Path-Flyer:
A Benchmark of Quadrotor Path Following Algorithms

USER GUIDE

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Introduction

This document is the user guide of the *Path-Flyer* simulator: a benchmark platform for testing path following algorithms on a quadrotor vehicle.

The benchmark has been build upon the Quad-Sim[1] platform, a quadrotor simulation tool developed on the Drexdel University for simulation and control of quadrotors. That is, it has been improved and modified to have a realistic mathematical and dynamic model of the quadrotor and its environment, to implement a proper structure to solve the path following problem and include various PF algorithms, and to incorporate new functionalities suited for the present benchmark.

Some key features of *Path-Flyer* are:

- It has a complete and experimentally validated model of the Asctec Hummingbird Quadrotor.
- Wind disturbance and noise on the measured states are modeled and can be customized.
- Two path following algorithms, *Non-linear Guidance Law* (*NLGL*) and *Carrot-Chasing*, and its adaptive versions have been implemented.
- Path following algorithms can be tested in diverse simulation scenarios.
- A user interface helps the user to modify test conditions and to explore simulation results.
- It is modular and programmable, meaning that new path following algorithms and/or reference paths can be incorporated with ease.

In this user guide it is found how to install the benchmark, how to use the user interface, how to modify parameters such as wind disturbance or noise, how to program a new algorithm and how to incorporate new path references.

Hope you find it useful. If you have any doubts do not hesitate to contact us.

Note: More information about the mathematical model of the quadrotor and its environment, the implemented path following algorithms and control structure, and the validation process of the *Path-Flyer* platform in the following publication:

Rubí, B., Ruiz, A., Morcego, B., and Pérez, R. (2019). Benchmark of Quadrotor Path Following Algorithms [SUBMITTED]. In 2019 15th IEEE International Conference on Control and Automation (ICCA).

[1] https://github.com/dch33/Quad-Sim

Installing the Benchmark

Installing the Benchmark is very simple: just copy the *Path-Flyer* folder provided within the benchmark files into the MATLAB work path. Make sure to add all folders and subfolders as shown in Fig. 1. Then open the `Path_Flyer.slx` Simulink model, and simulate!

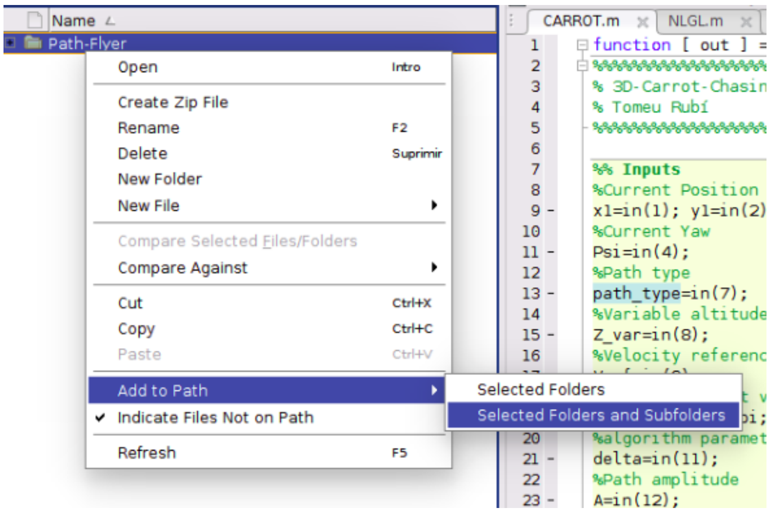

Figure 1: Add Folders and Subfolders.

Note: This benchmark has been developed with MATLAB R2017b version.

User Interface

In addition to the functionalities of the original Quad-Sim platform (grey blocks) this benchmark also presents a user interface to help the user to modify the path following simulation scenarios and explore simulation results. This user interface can be opened by double-clicking the *Path Following Controller* block in the Simulink model (Fig. 2).

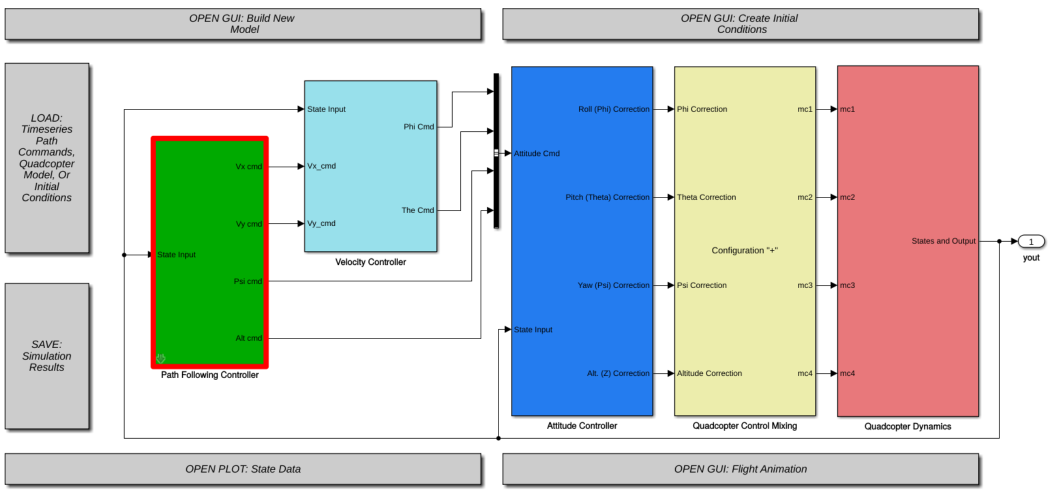

Figure 2: Double-click *Path Following Controller* to open the user interface.

The user interface (Fig. 3) is divided in two parts: the Path Following Control (red) and the Path Following Evaluation (blue).

In the Path Following Control part the user can:

1. Choose the path following algorithm from a drop-down list. In this version the available algorithms are *NLGL* and *Carrot-Chasing*, and its adaptive versions.

2. Specify the value of the control parameter of the algorithm (L for the *NLGL* and δ for the *Carrot-Chasing*). Some path following algorithms only have one parameter to tune (i.e. *NLGL* and *Carrot-Chasing*), however, if the algorithm has more than one control parameter, the other parameters will have to be declared inside the algorithm code.

3. Select the adaptive version of the chosen algorithm. That is, the control parameter or parameters of the algorithm are selected automatically. Note that if this option is active, the value of the control parameter specified previously is ignored. However, if there is not implemented an adaptive version of the algorithm, the simulator will run the standard version of it.

4. Choose the reference path from a drop-down list. In this version, four paths are available: a circle, a lemniscata (eight-shaped), a spiral and a line plus a circle path.
5. Specify the velocity reference of the Quadrotor.
6. Select amplitude of the path. That is, the radius of the circle (in the circular and line+circular paths), the radius of the small circle of the lemniscata and the growth rate of the spiral.
7. Select the number of turns on the path to be performed by the vehicle.
8. Select if the altitude of the path is variable or not. If this selector is not active the path reference is defined on the xy plane at $3\,m$ of altitude. If it is active, the path's altitude will be increasing constantly upon the evolution of the γ parameter, starting at $3\,m$.

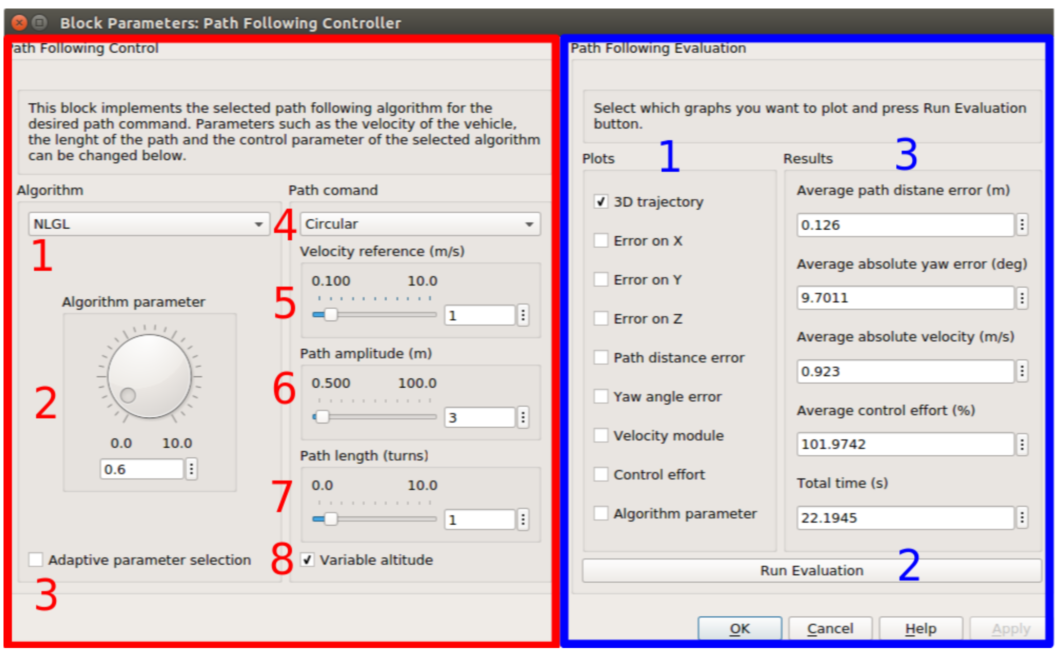

Figure 3: User interface.

In the Path Following Evaluation part the user can:

1. Choose which graphs want to plot.
2. Run an Evaluation that will plot the selected graphs and display relevant results of the previous performed simulation.
3. View relevant values of the last performed simulation, once the evaluation has been run.

Modifying Parameters

In this platform, diverse parameters can be modified: this section explains how to do it.

Model Parameters

The parameters of the quadrotor vehicle are stored in a `.mat` MATLAB structure, which is loaded at the time the Simulink model (`Path_Flyer.slx`) is opened. The structures are located in the */Quadcopter Structure Files/* folder. The fields of the model parameters structure are described in detail in the Quad-Sim documentation.

The user can modify the value of the parameters stored in the `Hummingbird_+.mat` structure, which contains the parameters of the Asctec Hummingbird Quadrotor (Fig. 4).

Field	Value
g	9.8100
d	0.1710
mass	0.6980
ct	7.1103e-08
cq	1.0088e-09
Jx	0.0034
Jy	0.0034
Jz	0.0060
Jm	1.3020e-06
Jb	[0.0034 0 0;0 0.0034 0;0 0 0.0060]
Jbinv	[291.4347 0 0;0 291.4347 0;0 0 166.6611]
dctcq	*3x4 double*
motor_m	0.0360
motor_dm	0.1710
motor_h	0.0160
motor_r	0.0139
ESC_m	0.0100
ESC_a	0.0130
ESC_b	0.0620
ESC_ds	0.0960
HUB_m	0.4140
HUB_r	0.0470
HUB_H	0.1100
arms_m	0.0250
arms_r	0.0075
arms_L	0.1340
arms_da	0.0580
T	0.0056
minThr	5
cr	37.6250
b	1075
plusConfig	1

Figure 4: Parameter structure of the Asctec Hummingbird vehicle (`Hummingbird_+.mat`).

Alternatively, the user can create a new structure file and complete it with the parameters of other quadrotor vehicle. It is important to note this structure must contain the same fields as the original structure. Then, the structure file that is pre-load on the `Path_Flyer.slx` must be modified. To do so, follow in the Simulink model:

`File` → `Model Properties` → `Model Properties` → `Callbacks` → `PreLoad` and replace the line `load(Hummingbird_+.mat)` by `load(YOUR_STRUCTURE.mat)` where "`YOUR_STRUCTURE`" is the name of the structure you have created (Fig. 5).

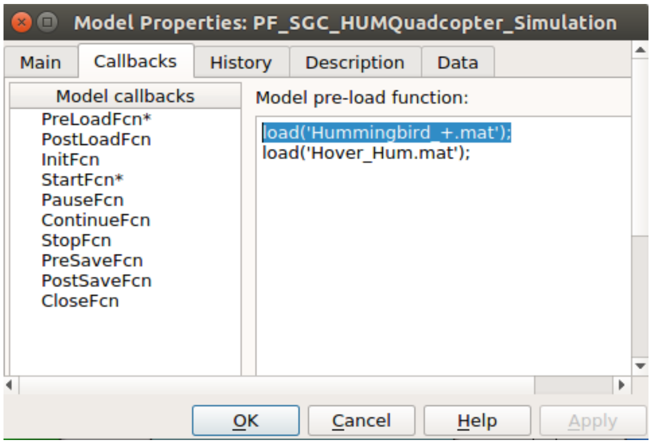

Figure 5: Modify `load(Hummingbird_+.mat)` to add your model structure name on the pre-load callback.

Initial Conditions

The initial conditions (IC) vector is stored in a `.mat` MATLAB structure, which, as the model parameter structure, is loaded at the time the Simulink model (`Path_Flyer.slx`) is opened. The IC structures are located in the */Initial Conditions/* folder. This structure is formed by the angular velocities (3, in $^{deg}/_{s}$), the Euler angles (3, in deg), the linear body velocities (3, in $^{m}/_{s}$), the position (3, in m) and the angular velocity of the motors (4, in rpm), as shown in Fig. 6.

Field	Value
P	0
Q	0
R	0
Phi	0
The	0
Psi	0
U	0
V	0
W	0
X	0
Y	0
Z	3
w1	4740
w2	4740
w3	4740
w4	4740

Figure 6: Initial Conditions vector.

The original IC structure, `Hover_Hum.mat`, defines an initial altitude of 3 meters, and the initial angular velocity of the motors at the hover state of Hummingbird vehicle. It is important to mention that an initial position of (x = 0, y = 0, z = 0) implies that the vehicle will start on the initial point of the reference path. Meaning that it will not necessarily start at the origin point on the space. Similarly, a value of 0 on the *Psi* angle means that the vehicle starts with the correct orientation to follow the path. Changing the value of the IC vector will represent an increment over this point and orientation.

As with the Model Parameters structure, the user can either modify the original IC vector file, or create a new structure following the same fields. We recommend to keep the original file, as creating a new one implies modifying more than one thing on the Simulink model.

If a new IC vector file is created, it will be necessary to change the preloaded IC structure on the `Path_Flyer.slx` Simulink model. To this end, follow this:

`File` → `Model Properties` → `Model Properties` → `Callbacks` → `PreLoad`

and replace the line `load(Hover_Hum.mat)` by `load(YOUR_IC_STRUCTURE.mat)` where "`YOUR_IC_STRUCTURE`" is the name of the structure you have created (Fig. 7).

Also, the user will need to modify a callback code on the Path Following Controller block user interface. To do this, right-click on *Path Following Controller* block on the `Path_Flyer.slx` Simulink model, and follow:

`Mask` → `Edit Mask` → `Parameters & Dialog`

and then, open the callback of the "*Path_type*" mask item as denoted in Fig. 9.

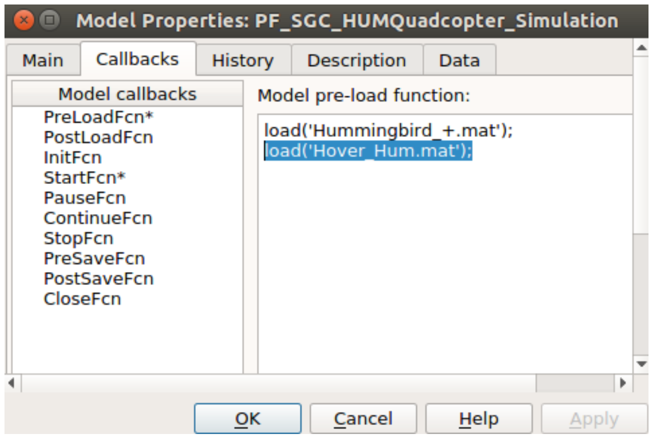

Figure 7: Modify `load(Hover_Hum.mat)` to add your IC structure name on the pre-load callback.

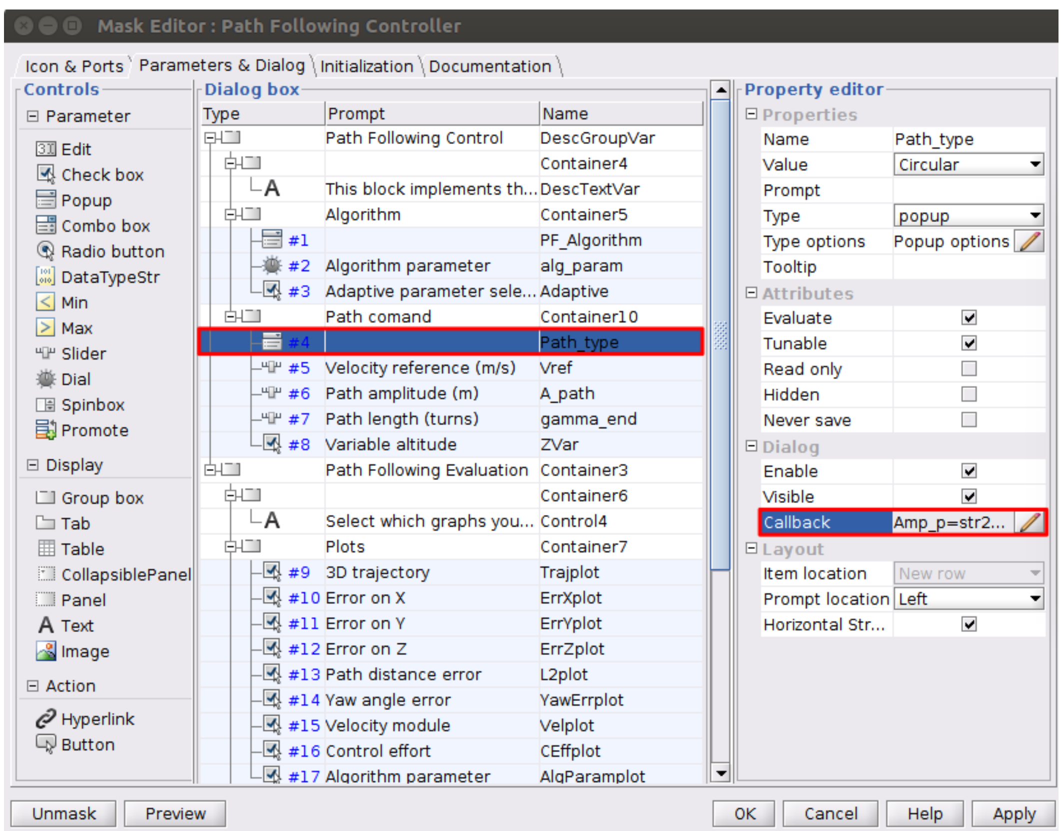

Figure 8: Open the callback of the `Path_type` mask item.

Finally, replace the line `load(Hover_Hum.mat)` by `load(YOUR_IC_STRUCTURE.mat)`, where "`YOUR_IC_STRUCTURE`" is the name of the structure you have created.

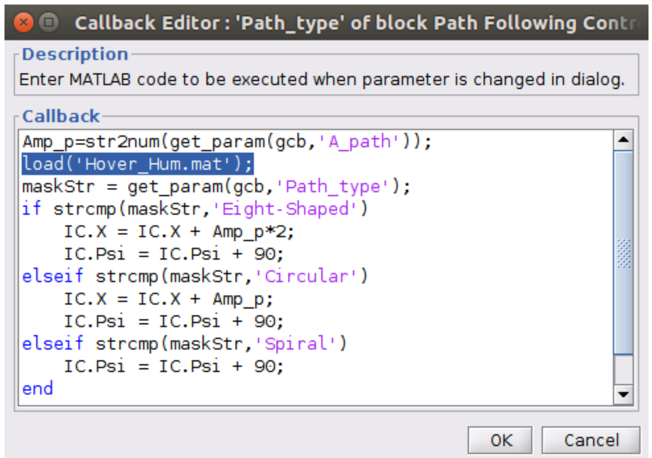

Figure 9: Modify *load(Hover_Hum.mat)* to add your IC structure name on the mask callbak.

Wind Disturbance

The wind disturbance section is found inside the *Quadcopter Dynamics* block on a block named *External Disturbances*, as shown in Fig. 10. In this block the user can generate any desired wind disturbance profile on each of the 3 axis. Wind disturbance signals are interpreted as wind velocities.

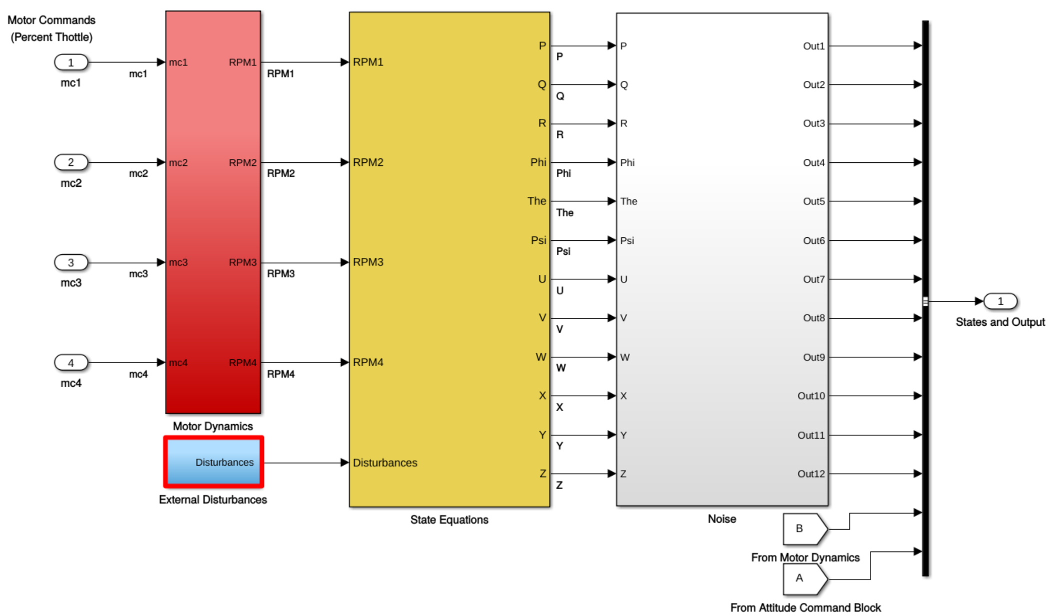

Figure 10: *External Disturbance* block is found inside the *Quadcopter Dynamics* block.

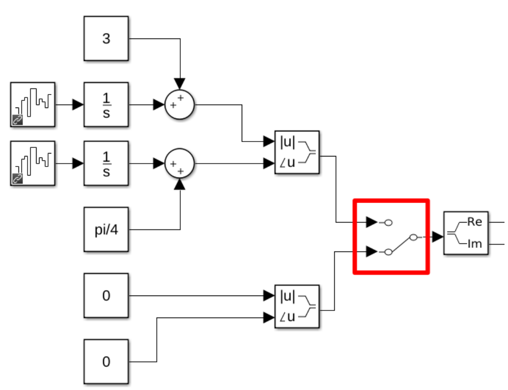

Figure 11: Wind disturbance velocities defined on the benchmark.

By default, there is not any active wind disturbance. Nevertheless, we defined a wind disturbance profile that can be activated anytime before or during a simulation by clicking on a selector, as shown in Fig. 11. The defined wind disturbance is a random walk signal on the x and y axis. This random walk is generated by integrating the signal of the *Band-limited white noise* simulink block to a constant value. This process is performed with the velocity module and direction of the wind, being 3 $^{m}/_{s}$ and $^{\pi}/_{2}$ rad the constant values, respectively. The resultant wind disturbance signal is shown in Fig. 12.

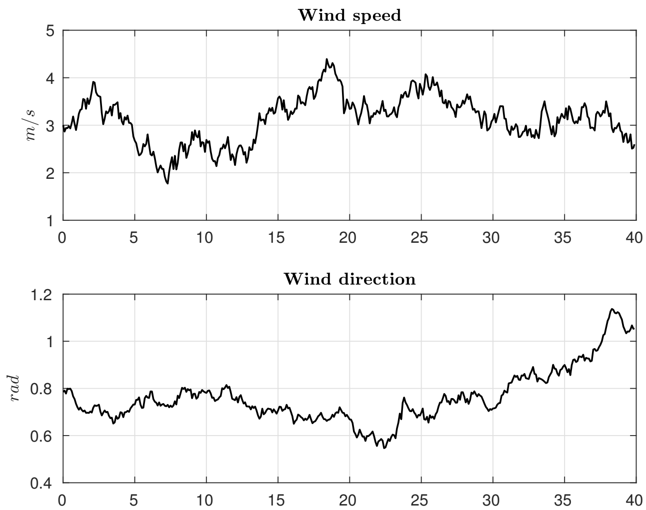

Figure 12: Wind disturbance generated with a random walk.

The user can modify the constant values of this random walk as well as the parameters of the *Band-limited white noise* block which are the seed of the random value generator, and other two values related to the frequency and amplitude of the signal. Alternatively, the user can create its own wind disturbance profile.

Measurement Noise

The Noise block is found inside the *Quadcopter Dynamics* block, as shown in Fig. 13.

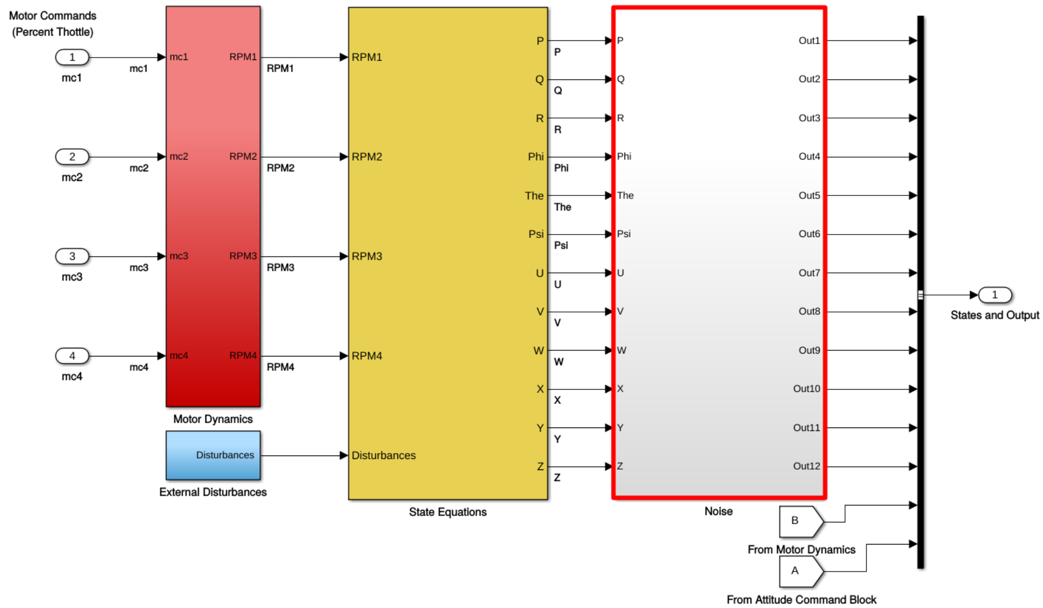

Figure 13: *Noise* block is found inside the *Quadcopter Dynamics* block.

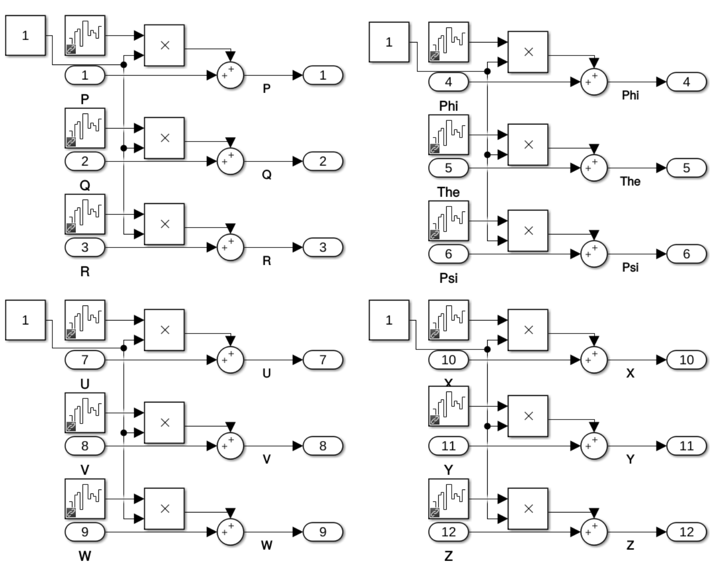

Figure 14: User can choose which states present noise and customize it.

In this block (Fig. 14) the user can choose which of the twelve measured states (position, velocity, orientation or angular velocity) must present noise. That is, if the value of the *Constant* simulink block related to each set of states is set to 1 noise will be introduced, and if constant is 0 it is disabled. Noise is generated by adding the signal of a *Band-limited white noise* block to the corresponding state. The user can customize the amplitude and frequency of the noise inside each of these blocks. In this benchmark noise signals have been set as those that resemble more the behavior of sensors of the real Asctec Hummingbird platform.

Implement Your Own Algorithm

In the */Functions/Path following/* folder (within the benchmark files) there exist a template function named `NEW_ALGORITHM_FILE.m` that the user can use to program a new path following algorithm in the benchmark. In this template, the inputs and outputs of the function and the initialization of the path are already defined. Note that those fields can not be modified. Additionally, there is an empty `"TO DO"` space where the user must implement its own algorithm.

Here are some considerations to care about when implementing a new algorithm:

- The inputs and outputs of the path following algorithm function are shown in Table 1. The user is free to use any of the stated inputs, but must fill all the outputs, with special attention to the velocities, altitude and orientation command references. The errors (`ErrX, ErrY` and `ErrZ`) must contain the distance between the vehicle and the closer point to the path on each axis. Remember to **put a simulation ending condition** (when vehicle completes the path) **that set the variable `End_Path` to `1`**.

- The reference path is discrete and is stored in three vectors, one for each component (`P_x`, `P_y` and `P_z`). The path is created with a parametric function that depends on parameter γ ($P_x(\gamma)$, $P_y(\gamma)$ and $P_z(\gamma)$). The γ parameter is defined from `0` to `g_end`. The value of `g_end` is obtained by multiplying the number of path "turns" (defined in the user interface) by 2π. Thus, it can be considered that γ is given in radians. Nevertheless, **paths are defined with a precision of $^1/_{1000}$ rads**, meaning that `P_x(1000)` corresponds to the value of the component x of the path at $\gamma = 1$ rad.

- When performing a simulation, the algorithm function is called continuously in the `Path_Flyer` simulink model. Thus, we recommend to use persistent variables to initialize constants in such a way that they are only defined on the first execution of the function.

Table 1: Parameters of algorithm template.

Name	Description
	INPUTS
`x, y, z`	Position of the vehicle in the three coordinates (in meters).
`psi`	ψ - yaw orientation (in radians).
`u, v`	Body velocities (in m/s) on the x and y direction, respectively.
`Path_type`	Variable the indicates which path must be created (circle, line, lemniscata, ...).
`z_var`	Variable that indicates if the created path must vary the altitude or not.
`Vref`	Desired velocity (in m/s).
`g_end`	Last value of γ of the path (needed to create the path).
`ALG_PARAMTER`	Parameter of the programmed algorithm that can be tunned in the user interface (Change the name to the corresponding parameter, if desired).
`A`	Variable that indicates the amplitude of the path.
	OUTPUTS
`u_cmd, v_cmd`	Command for the body velocities on the x and y direction, respectively, sent to the velocity controller.
`psi_cmd`	ψ_{cmd} - yaw orientation command sent to the attitude controller.
`z_cmd`	Altitude command sent to the altitude controller.
`ErrX, ErrY, ErrZ`	Instant distance error between the vehicle and the path on the x, y and z axis, respectively.
`End_Path`	Boolean variable. If this variable is set to 1, simulation is stopped.
`out(9)`	Output that can be used for debugging (currently linked to the algorithm parameter value).

Once the algorithm is programed in the provided template and the name of the template file is changed with the algorithm's name, the following steps must be followed to include the algorithm in the benchmark:

First, open the `PF.m` file, found in the */Functions/Path following/* path, and add a call to the algorithm's function as shown in Fig. 15. That is, include the line

`out = NEW_ALGORITHM_FILE(in(1:12));`

inside an "`elseif`" statement of variable `Algorithm`, which indicates which algorithm must be executed. Again, "`NEW_ALGORITHM_FILE`" represents the name of your algorithm file. In this example, the incorporated algorithm is the third one, thus, the algorithm is called inside the a "`Algorithm == 3`" `if` statement.

```
function [ out ] = PF( in )
%Inputs
Algorithm = in(13);
Adaptive = in(14);

%PATH FOLLOWING ALGORITHM
    if Adaptive == 0
        %Not adaptive
        if Algorithm == 1
            %NLGL
            out = NLGL(in(1:12));
        elseif Algorithm == 2
            %Carrot Chasing
            out = CARROT(in(1:12));
        elseif Algorithm == 3
            %NEW ALGORITHM
            out = NEW_ALGORITHM_FILE(in(1:12));
        end
    elseif Adaptive == 1
        %Adaptive
        if Algorithm == 1
            %NLGL
            out = NLGL_ad_2(in(1:12));
        elseif Algorithm == 2
            %Carrot Chasing
            out = CARROT_ad_2(in(1:12));
        end
        elseif Algorithm == 3
            %NEW ALGORITHM
            out = NEW_ALGORITHM_FILE(in(1:12));
    end
end
```

Non-Adaptive

Adaptive

Figure 15: Add a call to the algorithm's function inside the `Algorithm - if` statement.

Note that there is another variable named `Adaptive`, which indicates if the executed algorithm is adaptive of not. If both adaptive and non-adaptive versions of the algorithm have been implemented, add a call to the non-adaptive version inside the "`Adaptive == 0`" statement as shown:

```
if Adaptive == 0
    if Algorithm == 1
    ...
    elseif Algorithm == 3
        out = NEW_ALGORITHM_FILE(in(1:12));
    end
    ...
```

And add a call to the Adaptive version of it, inside the "`Adaptive == 1`" statement, as follows:

```
...
elseif Adaptive == 1
    if Algorithm == 1
    ...
    elseif Algorithm == 3
        out = NEW_ADAPTIVE_ALGORITHM_FILE(in(1:12));
    ...
    end
end
```

where "`NEW_ADAPTIVE_ALGORITHM_FILE`" is the name of the file wherein the adaptive version of the algorithm is implemented.

If **only the non-adaptive version of the algorithm has been implemented, add a call to this function on both sides** (when `Adaptive == 0` and when `Adaptive == 1`), in such a way that the algorithm will be executed without taking into account the value of the "*adaptive parameter selection*" button on the user interface (Fig. 3).

After adding a call of the algorithm on the `PF.m` file, the user must add a new field on the user interface algorithm list, in order to include it in the set of algorithms that can be simulated in the benchmark. To do so, right-click on *Path Following Controller* block on the `Path_Flyer.slx` Simulink model, and open the list of parameters of the mask:

`Mask` → `Edit Mask` → `Parameters & Dialog`
and then, open the "*popup options*" of the "*PF_Algorithm*" mask item as denoted in Fig. 16.

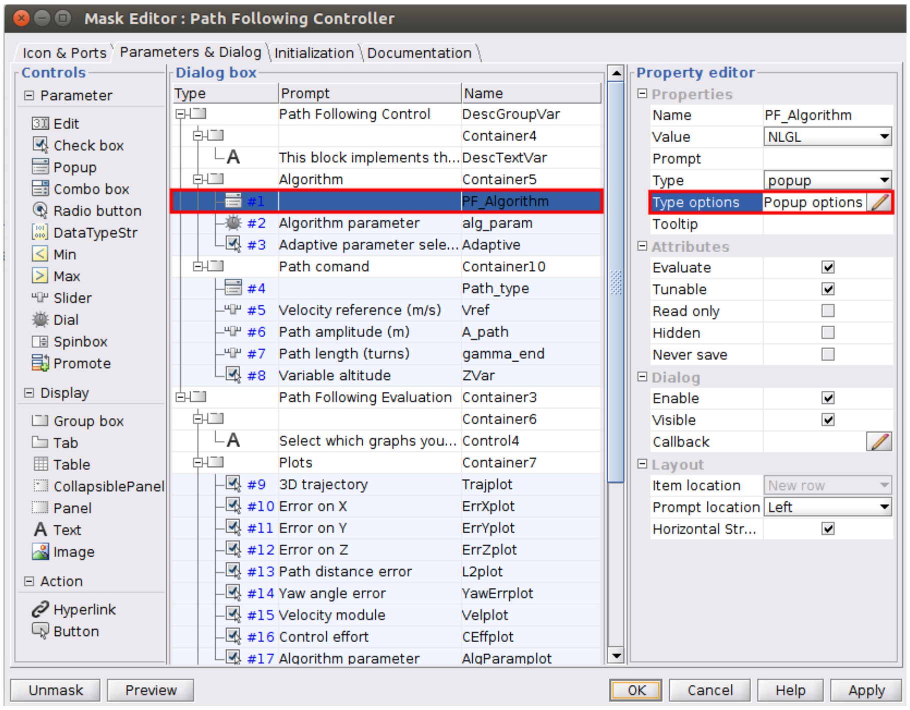

Figure 16: Open the *popup options* of the `PF_Algorithm` mask item.

Then, add the name of the implemented algorithm in the pop-up list (as it is desired that it appears in the user interface algorithm's list) as denoted in Fig. 17. It is important that the order of the algorithm names is preserved, since it is related to the value of the `Algorithm` parameter found in the `PF.m` file.

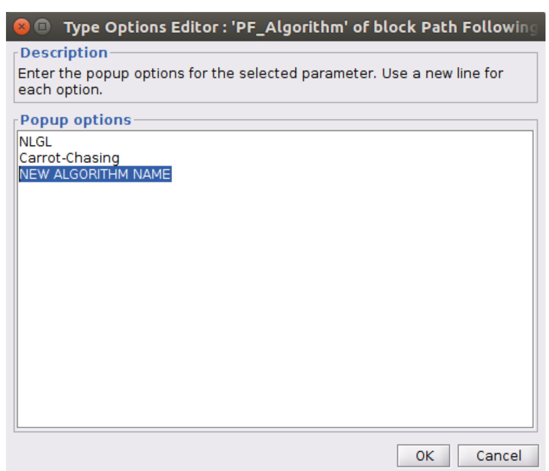

Figure 17: Add the name of the algorithm in list of the `PF_Algorithm` mask item.

Program a New Reference Path

In the */Functions/Path following/* folder (within the benchmark files) there is a function, named `CreatePath.m`, in which the reference paths are defined. To create a new reference path the user must program it inside a `swith-case` statement, as denoted by a `"TO DO"` inside the file (Fig. 18). The variable of the `swith-case` statement is named `type` and it is used to defined which path must be performed on each simulation (for instance, `type = 1` means that an eight-shaped path will be simulated).

```
        case 4
            %Path type: Line + circle
            x(1:1000)=0.01*gamma(1:1000);
            y(1:1000)=0;
            x(1001:g_final)=A*cos(0.001*(gamma(1001:g_final)-gamma(1000))-pi/2) + x(1000);
            y(1001:g_final)=A*sin(0.001*(gamma(1001:g_final)-gamma(1000))-pi/2) + A;
            if zvar == 1
                z=0.001*gamma+3;
            else
                z(1:g_final)=3;
            end
%       TO DO
%       case 5
%           %NEW PATH
%           %Fill x, y and z, for gamma = 1 to g_final

    end
    clear i

end
```

Figure 18: Create the path inside the `swith-case` statement on the `CreatePath.m` function.

The reference path is discrete and is stored in three vectors, one for each component (`x`, `y` and `z`). The path is programmed with a parametric function that depends on parameter `gamma` (`x(gamma)`, `y(gamma)` and `z(gamma)`). Note that `gamma` is different from the γ parameter stated in the previous section. That is, γ is the arc length parameter used to define the path mathematically (given in radians), while `gamma` is a parameter used to discretize and program the path. A value of $\gamma = 1\,rad$ corresponds to a value of 1000 of the parameter `gamma`, meaning that paths are defined with a precision of $^1/_{1000}$ rad.

In the `CreatePath.m` function, parameter `gamma` is defined from `0` to `g_final`. `g_final` parameter is different from the `g_end` stated in the previous section. That is, `g_end` defines the last point of the path that is being simulated (in rad), while `g_final` is the total length of the defined path (in $^1/_{1000}$ rad) and is usually longer than the simulated path (note that in a simulation, the traveled path length is not necessary the total length of the path). `g_final` is pre-defined to 100000, but its value can be modified to change the total path length if desired. Note that paths are created in such a way that a value of `gamma` of 6283 ($2 \cdot \pi \cdot 1000$) represents a full lap on the path. This condition must be taken into account when creating a new path.

Summarizing, to create a new path the user must fill all the three vectors components of the path (`x`, `y` and `z`) for each value of `gamma`, from `0` to `g_final`, assuring that a `gamma` = 6283 is when a lap is completed (if path is circular). This must be included inside an `swith-case` statement of the `type` variable on the `CreatePath.m` function.

After defining the path on the `CreatePath.m` file, the user must add a new field on the user interface path list, in order to include it in the set of paths that can be simulated in the benchmark. To do so, right-click on *Path Following Controller* block on the `Path_Flyer.slx` Simulink model, and open the list of parameters of the mask:

`Mask` → `Edit Mask` → `Parameters & Dialog`
and then, open the ”*popup options*” of the ”*Path_type*” mask item as denoted in Fig. 19.

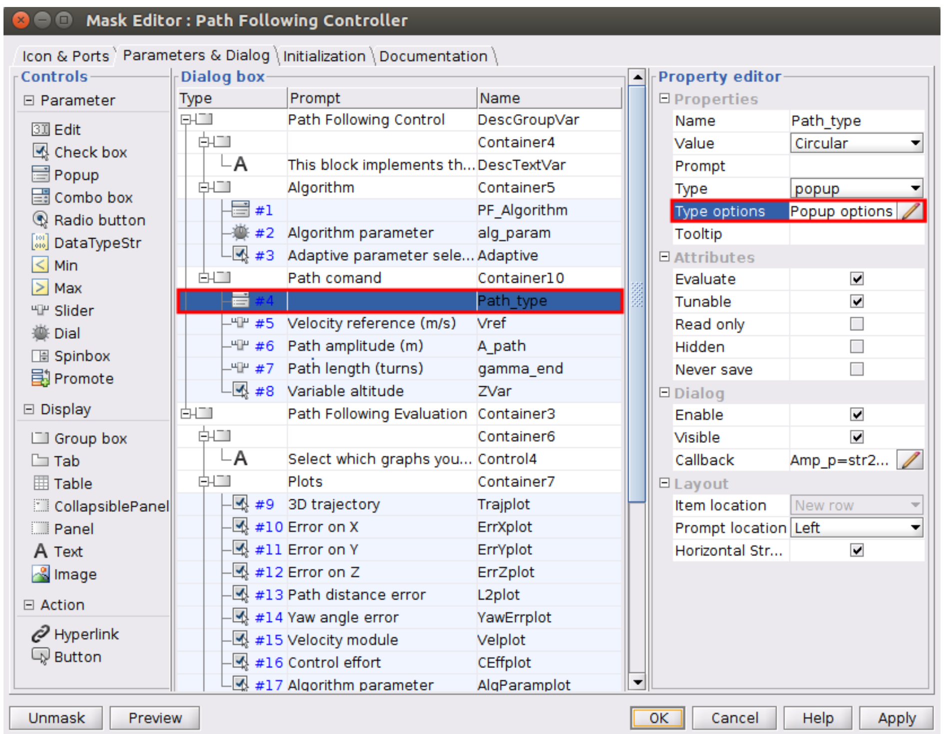

Figure 19: Open the *popup options* of the `Path_type` mask item.

Then, add the name of the created path in the pop-up list (as it is desired that it appears in the user interface path's list) as denoted in Fig. 20. It is important that the order of the paths names is preserved, since it is related to the value of the `type` parameter found in the `CreatePath.m` file.

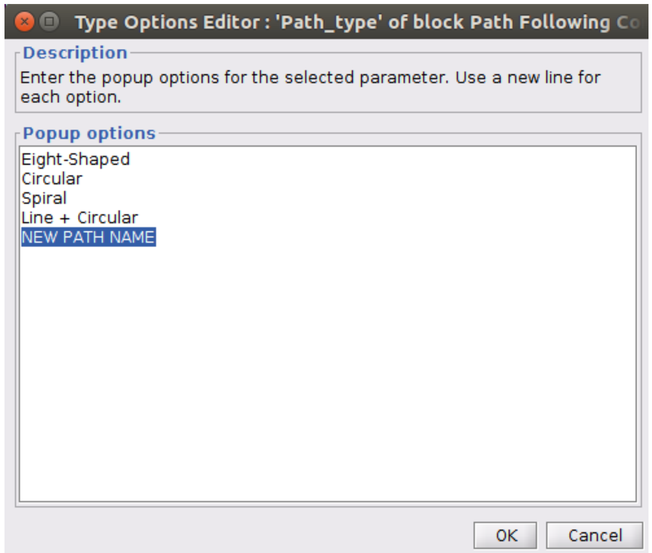

Figure 20: Add the name of the implemented algorithm in list of the `Path_type` mask item.