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**SET-UP AND EXPERIMENTAL TESTING OF A SMALL FLIGHT DATA  
ACQUISITION SYSTEM**

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# Abstract

The aim of this thesis is to setup, calibrate and test a commercially available flight controller, produced by 3D Robotics and called Pixhawk, as a small flight data acquisition and recording system to mount on a low cost and low risk flying test platform to be used for scientific research: a model scale fixed wing remote controlled (RC) aircraft was entirely designed and built for this purpose.

First of all, the acquisition system is presented, explaining in depth the entire setup, configuration and calibration process.

Secondly, the model aircraft design methods and manufacturing techniques used are discussed.

In the end, a ground test is conducted in order to prove the data acquisition and recording capabilities of the system.

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# Introduction

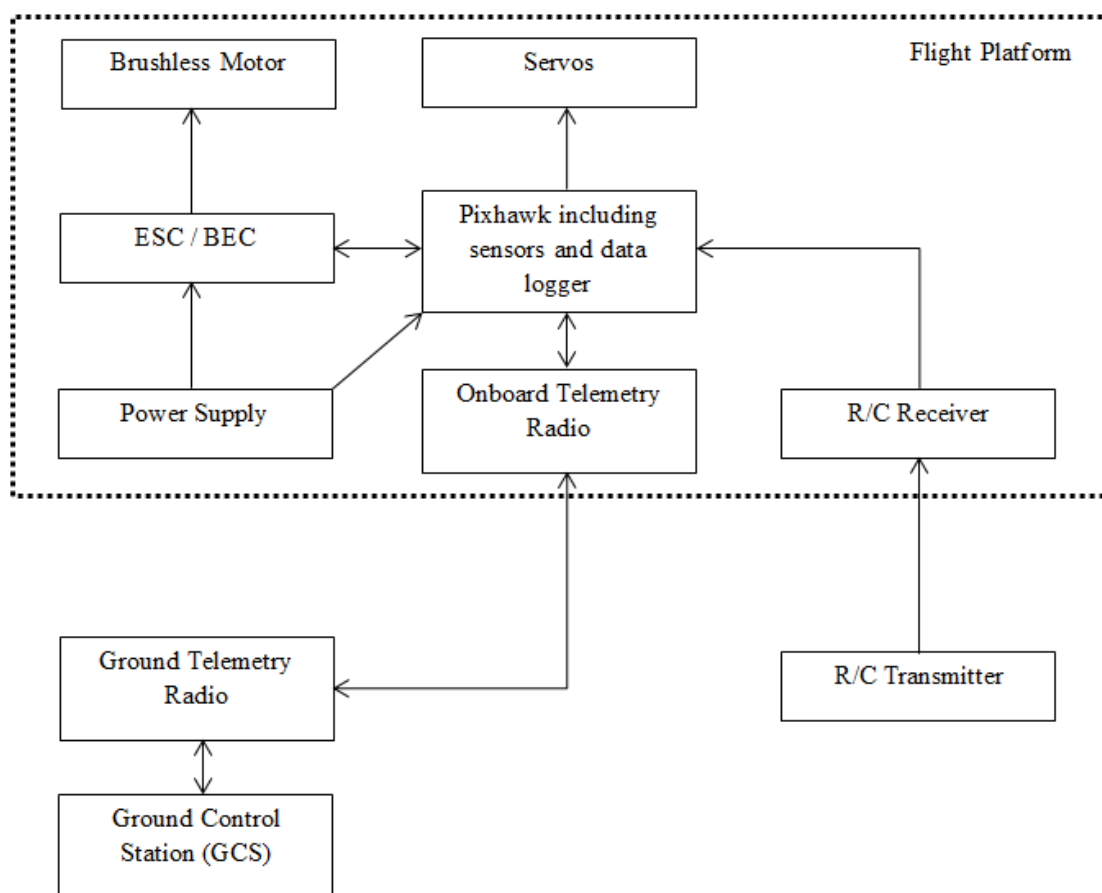
A Flight Data Acquisition System is an avionics system designed to collect, process and record flight data obtained by means of several sensors. These data typically relate to parameters such as air speed, altitude, vertical acceleration, heading, time, etc.

Apart from its obvious importance for flight safety in commercial aviation, flight data acquisition is a key procedure in the estimation of aerodynamics and flight performances of an aircraft. In particular, as an alternative to analytical and wind tunnel methods, flight data acquisition is fundamental for the implementation of system identification methods for developing dynamic models of highly coupled nonlinear systems like small Unmanned Aerial Vehicles (UAVs) [1], providing a base for reliable and robust control systems. This last application is of significant interest because of the increasing use of small UAVs for an expanding variety of tasks such as being potential low cost and low risk flying test platforms for scientific research.

Focusing on this area of interest, this work's aim is, in the first part, to describe in depth all the components, the setup process and potential uses of a small commercially available all-in-one autopilot system, produced by 3D Robotics, called Pixhawk [2]. In fact, apart from its powerful flight controller capabilities, which will not be analyzed in the present work, Pixhawk serves the dual purpose of flight data acquisition and recording, thanks to a certain amount of internal and external sensors and peripherals including a built-in micro SD card for high-rate logging over extended periods of time.

The second part is about the description of a model scale fixed wing R/C (remote controlled) aircraft, entirely designed and built for the purpose, which has been instrumented with Pixhawk in order to be used as a flight platform to gather flight data.

**Figure 1** shows a block diagram representing the actual architecture of the on board and on ground systems that have been used in this application.



**Figure 1** : Flight Data Acquisition and Recording System Overview

# 1. Instrumentation

## 1.1 Pixhawk

Pixhawk combines an high-performance Flight Management Unit (FMU) and a Input/Output (I/O) module in order to control the RC servos and ESC of the flight platform.

The FMU is provided with a powerful ARM<sup>®</sup> Cortex<sup>®</sup>-M4 embedded processor with which it can manage all the sensors, interfaces and I/O.

The elements that make Pixhawk a perfect flight data acquisition and recording system are its internal and external sensors and its built-in microSD socket thanks to which it can log data on a SD/SDHC card.



**Figure 2 :** 3DR Pixhawk autopilot system

Internal Sensors:

- ST Micro L3GD20H 16 bit gyroscope
- ST Micro LSM303D 14 bit accelerometer / magnetometer
- Invensense MPU 6000 3-axis accelerometer / gyroscope
- MEAS MS5611 barometer

External Sensors:

- 3DR uBlox NEO-7 GPS
- Honeywell HMC5883L magnetometer
- Measurement Specialties 4525DO airspeed sensor

These sensors are used to determinate the aircraft's current speed, position and attitude in terms of Euler angles.

## **1.2 Ground Control Station (GCS)**

A ground station is typically a software application, running on a ground-based computer, that communicates with the flight controller via wireless telemetry. It is firstly used for the set-up and configuration of the flight controller. After that, it displays real-time data on the aircraft's performance and position and can serve as a "virtual cockpit", showing many of the same instruments that you would have if you were flying a real plane.

A GCS can also be used to control the aircraft during flight, uploading new mission commands, setting parameters and downloading and analyzing the data gathered.

The ground station application chosen for this purpose is Mission Planner [3], a free, open-source, community supported application developed by Michael Osborne for the open-source APM autopilot project.



The telemetry connection between Pixhawk and ground station is achieved through the SiK telemetry radio: a small and light weight 433Mhz open source radio platform with a typical range of around 500 m.



**Figure 3 :** Complete GCS and radio system set-up

### 1.3 Radio system

In order to manually control the aircraft, a complete radio system is required. Pixhawk is compatible with any receiver that has a PPM (pulse-position modulation), S-BUS or Spektrum/DSM output to carry the signal.

For traditional single-wire-per-channel pulse width modulation (PWM) receivers a PPM encoder can be used to convert the receiver outputs to PPM-SUM.

In this application the Graupner MX-12 transmitter with an Assan X8D 2.4GHz hack module and an Assan X8 R6M 6Ch Micro 2.4GHz receiver are used.

Thanks to the I/O module, Pixhawk is capable of recording the PWM signals of each radio channel, which can be converted into deflection angles of the control surfaces (ailerons, elevator, rudder) through a calibration procedure.

#### **1.4 Power supply configuration**

Pixhawk can be powered by any 3S or 4S Lithium Polymer battery (LiPo) through the 3DR power module, which provides steady 5 V up to 90 A of current.

The power module itself does not supply power to the servo rail, for this reason a battery eliminator circuit (BEC) is needed. To this end, the components used are a Turnigy nano-tech 2200mah 3S 45~90C LiPo battery pack and a 5.5 V / 4 A SBEC integrated in the Hobby King 60A electronic speed controller (ESC) used to control the Turnigy Aerodrive SK3 3542-1000kv Brushless Outrunner Motor.

## 2. Set-up and configuration

### 2.1 Orientation and positioning

Both the main Pixhawk board and the external 3DR UBlox GPS module should be housed within a vibration dampening case and mounted with the white arrow pointing towards the front of the aircraft. This way the accelerometer based altitude and horizontal position estimates do not drift far off from the real values due to high vibrations and the system can measure the correct heading of the aircraft during the flight.

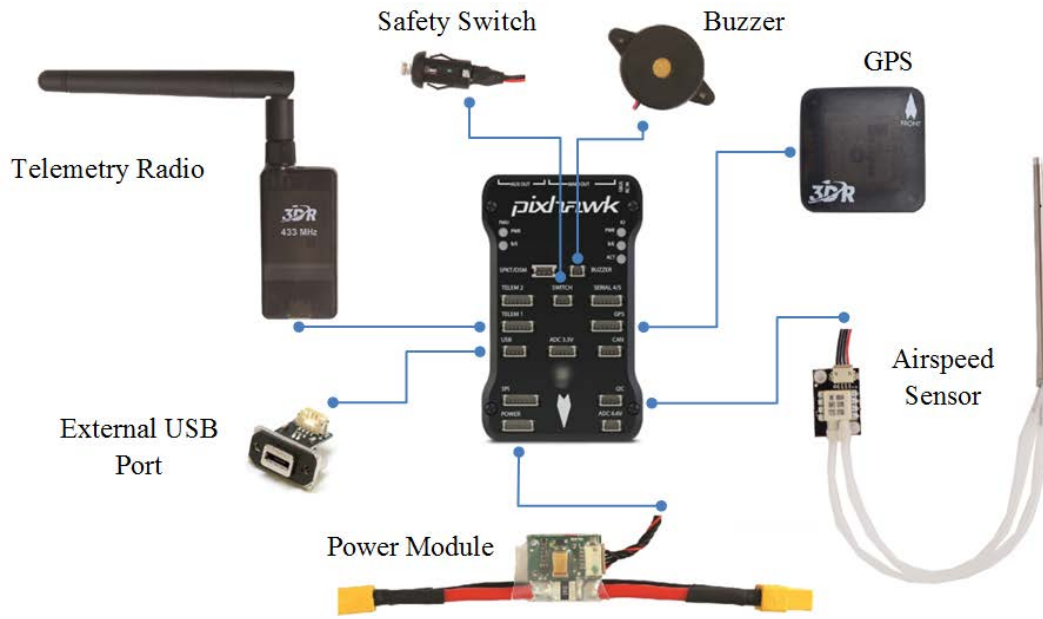
To this end, a custom-made expanded polystyrene case was built using a CNC hot wire foam cutting machine based on the MM2001 interface board [4]. It is used to keep the components perfectly aligned and fixed into the aircraft's fuselage.

In order for the on-board sensors to work properly, the case is placed close to the aircraft's center of gravity too.

### 2.2 Wiring configuration

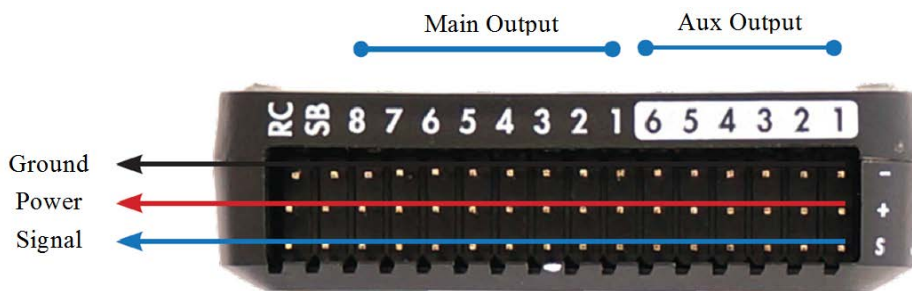
Pixhawk requires a lot of wiring connections in order to be powered and to communicate with each external peripheral. These connections, especially the ones to the power module, can generate magnetic interferences that affect the compass. For this reason, power cables are kept as far as possible from the board.

Concerning the required wiring configuration, **Figure 4** represents a simplified wiring schematics of the Pixhawk and all its components.



**Figure 4 :** Pixhawk wiring schematics

In addition, **Figure 5** shows Pixhawk’s output servo rail, which is part of the I/O module and is used to obtain the receiver’s PPM-SUM output through the RC IN port and emit a PWM signal for each main out channel in order to control the servos and the ESC. The servo rail itself is powered by means of the internal 5V BEC of the ESC. It is important to know that using a BEC to power the servo rail offers a redundant power source to the Pixhawk main board itself: if the primary source fails, Pixhawk will automatically switch to this second power source.



**Figure 5 :** Pixhawk’s output servo rail

Because of the RC transmitter being set on Mode 1 configuration (throttle and ailerons on the right hand control sticks, elevator and rudder on the left hand control sticks), the control channel wires are connected to the main output signal pins in this order:

- Pin 1 : Throttle
- Pin 2 : Ailerons
- Pin 3 : Elevator
- Pin 4 : Rudder

However, Pixhawk is set to read the inputs in a different order by default. To change this setting it was needed to set the relative RCMAP parameters via the MAVLink protocol, using Mission Planner. This operation will be discussed in chapter 3.

### **2.3 Ground Control Station installation and firmware upload**

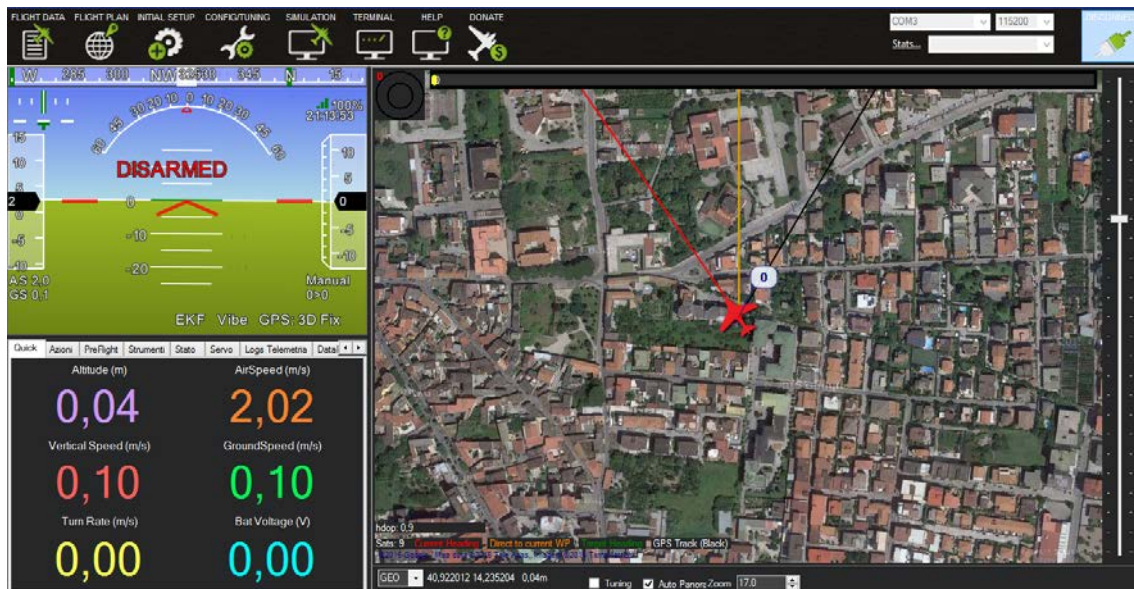
After installing Mission Planner GCS Software on a ground station laptop, it is needed to attach it to the Pixhawk using either a standard micro USB cable or the SiK Telemetry System and let it detect and install the right driver software.

The first step to setup Pixhawk properly is to download the latest version of the ArduPlane firmware and to upload it on the board.

At this point, the specific COM port and the appropriate data rate for the connection (typically 11520 for the USB and 57600 for the telemetry radio) are chosen.

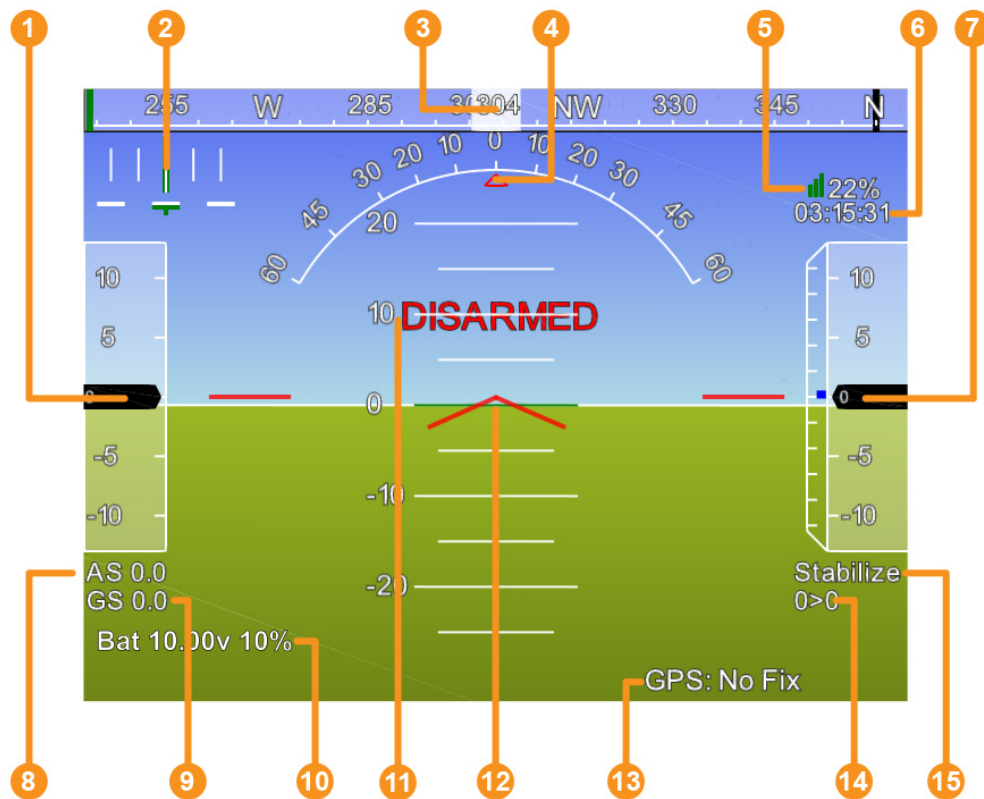
## 2.4 Ground Control Station Flight Data screen

Once the connection is established, it is already possible to test the firmware by switching to the Mission Planner Flight Data screen where three main areas of information are shown.



**Figure 6 :** Mission Planner Flight Data screen

- Heads-Up Display (HUD) Area : this area combines an attitude indicator (AI), also known as an artificial horizon, indicating pitch (fore and aft tilt) and bank (side to side tilt) angles, a heading indicator, informing on the aircraft's heading, and also a series of other indicators that are shown in the detailed view of the HUD given in **Figure 7**.

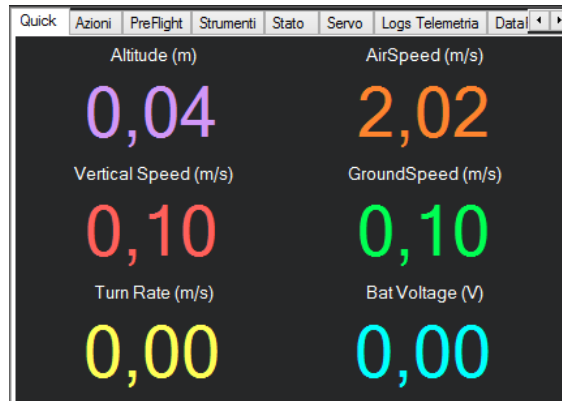


**Figure 7 : GCS Flight Data HUD**

(1) Pitch Angle, (2) Cross Track Error and Turn Rate, (3) Heading, (4) Bank Angle, (5) Telemetry Status, (6) GPS Time, (7) Rate of Climb, (8) Air speed, (9) Ground Speed, (10) Battery Status, (11) Arming Status, (12) Artificial Horizon, (13) GPS Status, (14) Waypoint Distance, (15) Autopilot Mode

- Control and Status Area : in this area several different menu items can be selected. Some of them provide real time information about all of the flight parameters. In addition it is possible to use this area to perform some control actions like changing the current flight mode or arming/disarming the aircraft's motor for safety reasons.

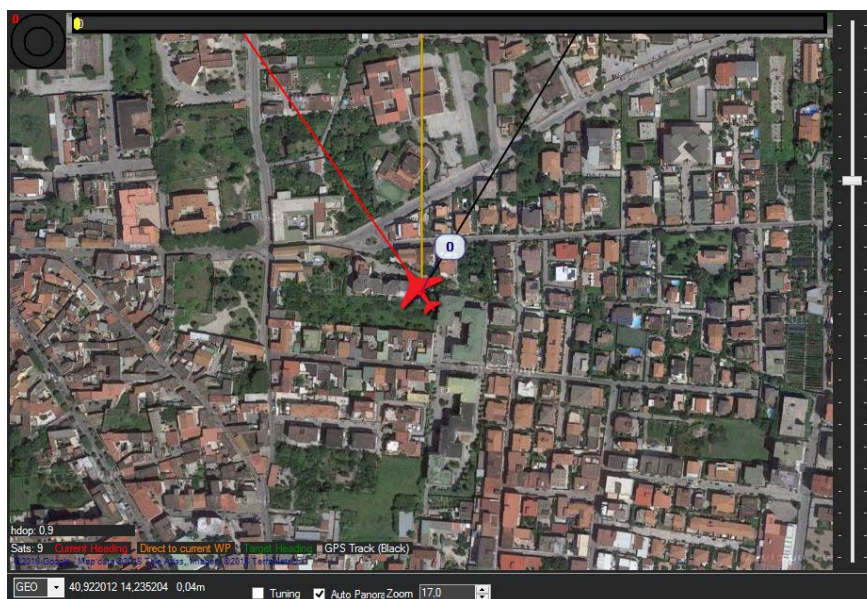
The Telemetry Logs section is used to view, analyze, play back and export the telemetry logs that are recorded by Pixhawk during the flight.



**Figure 8 :** Control and Status Area

- Map Area: this area displays the satellite imagery of the flight zone, showing with different colored lines the current heading of the aircraft (red), the direction to the next waypoint (orange), the target heading (green) and the GPS Track (black).

It is also possible to send some commands to the aircraft such as “fly to here” or “point camera here” if a camera with gimbal is mounted.



**Figure 9 :** GPS Map Area



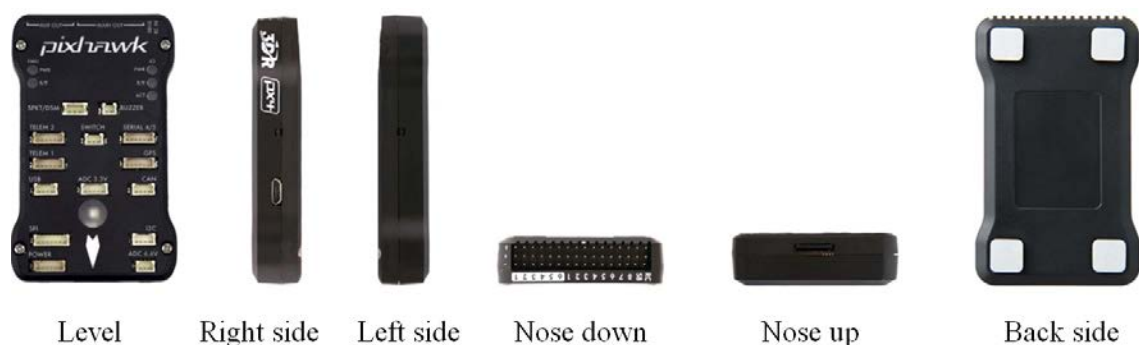
# 3. Calibration

As part of the first time setup, a proper calibration of each sensor and peripheral is required. To this end, Mission Planner offers a series of guided tools to perform these calibrations under the “Initial Setup” tab.

## 3.1 Accelerometer calibration

This calibration is needed in order to establish the attitude that Pixhawk considers level while flying. It was performed before mounting it on the flight platform in order to make it easier and more precise.

It is achieved by placing the board in each calibration position, which is given by Mission Planner, consequently: level, on right side, left side, nose down, nose up and on its back.



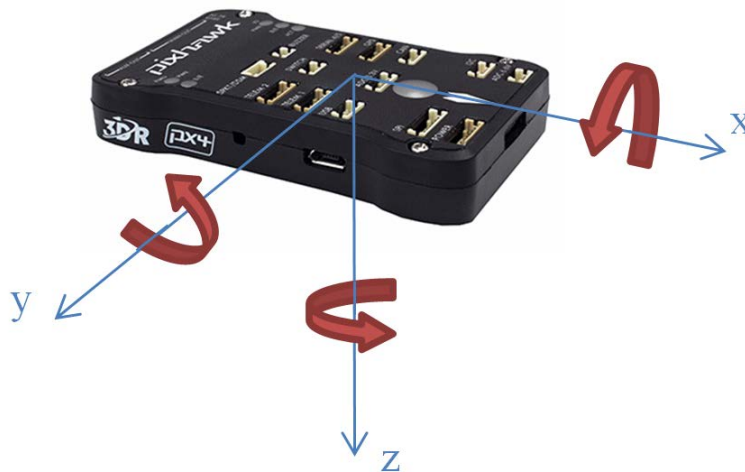
**Figure 10 :** Accelerometer calibration positions

### 3.2 Compass calibration

This procedure is used to let the internal/external compass detect the cardinal directions. It is done by starting the Live Calibration feature in Mission Planner.

It is achieved by holding the board in the air and rotating it slowly around the three axis, pointing it firstly towards North and all the other directions then.

The calibration automatically completes when all the data needed is acquired. At this point new offsets are calculated in order to compensate for hard iron distortions.

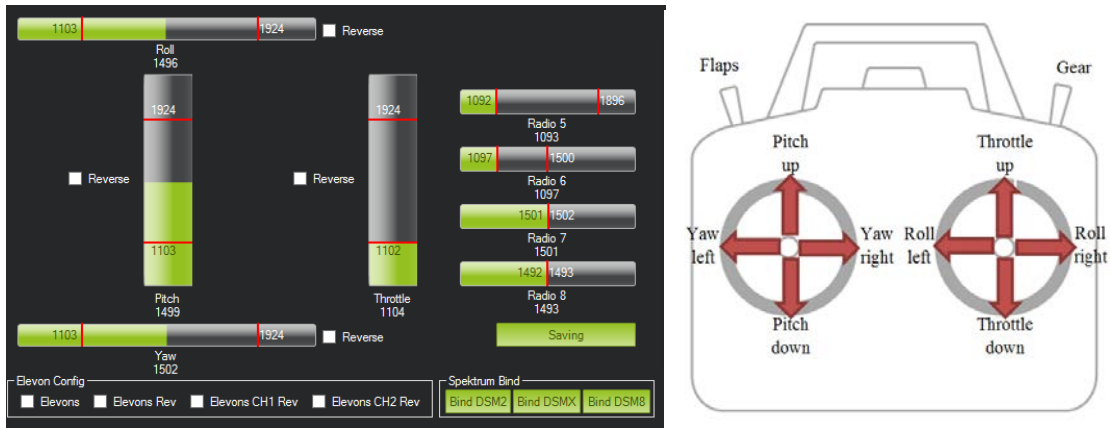


**Figure 11 :** Compass calibration rotations

### 3.3 Radio control calibration

Calibrating each of the transmitter channels is fundamental because it establishes the minimum and maximum pulse widths of the PWM signals emitted.

The procedure consists in moving each of the transmitter's sticks/switches through their full range and record the maximum and minimum positions.



**Figure 12 : RC transmitter calibration positions**

By default the RC input channels are:

- Channel 1: Roll
- Channel 2: Pitch
- Channel 3: Throttle
- Channel 4: Yaw

But the Graupner MX-12 transmitter is set to the following output channels:

- Channel 1: Throttle
- Channel 2: Roll
- Channel 3: Pitch
- Channel 4: Yaw

In order to set these channels, the default `RCMAP_PITCH`, `RCMAP_ROLL`, `RCMAP_THROTTLE` and `RCMAP_YAW` parameters were changed in the Mission Planner's Full Parameter List to the corresponding numbers.

### 3.4 ESC calibration

According to the ESC's manual, the calibration was achieved by connecting the LiPo battery to the ESC after turning the transmitter on with the throttle stick set to maximum and, after hearing the musical tone, disconnecting the battery. This operation sets the full throttle response range.

### 3.5 Brushless motor static thrust test

A test rig was built in order to establish an experimental static thrust curve for the Turnigy Aerodrive SK3 3542-1000kv Brushless Outrunner Motor mounting an APC 11 x 4.7 SF propeller.

The rig consists of a wooden stand, on which the motor is mounted, whose base is fixed on a digital scale. The initial weight of the entire equipment is read: at this point, thrust generated at each throttle level is established by subtracting the the new weight to the starting one.

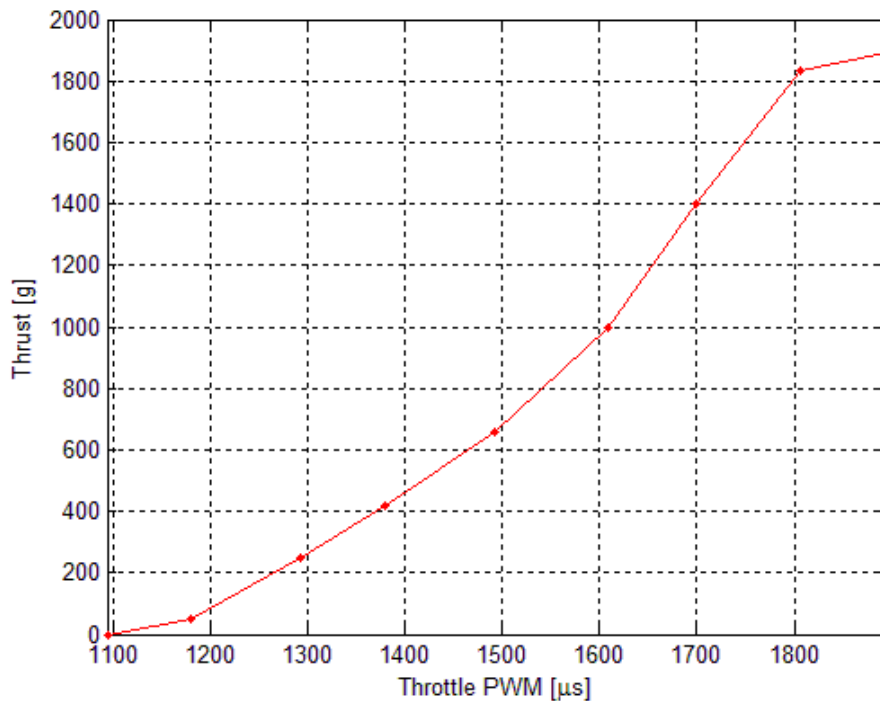


**Figure 13 :** Static thrust test rig

This operation was done at different throttle levels reading the relative pwm signal values from Mission Planner in real time. In addition, thanks to a Turnigy 180A watt meter and power analyzer, the electrical current and power absorbed at each step was acquired. The final results are given in **Table 1** and **Figure 14**.

Throttle %	PWM	Power [W]	Current [A]	Thrust [g]
0	1094	0	0	0
10.7	1180	12.5	1	50
24.8	1293	39.7	3.19	250
35.5	1380	71.2	5.75	420
49.5	1493	125	10.23	660
63.9	1609	211.2	17.49	1000
75	1699	331.8	28.34	1400
88.5	1807	518	45.24	1832
100	1896	526	46.43	1892

**Table 1** : Static thrust test results



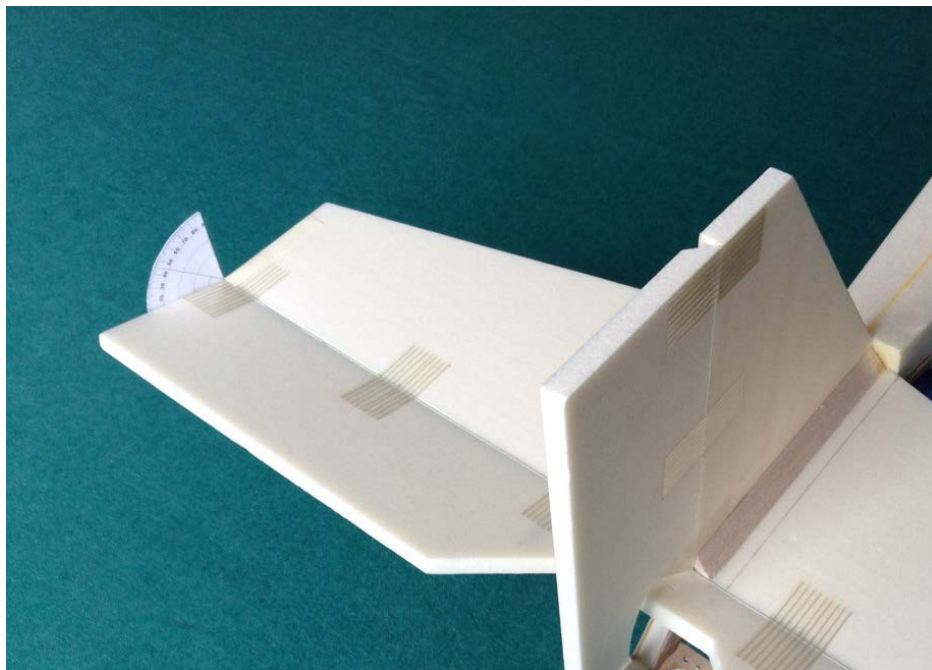
**Figure 14** : Experimental static thrust curve

### 3.6 Control surfaces deflection angles calibration

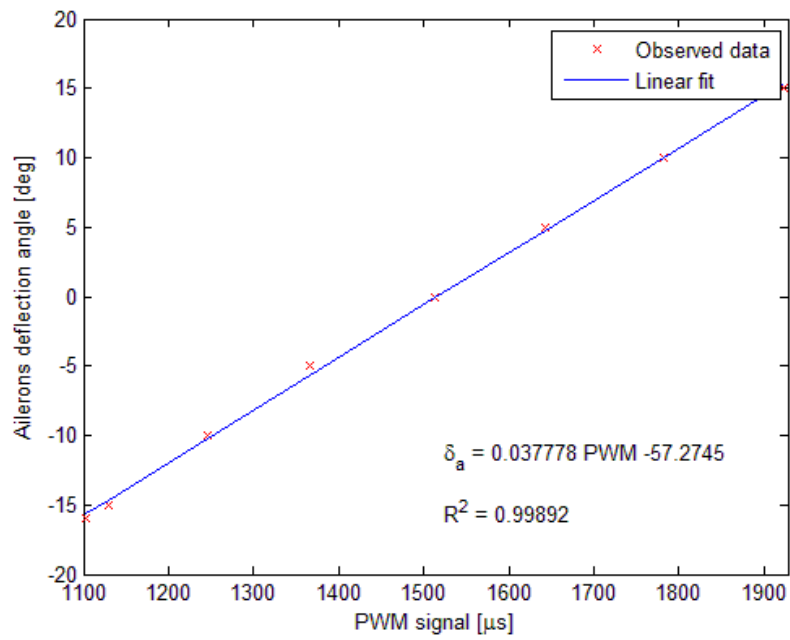
Pixhawk's sensors are not capable of detecting the deflection angles of the aircraft's control surfaces directly. In fact, it is only possible to acquire the pwm values of the servo inputs only. Thus a relationship between servo signals and deflection angles can be found by means of a specific calibration.

The procedure used was to mount a protractor beside each control surface and, by gradually moving the sticks of each transmitter channel, read the corresponding PWM signal value and deflection angle.

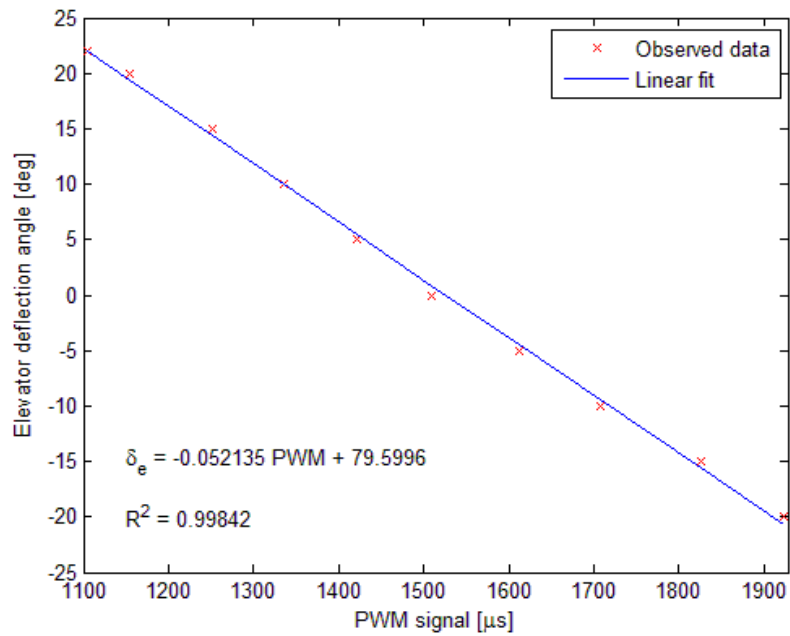
By convention, angles were assumed positive if generating nose up pitching moment for the elevator, right wing down rolling moment for the ailerons and nose right yawing moment for the rudder.



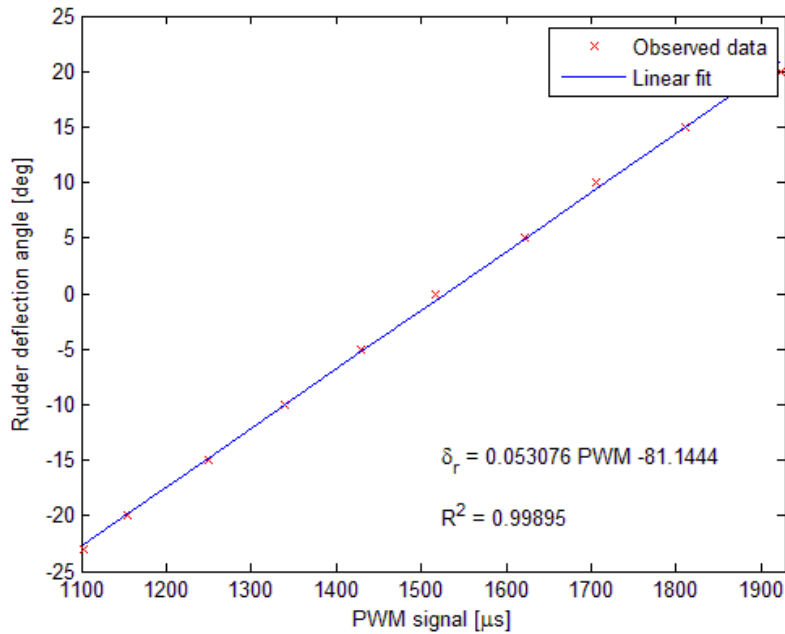
**Figure 15** : Protractor set-up for elevator calibration



**Figure 16 :** Ailerons calibration curve with regression line and coefficient of determination



**Figure 17 :** Elevator calibration curve with regression line and coefficient of determination



**Figure 18** : Rudder calibration curve with regression line and coefficient of determination

### 3.7 Airspeed sensor calibration verification

The external airspeed sensor is composed of a pressure sensor board attached to a Pitot tube with silicone rubber tubing.

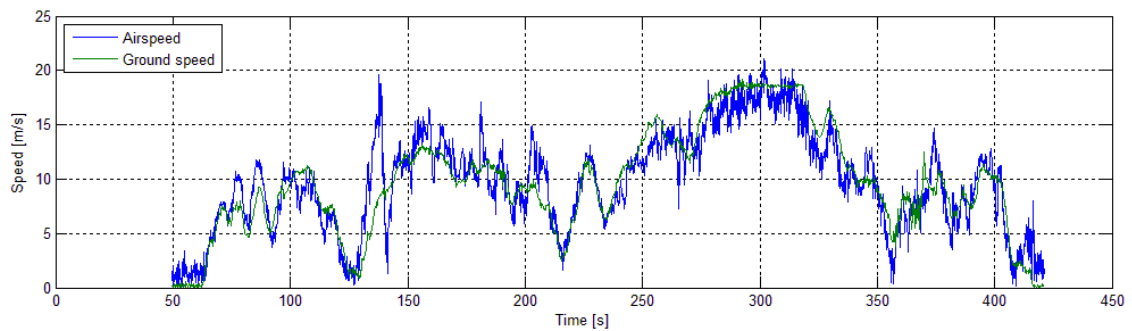
The sensor board is already factory calibrated. To verify the reliability of the sensor's calibration, a test was conducted: the pitot tube was mounted at the end of a wooden beam coming out of the side of a car. Data acquisition was started and the car was driven around. The aim of the test was to compare the ground speed acquisition obtained through the GPS to the airspeed obtained from the Pitot tube.





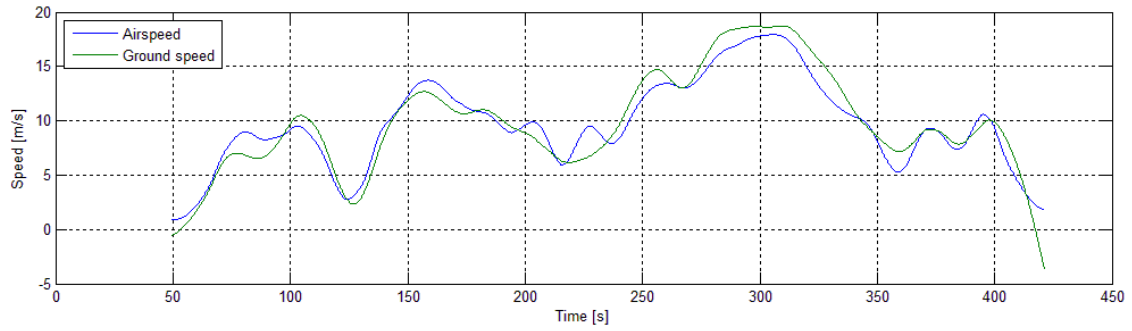
**Figure 19** : Airspeed sensor calibration verification test set-up

The results are shown in **Figure 20** and seem to be acceptable considering the fact that the test was conducted in bad wind conditions (some peaks in airspeed values caused by wind gusts can be observed).



**Figure 20** : Non smoothed airspeed and ground speed comparison

In order to get rid of the signals noise, a locally weighted scatterplot smoothing was applied to the data. This way the results are much more readable.



**Figure 21** : Smoothed airspeed and ground speed comparison

## 4. Model aircraft: Protohawk

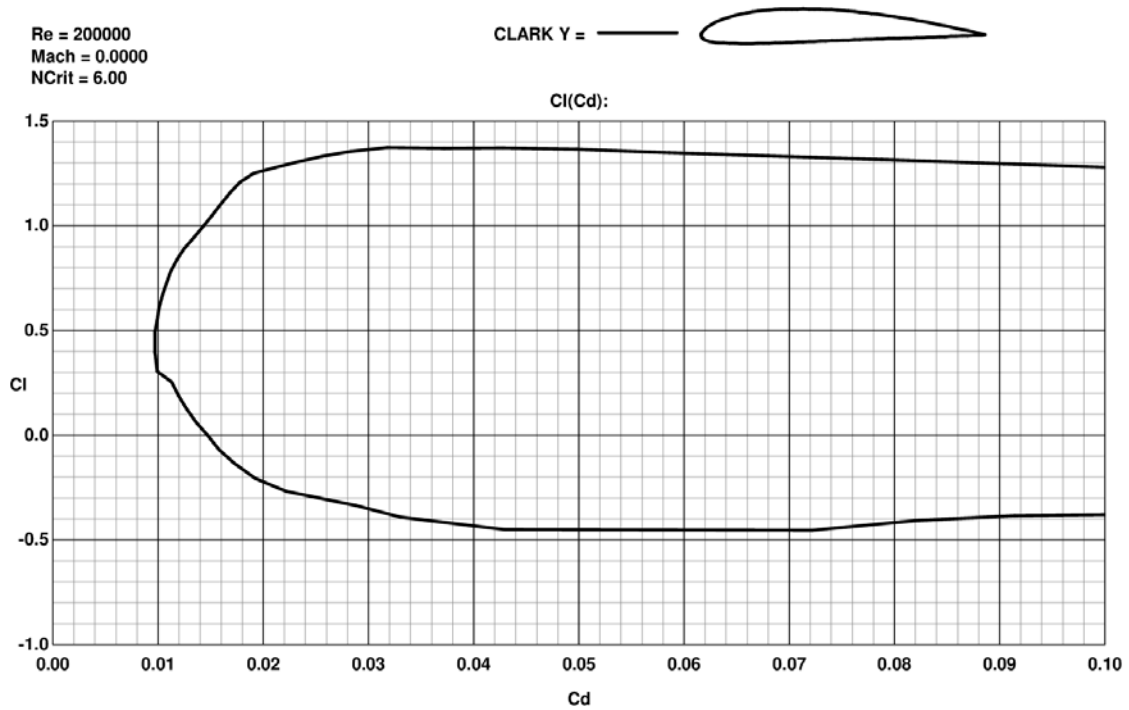
A model scale RC aircraft was entirely designed and manufactured according to the mission requirements of having a low cost and low risk flight platform to be instrumented with the flight data acquisition and recording system. The final result was given the name of Protohawk.

### 4.1 Airframe design

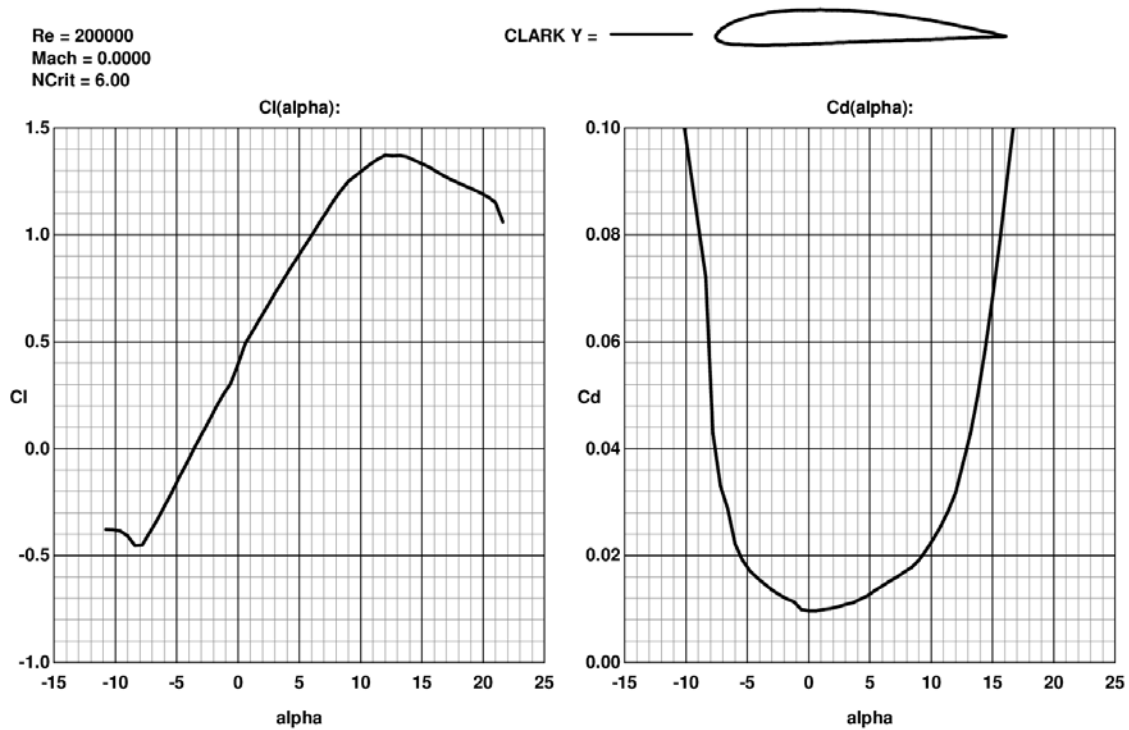
The design of Protohawk was strongly inspired by the American Piper J-3 Cub light aircraft that was built between 1937 and 1947 by Piper Aircraft. In fact, a high-wing conventional tail design was chosen.

Due to its traditionally recognized high performance at medium-low Reynolds numbers, the Clark Y airfoil was chosen. The expected Reynolds number for the aircraft, having a wing chord length of 241 mm and an estimated cruise speed of around 13 m/s at sea level is around 200'000.

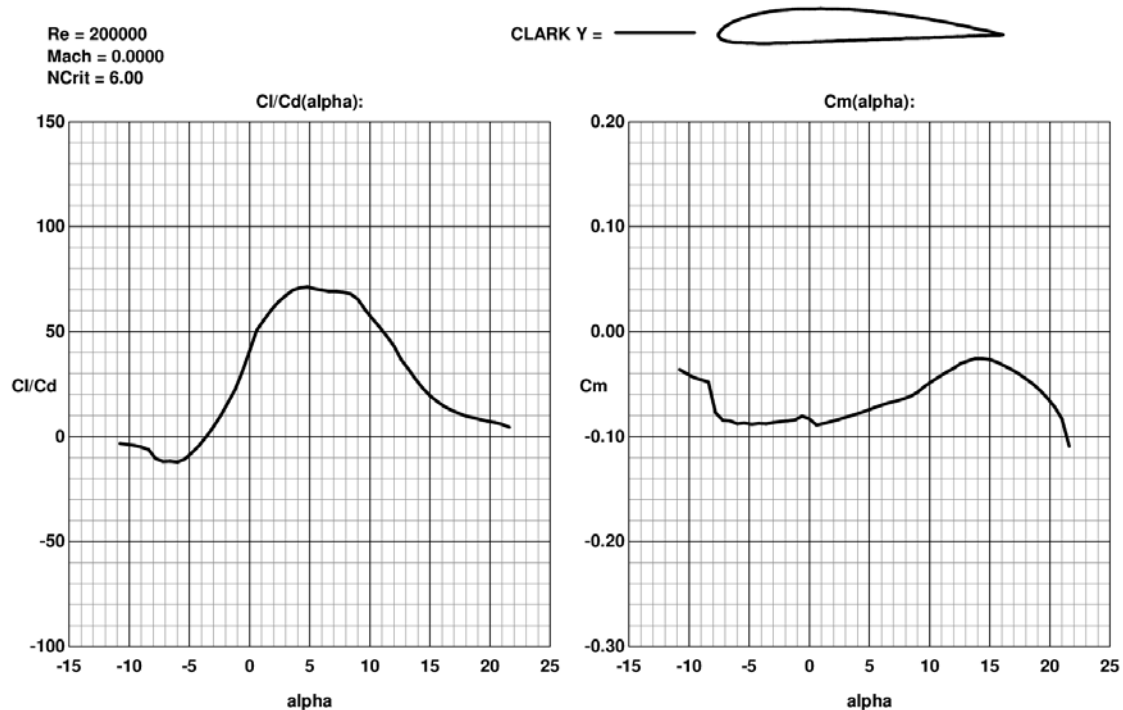
The following figures show the main polars of the Clark Y airfoil at  $Re = 200'000$  and different angles of attack obtained using the Profili 2.30c Pro graphical interface software to Xfoil, an airfoil analysis tool developed by Mark Drela at MIT in the 1980s.



**Figure 22 :** Lift coefficient versus drag coefficient graph



**Figure 23 :** Lift coefficient and drag coefficient versus angle of attack graphs

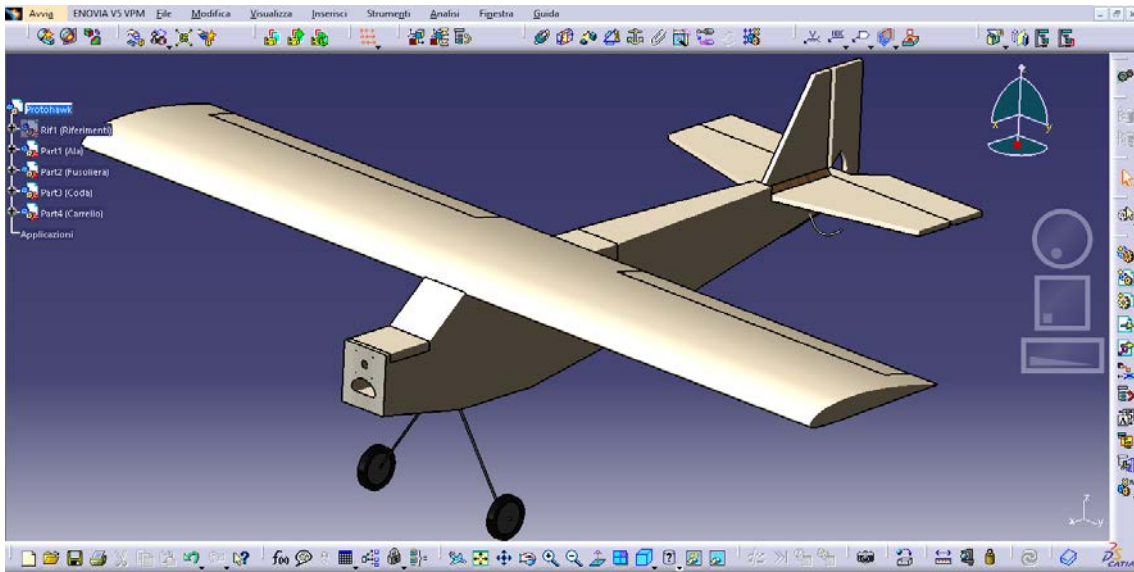


**Figure 24 :** Lift to drag ratio and pitching moment versus angle of attack graphs

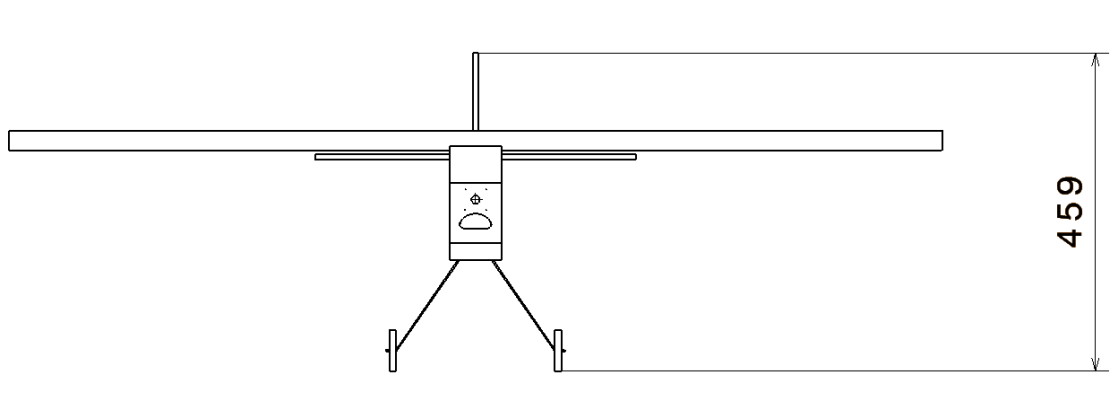
Starting from the airfoil, the rest of the design was done trying to keep the geometry simple but effective, with the aim of having a fuselage wide enough to carry the instrumentation and a minimum wing span capable of sustaining the weight of the model. The high-wing configuration gives extra stability to the aircraft resulting in an easier handling.

The design was entirely computer-aided through the use of Dassault Systèmes CATIA V5R21 and Autodesk AutoCAD 2016 softwares. The top-down modeling technique was used for its flexibility and intuitiveness.

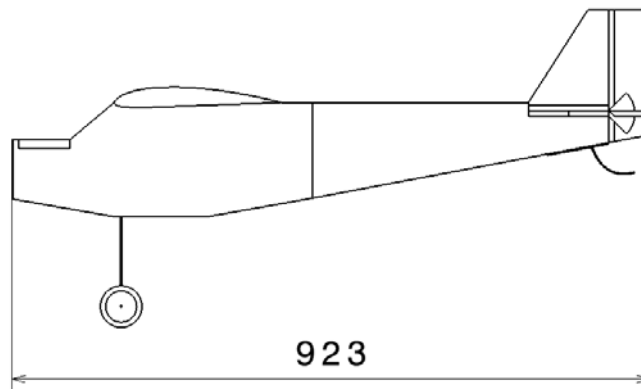
The final design model is shown in the CATIA Assembly Design environment in **Figure 25**. **Figure 26**, **Figure 27** and **Figure 28** represent the three projection views of the 3D model created using the CATIA Drafting environment. Measures are given in millimeters.



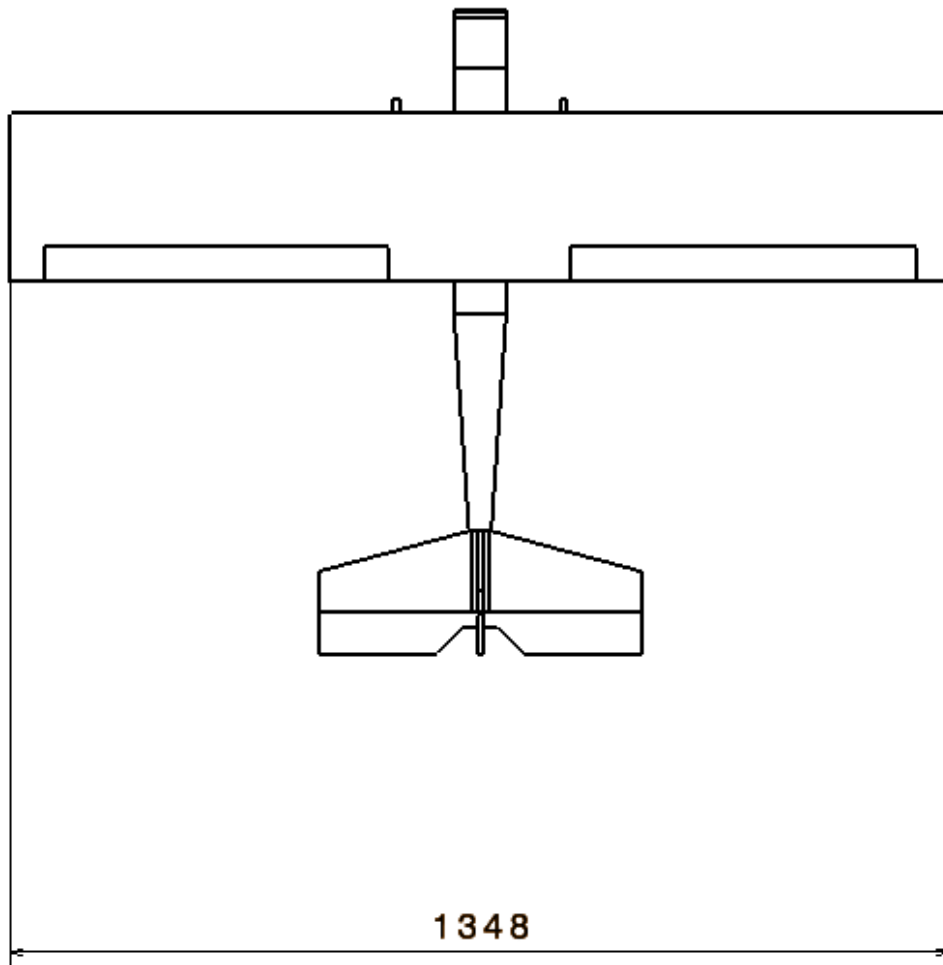
**Figure 25 :** 3D CAD model view in CATIA Assembly Design environment



**Figure 26 :** Front view



**Figure 27 :** Side view



**Figure 28** : Top view

## 4.2 Geometric data and mass properties

**Table 2**, **Table 3** and **Table 4** include all the most important geometric parameters of the aircraft.

Wing	Measure	Unit
Area	0.325	m <sup>2</sup>
Span	1.348	m
Aspect Ratio	5.59	
Root Chord	0.241	m
Tip Chord	0.241	m
Taper Ratio	1	
Aileron Area	0.025	m <sup>2</sup>
Aileron chord to wing chord ratio	0.21	
Spanwise station of aileron starting section in fraction of half wing span	0.067	
Spanwise station of aileron ending section in fraction of half wing span	0.438	

**Table 2** : Wing geometric data

Horizontal Tail	Measure	Unit
Area	0.066	m <sup>2</sup>
Span	0.464	m
Aspect Ratio	3.262	
Root Chord	0.176	m
Tip Chord	0.118	m
Taper Ratio	0.67	
Elevator Area	0.028	m <sup>2</sup>

**Table 3** : Horizontal tail geometric data



Vertical Tail	Measure	Unit
Area	0.022	m <sup>2</sup>
Span	0.192	m
Aspect Ratio	1.675	
Root Chord	0.176	m
Tip Chord	0.09	m
Taper Ratio	0.511	
Rudder Area	0.0112	m <sup>2</sup>

**Table 4 :** Vertical tail geometric data

Assuming the origin of the model's reference system located into the middle point of the leading edge, the x axis coincident with the roll axis and pointing to the nose, the y axis coincident with the pitch axis and pointing to the left and the z axis coincident with the yaw axis and pointing upwards, **Table 5** shows the main mass properties of the fully instrumented aircraft: take-off weight, position of the center of gravity and moments of inertia.

Mass properties	Measure	Unit
Take-off weight	1.146	kg
Empty weight	0.537	kg
Battery weight	0.168	kg
Payload (Pixhawk and peripherals)	0.152	kg
Engine and propeller weight	0.173	kg
Avionics (ESC/BEC, servos and receiver) weight	0.116	kg
$x_{CG}$	-0.064	m
$y_{CG}$	0	m
$z_{CG}$	-72.907	m
$I_{xx}$	0.049	kg x m <sup>2</sup>
$I_{yy}$	0.053	kg x m <sup>2</sup>
$I_{zz}$	0.092	kg x m <sup>2</sup>
$I_{xy}$	0	kg x m <sup>2</sup>
$I_{xz}$	0.004	kg x m <sup>2</sup>
$I_{yz}$	0	kg x m <sup>2</sup>

**Table 5 :** Mass properties and moments of inertia

### 4.3 Manufacturing

Almost every part of the aircraft is made out of  $40 \text{ kg/m}^3$  extruded polystyrene (XPS) manufactured using a Computer Numerical Controlled (CNC) hot wire foam cutting machine: it is a four degree of freedom CNC system in which a nickel chrome alloy (Nichrome) resistance wire is held, in tension and with a voltage applied, between two guides. The two guides can move independently, this way it is possible to cut even prismatic or tapered shapes either out of XPS, expanded polystyrene (EPS) or expanded polypropylene (EPP).



**Figure 29** : CNC hot wire foam cutting machine

Starting from the 3D CAD model, a root and a tip profile for each fuselage section and wing panel was extracted and imported into GMFC software which gives the instruction to the machine.

Afterwards, the parts were assembled together using either aliphatic or epoxy glue. In the most critical spots, wooden or carbon fiber reinforcements were used. For example a 2 x 12 x 1000 mm carbon fiber rectangular rod is used as main wing spar.

The control surfaces were hinged with fiberglass thread reinforced polypropylene adhesive tape and the landing gear made out of a 3 mm harmonic steel rod.

The final result of the assembly is shown in **Figure 30**.

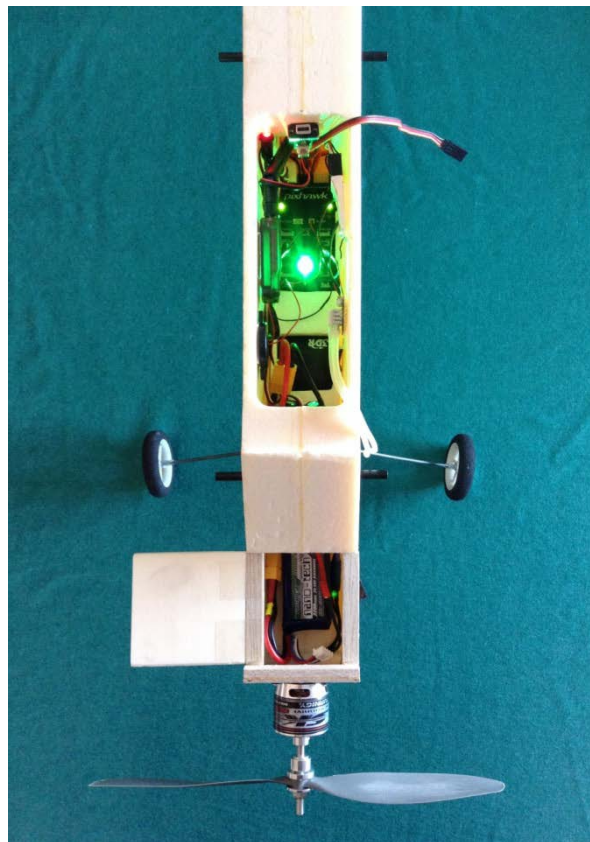


**Figure 30** : Protohawk complete assembly

#### 4.4 Instrumentation mounting

Each component of the on-board instrumentation presented in chapter 1 was mounted on the aircraft trying to keep the center of gravity as near as possible to the one defined by project.

The main Pixhawk board and the GPS module were stored in the expanded polystyrene case after doing all the wiring connections described in chapter 2. Afterwards, the case was fixed to the bottom of the accessible part of the fuselage. The other components were fixed to the sides using high strength polyester Velcro strips. The battery, which is one of the heaviest components, was stored in the nose compartment. Finally, the wing can be attached using 80 mm natural rubber bands. The Pitot tube was fixed to the left wing tip.



**Figure 31** : Complete instrumentation mounting on Protowalk

## 5. Flight data acquisition test

As soon as the system is armed, dataflash logs are automatically created and recorded on the Pixhawk onboard SD card. After the flight it is possible to download them via MAVLink protocol using Mission Planner.

### 5.1 Ground test

In order to check if the flight platform is capable of data logging during flight, a first test was conducted on ground for safety reasons.

The completely assembled and instrumented aircraft was positioned on a table and the system was powered up. Simultaneously the ground control station was activated and Mission Planner launched. After the connection via telemetry radio was established, it was already possible to obtain real time data from the aircraft as expected. In parallel, the system was acquiring and recording data on the SD card.

At this point the aircraft was manually rotated around the roll, pitch and yaw axis consequently in order to simulate a change in attitude during flight. Afterwards, the control surfaces and the motor were tested to check the RC channels signals. In addition some air was blown towards the entrance of the airspeed sensor in order to check its activity.

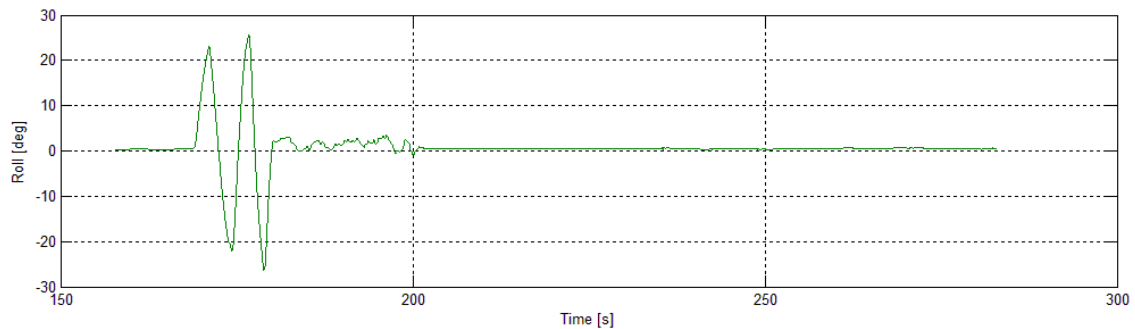
At the end of these operations, the system was disarmed and the dataflash log was downloaded on the laptop using Mission Planner, selecting the “DataFlash Logs” tab and pushing the “Create Matlab File” button.

The file obtained with this procedure is a Matlab data file (.mat) which basically loads a series of arrays into Matlab workspace containing the values of each parameter at each time.

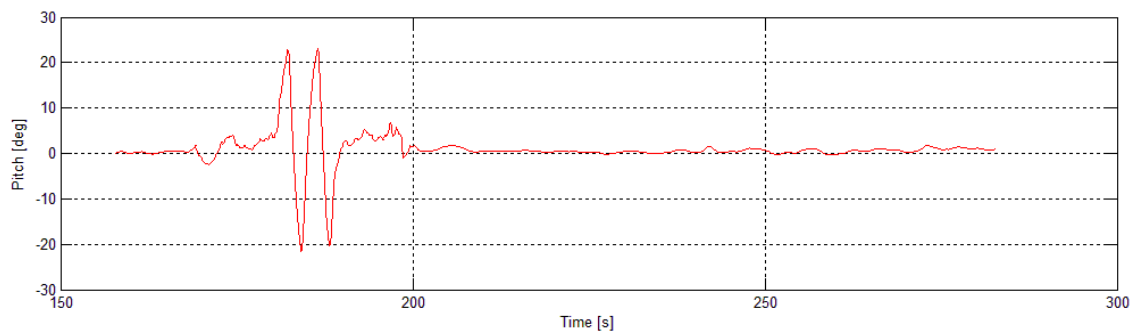
A Matlab script was written in order to extract the data of interest from these arrays, which in this case were:

- Roll, pitch and yaw angles estimations
- Airspeed and groundspeed
- RC outputs

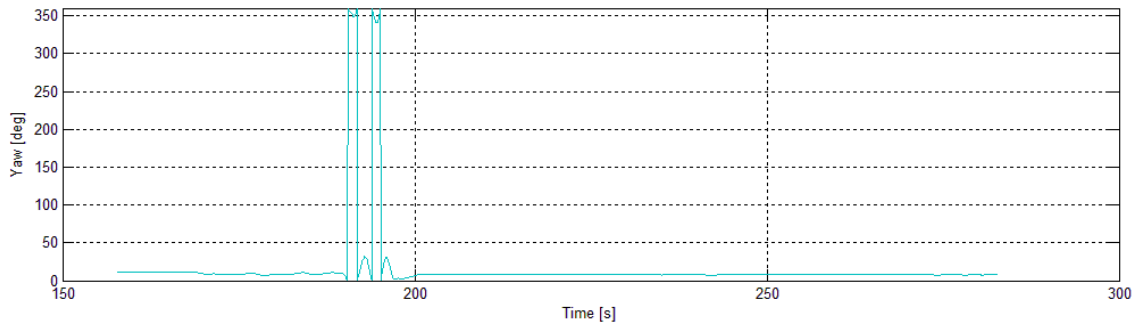
Using the control surfaces deflection angles calibration explained in chapter 3 it is also possible to determine the angles of deflection from the RC outputs. The following figures show the results of the test.



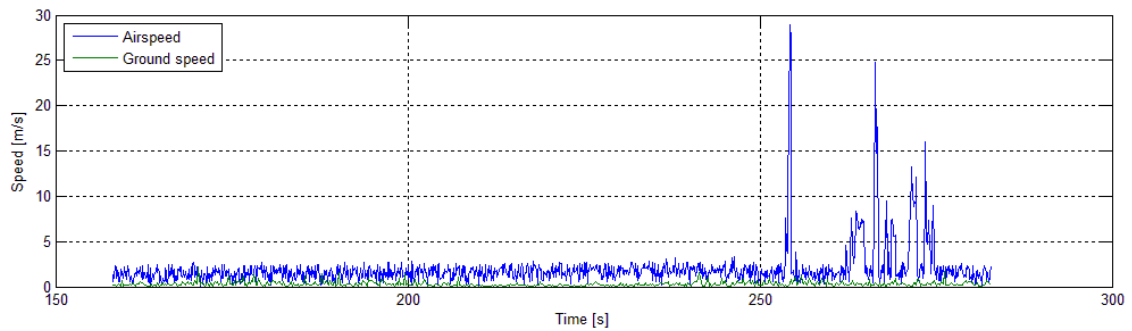
**Figure 32 : Roll angle versus time**



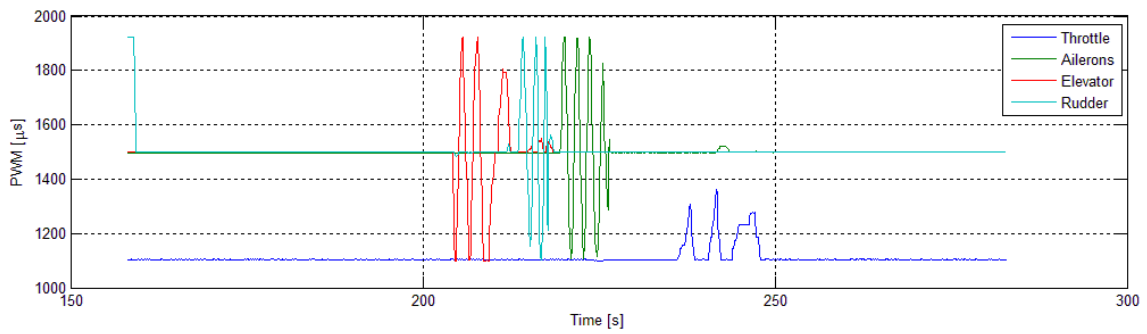
**Figure 33 : Pitch angle versus time**



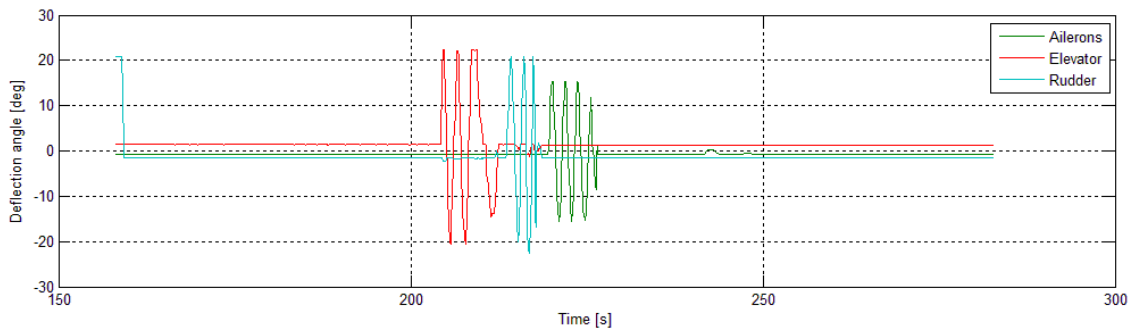
**Figure 34 : Yaw angle versus time**



**Figure 35 : Airspeed and ground speed versus time**



**Figure 36 : PWM signals versus time**



**Figure 37 : Control surfaces deflection angles versus time**

# Conclusions

The setup, configuration and calibration procedures of a small commercially available all-in-one flight controller system, produced by 3D Robotics and called Pixhawk have been described.

A model scale RC aircraft has been totally designed and built in order to create, after being instrumented with Pixhawk and all of its peripherals, a low cost and low risk flying test platform to be used for scientific research.

The final product was ground tested to verify its capability to correctly acquire flight data and record it on a micro SD card.

The data collected was finally extracted and analyzed with the use of a Matlab script.

The next step will be to conduct a series of flight tests to start acquiring real flight data that can be used for a multitude of purposes such as theoretical model validation, performance analysis and system identification.



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