 gyroscope. Bearing in mind that the MPU6050 gyroscope has a full-scale range of $\pm 250°/s$, which is the maximum usable frequency, we can conclude that this will also be the cut-off frequency ω_c in $°/s$. We can calculate the cut-of frequency f_c in Hertz by implementing the following equation:

$$f_c = \omega_c/360 = 250/360 = 0.69\text{Hz}$$

Which is the lowest limit of the low-pass filter cut-off frequency. If this cut-off frequency makes the signal not responsive enough, then it has to be increased until this problem is gone.

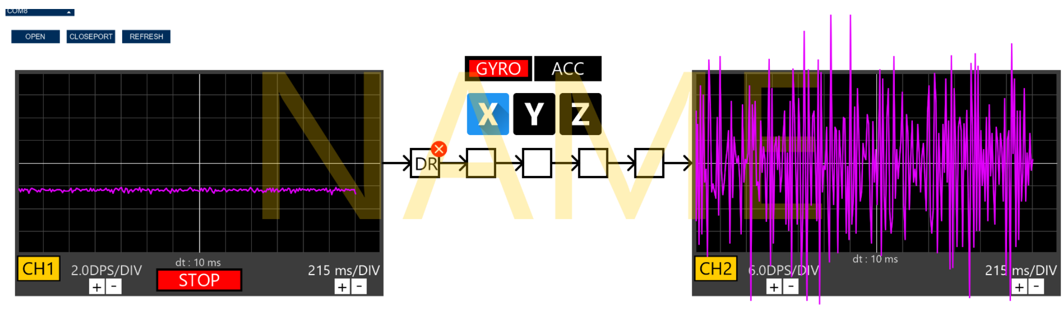

Figure 1.22: Illustration of how a D controller amplifies the noise in a signal, even when the motors are not spinning.

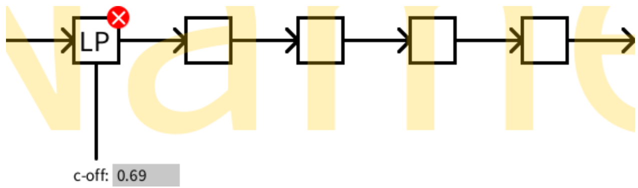

Figure 1.23: The first filter block for a gyroscope can be set to be a low-pass filter (LP) with a minimum cut-off frequency of 0.69Hz.

Second block: high-pass filter (HP) or bias compensation (BC)

The gyroscope is needed to get angle measurements. Since the gyroscope outputs angular velocity measurements, which are in units of [$^\circ/s$], integration is needed to obtain angles [$^\circ$]. As mentioned before, gyroscopes suffer from significant bias-offsets, and integrating such measurements will result in ever-increasing errors, even for a gyroscope in rest on a perfectly flat table. To prevent this problem from happening, this bias-offset has to be removed, by either using a bias compensation (BC) or a high-pass filter (HP). The difference between the two being that the former is static, while the latter is dynamic. This means that a bias compensation would not adapt itself were the bias-offset to change, while the high-pass filter would. Even though the offset of a gyroscope can change with increasing sensor temperature, this change is negligible, and a bias compensation can thus still be used. Compared to a high-pass filter, using a bias compensation is easier, because for a good result it suffices to input the amount of measurements that it will take to calculate the average. While the cut-off frequency of the high-pass filter will require adjustments. The use of a bias compensation for gyroscope readings is shown in figure 1.24, where 500 readings are inputted for the bias calculation.

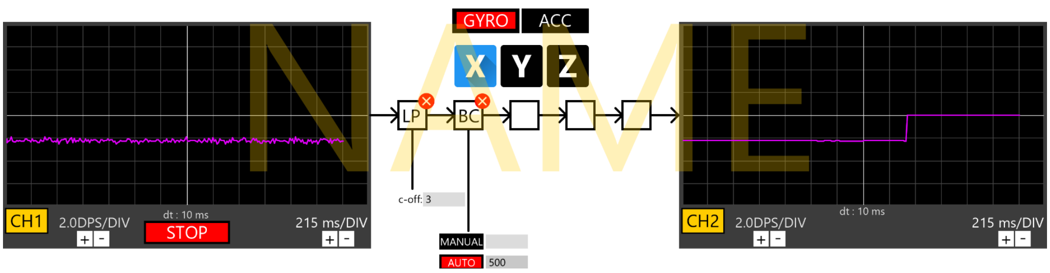

Figure 1.24: The second filter block for a gyroscope can be set to be a bias compensation (BC) with an input of 500 measurements.

In case a high-pass filter is selected, as shown in 1.25, a cut-off frequency will be needed. To find out this frequency, we need to know how fast the offset changes or moves. When analyzing the gyro measurements, we can conclude that the offset stays the same and does not move. This means that the rate of change of the offset ω_c is approximately

$0°/s$. To get the cut-off frequency f_c in Hertz, we again apply the previous equation:

$$f_c = \omega_c/360 \approx 0/360 \approx 0\text{Hz}$$

Thus, the cut-off frequency of a high-pass filter has to be approximately equal to zero, for example: 0.001Hz. Further adjustments can be made later. Note that it is highly recommended to first input a much higher cut-off frequency, for example 1Hz, in order to not wait a few minutes until the signal bias is removed.

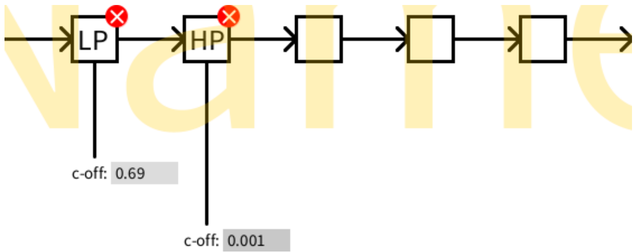

Figure 1.25: The second filter block for a gyroscope can be set to be a high-pass filter (HP) with a cut-off frequency of 0.001Hz.

Third block: integration (INT)

For the third filter block, we will choose the integration (INT) to convert the angular velocity [$°/s$] to an angle [°], as shown in figure 1.26. This angle will be used in the complementary filter or when no complementary filter and no Kalman filter are selected.

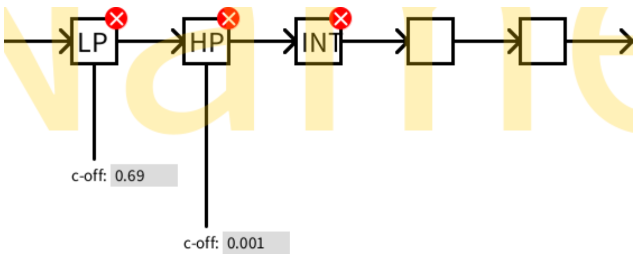

Figure 1.26: The third filter block for a gyroscope can be set to be an integration (INT) to convert the angular velocity into an actual angle.

If the angle reading keeps going to zero, while, in reality, the angle did not change, it means that the cut-off frequency of the high-pass filter is too high and needs to be reduced. This is illustrated in figure 1.27.

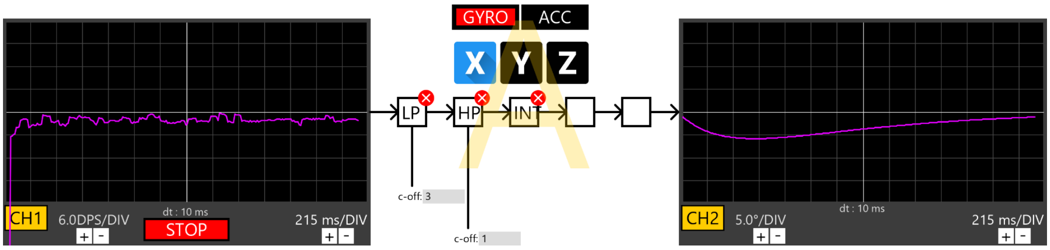

Figure 1.27: When the high-pass filter cut-off frequency is too high, the angle reading will always tend to go to zero, even when, in reality, it does not.

Next step: Kalman filter block selection

When all needed filters are selected and their respective inputs are filled in, the next step is to right click on a filter block whose signal will be used for the Kalman filter. This selected block will turn green. The Kalman filter uses rotational velocities and accelerometer angles to calculate the Kalman angle, therefore, a block where the unit is still $^\circ/s$ has to be clicked on. This is mentioned further beneath the blocks ('Choose a rotation rate signal to use for the Kalman filter by right clicking on a block.'), as can be seen in figure 1.28. Accordingly, the second block has been chosen for the Kalman filter, which is an angular velocity signal where the noise and bias have been filtered out.

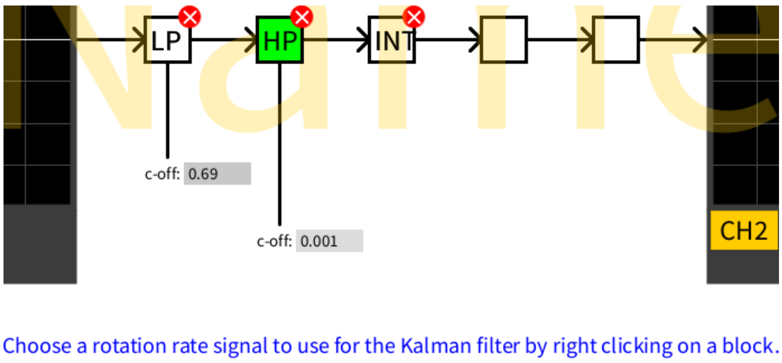

Figure 1.28: When all filters are selected and inputs are filled in, a Kalman signal block has to be selected by right clicking on it. This selected block will turn green.

1.3.2 Accelerometer

The acceleromter will be used to calculate the trigonometric accelerometer angle and the position.

First block: low-pass filter (LP)

The accelerometer has a noisy character and is sensitive for vibrations. Additionally, the same reason mentioned for the gyroscope, where the D-controller will amplify the noise, applies here also. Thus, for the first filter block, we can use a LP-filter with a cut-off frequency that is lower than the one for the gyroscope, which was 0.69Hz. A cut-off frequency of, for instance, 0.1Hz can be introduced. See figure 1.29.

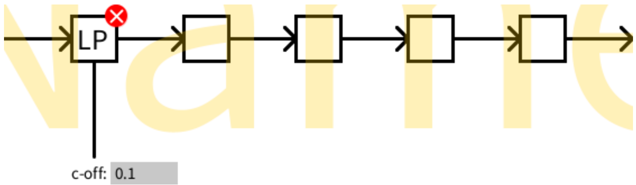

Figure 1.29: The first filter block for an accelerometer can be set to be a low-pass filter (LP) with a cut-off frequency of 0.1Hz.

Again, if the signal is not responsive enough, the cut-off frequency of the low-pass filter must be increased.

Second block: high-pass filter (HP)

As we have discussed in section **??**, the accelerometer outputs the gravity component (in $[m/s^2]$) on each of the three axes, depending on how it is tilted. If, for instance, the accelerometer is positioned in a way that the gravity is perpendicular on the x and y-axis, and makes an angle of 180° with the z-axis, the x and y-axis will both output a measurement of $a = 0m/s^2$, while the z-axis will output $a = 9.81m/s^2$, while the sensor is not moving and has not moved at all. When a position measurement is wanted, the accelerometer outputs have to be integrated twice to go from $[m/s^2]$ to $[m]$. If the measurement of $a = 9.81m/s^2$ is integrated twice, this will result in a constantly increasing position measurement because of the error accumulation, while the sensor is staying at one place. So, a gravity component output on an axis is considered as an undesired bias-offset in this situation. To remove this bias, we apply a high-pass filter with a cut-off frequency that is approximately equal to zero. We, again, take $f_c = 0.001$Hz. This is shown in figure 1.30. Contrary to a gyroscope, a bias compensation will not work for an accelerometer, because its offsets change depending on the tilt angles of the accelerometer.

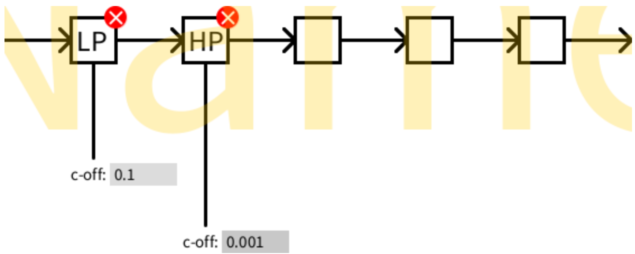

Figure 1.30: The second filter block for an accelerometer can be set to be a high-pass filter (HP) with a cut-off frequency of 0.001Hz.

Third block: integration (INT)

As stated in the previous paragraph, the accelerometer needs to be integrated twice to convert the acceleration into a position. Consequently, the third block can be chosen to be an integration (INT), as illustrated in figure 1.31. At this stage, we have converted the acceleration [m/s^2], into a velocity [m/s]. Making one short movement on a specific axis, without return and with stopping at the end, gives an acceleration and velocity signal as shown in figure 1.32.

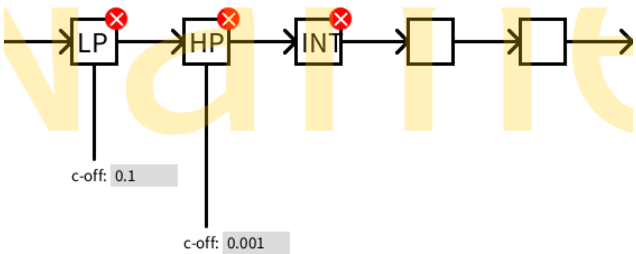

Figure 1.31: The third filter block for an accelerometer can be set to be an integration (INT).

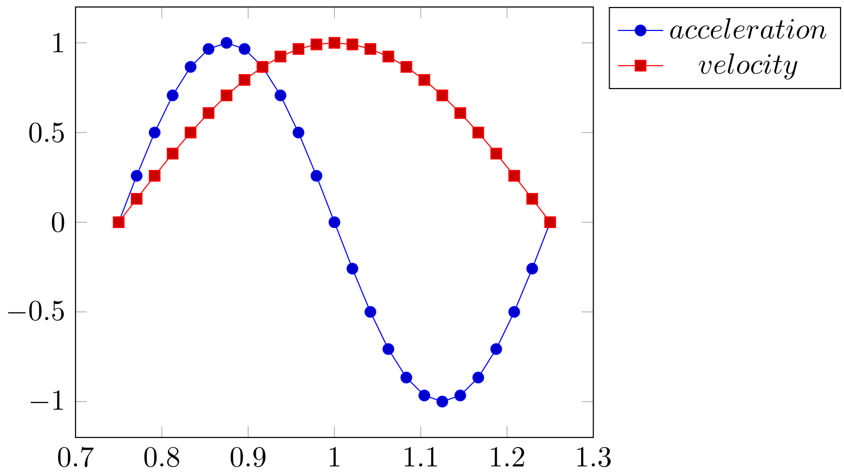

Figure 1.32: Illustration of what the acceleration and velocity signals look like when making one short one-directional movement without a comeback.

Thus, the high-pass filter cut-off frequency of the second block has to be adjusted until the velocity signal looks like illustrated in figure 1.32.

Fourth block: high-pass filter (HP)

Even though there is only on integration left to reach our goal, we can't integrate right away. In fact, an additional high-pass filter needs to be applied. To understand why, we look at the basic formula for an integration:

$$\int f'(x)\,dx = f(x) + C \tag{1.1}$$

Based on this basic formula, we know that after each integration, an additional constant C is included. Hence, integrating a second time, with the presence of this constant, would again result in an accumulation of error. Therefore, this constant has to be removed by using a high-pass filter one more time. A cut-off frequency f_c of 0.001Hz will be filled in anew. See figure 1.33.

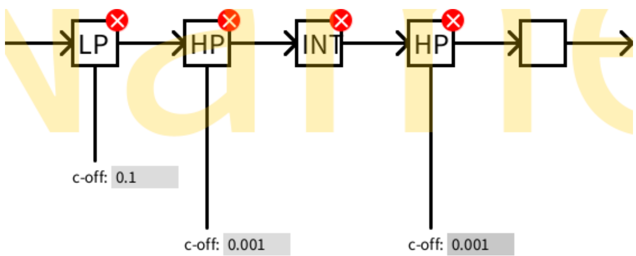

Figure 1.33: The fourth filter block for an accelerometer can be set to be a high-pass filter (HP) with a cut-off frequency of 0.001Hz.

Fifth block: integration (INT)

Finally, we are ready to integrate for a last time, converting the velocity $[m/s]$ in to a position $[m]$. See figure 1.34.

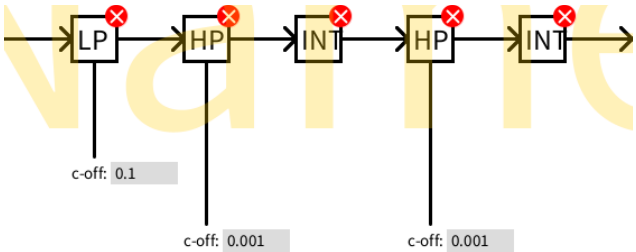

Figure 1.34: The fifth filter block for an accelerometer can be set to be an integration (INT).

The high-pass filter cut-off frequency of the fourth block has to be adjusted until the position signal is correct.

Next step: Kalman filter and complementary filter block selection

After all the necessary filters and their respective inputs have been chosen, the next step is to select the accelerometer signal block that will be used for the Kalman filter and complementary filter. This signal has to be an acceleration $[m/s^2]$ with the gravity component offsets still present, because this is how the trigonometric accelerometer angle is calculated. For these reasons, the first signal block will be selected, as shown in figure 1.35. This block will turn green.

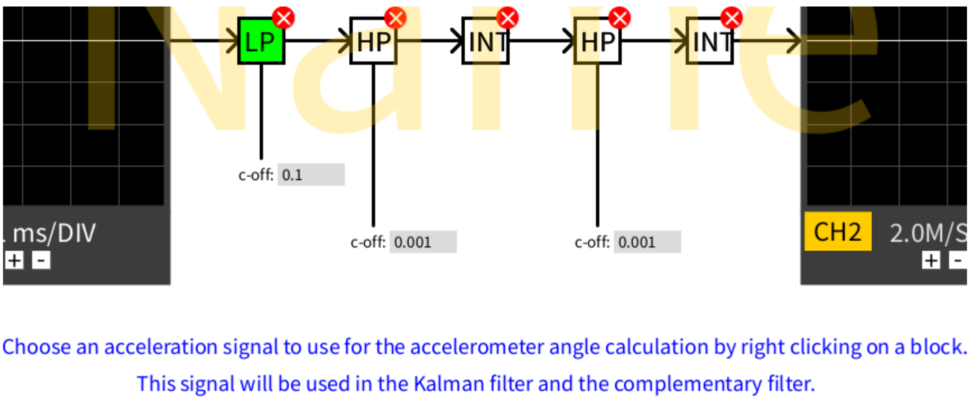

Figure 1.35: When all filters are selected and inputs are filled in, a signal block has to be selected for the Kalman and complementary filter by right clicking on it. This selected block will turn green.

1.4 GUI: PID regulation recommendations

The PID regulation part of the tutorial is also subdivided in two parts:

1. PID regulation of the angle
2. PID regulation of the position

So, we first have to make sure that the quadcopter is stabilized in the xy-plane, so that the quadcopter can perfectly fly parallel to this plane. Then, the quadcopter has to be stabilized in position, so that it can reach certain x,y, and z positions in a stable manner.

1.4.1 PID regulation of the angle

For this part, the quadcopter should be carefully attached to the bands on opposite arms. The motors that are fixed on these attached arms should not have any propellers on them. This is shown in figures 1.1 and 1.2.

Following, the GUI should be opened at where it was left, and 'RETURN' should be clicked to go back to the control system panel, as explained in step 11 of the user manual (figure 1.15).

Next, the student has to decide whether he wants to activate the Kalman filter, the complementary filter, or no filter at all, based on what gives him the best results. This is explained in step 12 (figures 1.16, 1.17, and 1.18). If the student chooses the complementary filter, he will have to fill in the percentage of trust that he gives to the accelerometer angle and the gyroscope angle, respectively. The default trust is 50% each.

Then, the motor block has to be activated by clicking on it, as shown in step 14 (figure 1.20), and the up-arrow on the keyboard has to be pressed until the motors spin at a satisfactory speed. The student can decide if a deadband filter should be applied.

Now, the Ziegler-Nichols method will be used as a first approximation for the main gain K_C, the integral time constant τ_I, and the derivative time constant τ_D. We follow the steps shown below (Ellis, 2004):

1. Set the integral time constant τ_I to 999 and the derivative time constant τ_D to zero.

2. Increase the main gain K_C until the system oscillates with a constant amplitude.
3. K_{crit} is equal to K_C at this point, and T_{crit} is the oscillation period.
4. Set the values of K_C, τ_I, and τ_D in accordance with table 1.1.
5. Fine tune the constants by a trial-and-error approach.

Type	K_C	τ_I	τ_D
P controller	$0.5 \cdot K_{crit}$	0	0
PI controller	$0.45 \cdot K_{crit}$	$0.83 \cdot K_C \cdot T_{crit}$	0
PID controller	$0.6 \cdot K_{crit}$	$0.5 \cdot K_C \cdot T_{crit}$	$\frac{0.125 \cdot T_{crit}}{K_C}$

Table 1.1: Table with K_C, τ_I and τ_D setting values for a P, PI and PID controller, respectively. Adapted from Ellis, 2004.

We will elaborate step 5 more:

- Increase K_C if the behaviour is not responsive enough.
- If you are satisfied with the responsiveness of the system, but there are oscillations, then increase τ_D.

1.4.2 PID regulation of the position

Click on the motor block on the control system panel to deactivate the motors, and detach the quadcopter from the bands. Put the remaining two propellers on the remaining motors. Select the accelerometer in the oscilloscope and reactivate the motors by clicking on its block. Apply a deadband filter if needed. Fill in an input of $0.15m$ in the z-direction (see figure 1.36), and follow the steps of the Ziegler-Nichols method once again, as explained in the previous section. When done, make the quadcopter come back to $z = 0m$.

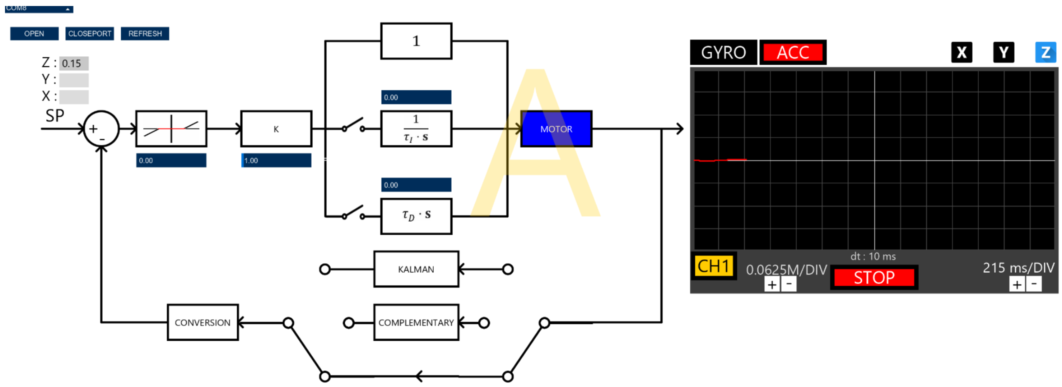

Figure 1.36: PID regulation for the position

1.5 Making the drone fly a small trajectory

This is the final part of the tutorial, where you have to fill in inputs for the x, y, and z-position. For this part, you keep the accelerometer sensor and motors on. An example for a trajectory would be:

$$x = 1 \quad [m]$$

$$y = 1 \quad [m]$$

$$z = 1 \quad [m]$$

This is shown in figure 1.37.

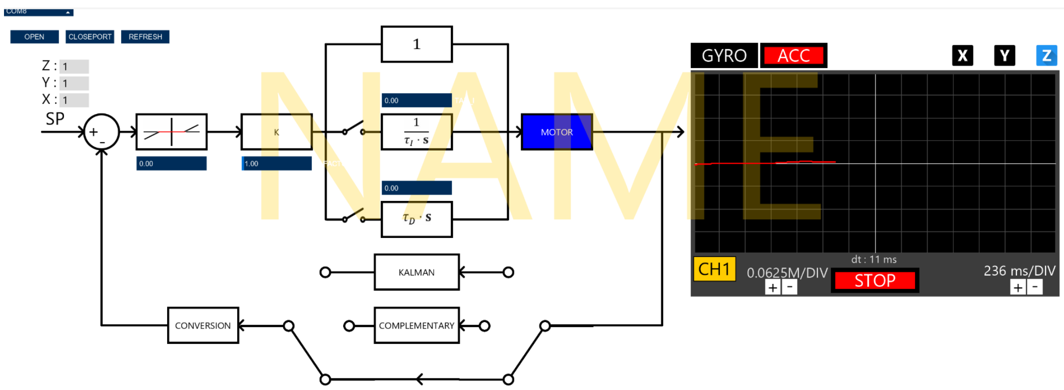

Figure 1.37: Filling in x, y, and z-values for the trajectory. Note that the inputs are in units of $[m]$.