A study into automation of a quadcopter

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Contents

Abstract

This research paper will focus on Quadcopters, more specifically different algorithms that can make it autonomous and the applications that ensue. The main purpose of this research paper is to learn more about automation, electronics and how they interact with real life situations. The task is to automate various parameters using PID algorithms so that sustained automated flight can happen without the need for a human operator.

Introduction

Flight was only an ideal for many centuries and was not possible until the 20th century when the Wright brothers succeeded in inventing and making the first airplane and the first sustained and controlled human flight on December 17, 1903.

As time has passed, technology has become more advanced and the materials lighter hence we now face an incredible technological era where engineers and physicist are able to create and send autonomous vehicles (such as the Curiosity Rover) to Mars [1]. This is mainly due to the staggering advances in microprocessor technologies, as even our smart phones can far outdo the processing power used to send the first man to the moon (The Apollo Guidance Computer, with 15 data bits and one parity bit). [2]

This vast expansion in processing capability has given birth to many aircrafts (autonomous and not) that would not be able to fly without the use of advanced algorithms and increased processing capabilities. Examples of these are the B2 stealth bomber, F117 NightHawk, and of course the infamous M1 Predator drone. All these have one big thing in common; they use computer technologies to simplify the job of the operator/pilot.

Problem analysis

Drones have recently been associated with military and invasive uses however there remain many areas in which drone technology can be used to save lives, instead of the opposite. Automated flight in particular has many applications where intelligently designed systems can be used to deliver relief in inaccessible areas. In current times where weather phenomena are getting more unpredictable and there is a need to provide improved support for emergency relief efforts. Technological advances relating to accessibility and price of drone components means that using drones to aid relief efforts has become increasingly feasible. An example of such use is firefighting where many departments all over the world have added some form of UAV for arial reconnaissance of a host of different types of fires. A California National Guard Predator drone was even used to give firefighters battling a forest fire in Yosemite “an almost immediate view of any portion of the flames” [3]. This however is a very advanced drone which would be impractical to imitate.

In assessing how a relatively simple UAV controlled by a chip can help in real world situations, it becomes evident that several different applications need to be considered. These are usually photographic reconnaissance, transport or data acquisition some sort, all depending on the design and types of sensors used.

Photographic reconnaissance drones vary from simple Quadcopters with GoPros attached to high-tech military surveillance UAVs. They provide the distinct advantage that they can fly into high-risk scenarios without endangering human life and relay useful information back, be it for a fire department or a countries military.

Transport drones are a rarer breed then their reconnaissance counterparts. This has to do with the fact that Li-Po battery powered drones have very strict limitations due to battery weight and subsequent power consumption of the devices. Such solutions are useful only for smaller urban environments where accessibility by road has been hindered in some way. Amazon has also looked into this technology for delivering packages with somewhat lacking results due to FAA regulation. There still remains a lot of work that needs to be done before regulatory uncertainty in this field is reduced.

Data acquisition drones are usually ones that have high tech terrain mapping equipment or similar. Such an application is mostly for research, but for relief efforts such a program could be useful for mapping floods as global water levels increase knowing the extent of the damage would be an invaluable resource to humanity. Other such uses are also mapping caves using quadcopters with advanced sensing equipment.

In choosing the simplest application it becomes evident that transport is a good option. There are many real world applications for transport, especially by air, for the purpose of emergency relief. The only situation where the use of a drone becomes a real option is where for some reason acute assistance is needed in an area that is or has been made inaccessible. Due to the nature of the project, a quadcopter provides a simple platform from which to design a delivery/return behavior that can provide a small relief “package” where it is acutely needed. UAVs have been used to ferry medical samples to labs over longer ranges [4]. This application supports the idea of overcoming the inaccessibility of an area due to some circumstance, i.e. floods. Drones can also be used to deliver medicine in natural disasters, as shown by the Matternet drone in Haiti. Where drones with remote pilots were used to deliver medicine where it was needed, as opposed to the older slower form of logistics which “a truck carrying a big box of medicine every quarter” [5]. The same source also discusses the ability to create a courier service that isn't prone to traffic or other risks. Such a courier service could be invaluable between medical centers for sending samples/tools between them. For the purpose of this project the quadcopter has been chosen as a transport platform, given the limitations this poses, the design will mainly be for small packages such as essential medicines, antibiotics and hygiene kits. This design could also be used to deliver sterilized operating equipment to doctors in the field.

All of the above mentioned applications require that there be a “special” category for drones that are designed in disaster relief. As it stands now the law in Denmark about drones is basically that of a private RC helicopter. The following is a translated breakdown of the rules that pertain to flying of “drones” in Denmark [6]: For Drones less than 7kg:

- Flying must be conducted in a manner such that other lives and property are not put at risk. Also such that minimal distress is caused in the area it is flown.
- Distance to the runway/runways on a public airport (as given by the “Kort go Matrikelstyrelsens” map) must be at least 5km.
- Distance to the runway/runways on a military airport (as given by the “Kort go Matrikelstyrelsens” map) must be at least 8km.
- Distance from urban dwellings and larger public roads must be at least 150 m.
- Maximum altitude permitted is 100m above the terrain.
- Closely inhabited areas including summer houses, inhabited camping sites and outdoor areas where a large number of people are gathered in free air may not be flown over.
- Particularly sensitive natural areas which are mentioned in the rule set regarding pilotless aero planes (BL 9-4) may not be flown over.

There still remains uncertainty in what type of sensing equipment equates to an invasion of privacy, if that information is saved or purely used to navigate, then overwritten. However these rules are for private flight, relief oriented solutions would in most likelihood be exempt from this. However for the time being this limits testing capacity to large indoor facilities. For this project a thanks needs to be mentioned to the Blue Water Dokken handball arena, whom generously allowed the testing of the Quadcopter indoors for a couple of days in the arena. (See acknowledgements for further info)

Quadcopters date as early as the 20’s and they were initially a US Army project. In the next 94 years, quadcopters have become lighter and more emphasis has been put into this new technology because of its wide range of applications. [7]

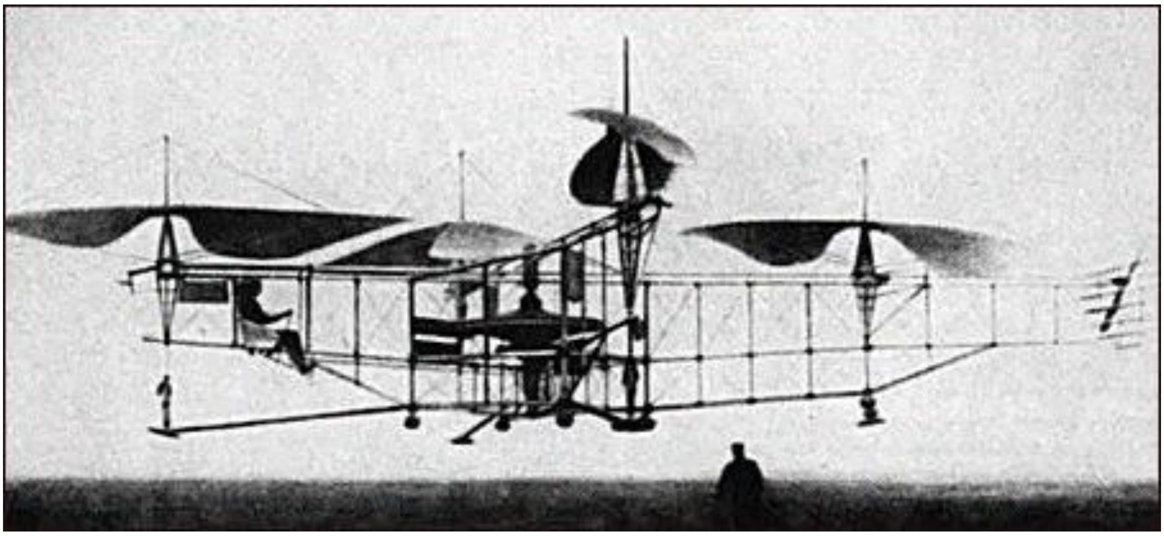


Figure 1- Primitive Quadcopter which dates back to 1920

Quadcopters are the living proof of the outstanding ingenuity of engineers as the recent models of quadcopters are capable of doing incredible things such as balancing sticks, catching balls, surveilling different areas and being a decisive tool in some military missions as they are able to operate in the most hostile areas without endangering the human beings that operate them. Nowadays, Quadcopters are even being used for transportation. The American retailing giant Amazon, has developed a delivering system concept using drones called Amazon Prime Air. Although this concept is not fully viable due to regulations it could (in the future) be a good way to deliver packages and loads in a matter of minutes or hours (depending on the distance). Amazon estimated that the Amazon Prime Air can cover an area of 10 miles (16.09 km) with a cargo of 2.3 kg in about 30 minutes. [8] Amazon is not the only company that is considering delivering packages via drones. DHL, the German delivery giant is also testing a delivery system using drones that can guide themselves using a GPS system. [9]

The practical applications of quadcopters don't stop on the surface of the Earth. NASA is even considering sending a quadcopter to the surface of Titan (one of Saturn’s largest moons) in the attempt to explore it and collect data. It can be seen that the practical appliances of a Quadcopter are limited only by ones imagination. [10]

Without doubt, these machines have a lot of practical applications depending on the desired outcome, but this research paper will try to narrow it down to more comprehensible and evaluated list. In order to do this the following needs to be considered:

- **Why autonomous?**

Considering that there are tasks that are safer, faster and more efficiently done by machines, this allows humans to be freed from the monotony of these tasks. When Fukushima nuclear reactor needed to be assessed in April 2011, the right tool for the job was the T-Hawk drone made by Honeywell (Honeywell Aerospace, 2014). In an environment that no human being could have survived, it is clearly an advantage that should be explored and exploited to maximum. 11

- **Why VTOL?**

Considering the large range of needs for a flying vehicle, there are very specific uses for “Vertical Takeoff and Landing” aircraft, be it out of space considerations or lack of runways. But with VTOL capability comes also hovering above a fixed point and that is a very specific advantage in many of the situations mentioned above.

- **Why Quadcopter?**

Everybody knows they are inherently unstable and require either a motor for each rotor or an extremely complicated distributed transmission in cases where only one engine is preferred. While a single rotor mounting large blades offers benefits in efficiency, the solution also comes with added complexity due to the pitch control mechanism, therefor extra weight.

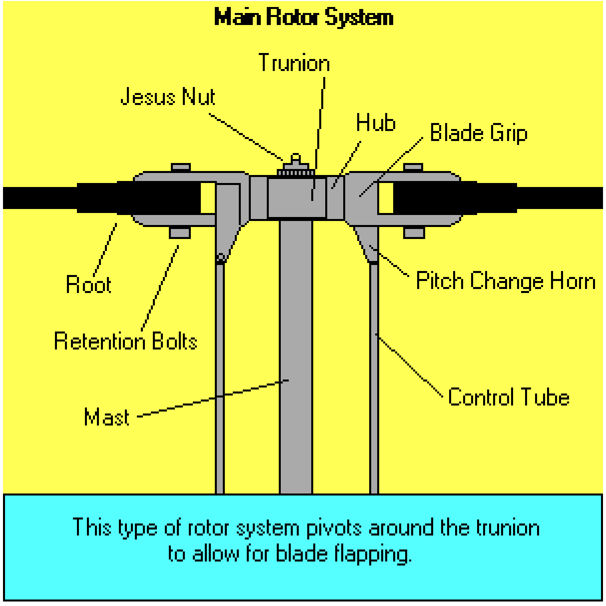


Figure 2- Main Rotor System [12]

Tri-rotors have solved the inherent torque problem by varying thrust through its motors, but an imbalance due to the torque effect of the three blades rotating in an asymmetric configuration. This is a very complicated design to implement as it is more unstable then its quad rotor counterpart.

Quadcopters solve this problem by using 4 motors/rotors, and insuring control by varying thrust to those motors according to the desired direction. They also come at a price, but the balance offered between simplicity, stability and power requirements is what makes them ideal for various applications involving VTOL, point to point, point to multiple points, remotely controlled flight and hovering.

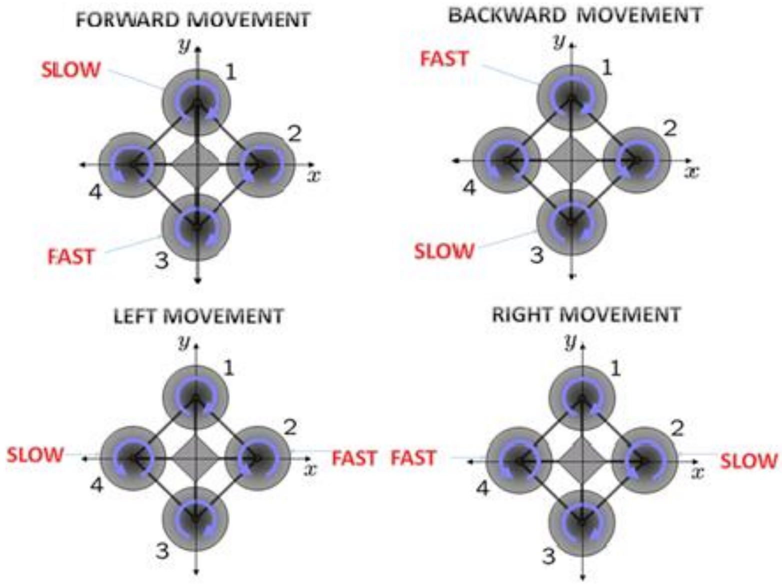


Figure 3- How Quadcopters move in certain directions [13]

Although Quadcopters have a lot of practical applications, this technology has some drawbacks as well, making it not so viable in some matters. Quadcopters are expensive to build and their range is rather lacking. The range of a Parrot AR.Drone 2.0 that has a 1000mAh (1Ah) battery is about 12 minutes of flight-time. The cost of such a drone is about 300$ [14]. These Quadcopters are for private use and have a relatively small range for a high price. On the pro side, it has to be mentioned that such devices eliminate dependency on infrastructure, making it the perfect (small sized) vehicle in inhospitable and inaccessible areas. Provided they remain within the range parameters.

Potential uses

As the world faces climatic change and constant conflicts, once the problems of autonomy and cost are solved, Quadcopters are a technology of the future. They can bring medicine to military camps; food and emergency relief to affected areas and can be even used in military purposes.

An IMF study says that more and more people are being affected by natural disasters and are currently living in areas at risk from natural disasters; “Over the past two years, 700 natural disasters were registered worldwide affecting more than 450 million people”, according to the IMF study [15]. On Friday 11 March 2011, Japan was seriously affected by an earthquake of magnitude 9.0 on Richter scale. The earthquake caused tsunami waves that had a peak of 30 m [16]. The study states that Japan's- “Power, gas and water supplies were disrupted and road, railways, airports, schools and other infrastructure were severely damaged.”[17]

In case of such a natural disaster where the railways and roads are be affected, quadcopters could be a very reliable and efficient mean of transporting supplies and medicine from one point to another. They can be quickly dispatched from a number of mobile or fixed dispatch points and be able to provide assistance over a large area with minimal human risk. Used for search/rescue with advanced sensing or even mini flying defibrillator pads, the applications are endless.

According to the website of a non-profit organization [18] the number of natural disasters has increased in the past years and the most affected area is Asia-Pacific. According to the same website, the number of natural disasters has increased from 75 events per annum in 1980 up to a peak of over 200 events per annum in the year 2000.

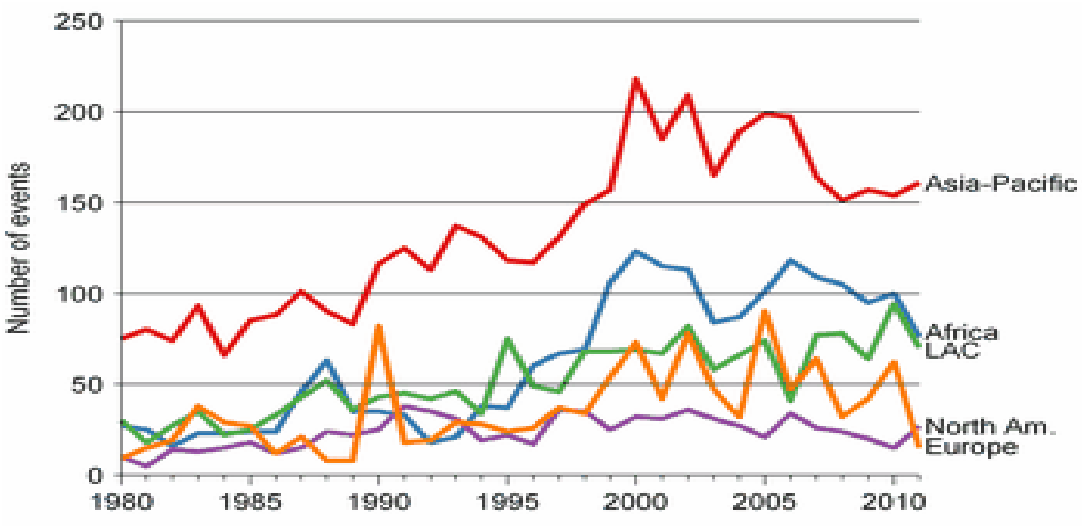


Figure 4- Graphic showing the number of natural disasters per annum in different regions [19]

It can be seen on the graph above that beside the Asia-Pacific region, Africa has also registered an increase in the number of natural disasters. The area with almost no increase in the number of natural disasters is North America and Europe.

Considering the aforementioned data it is evident that drones may be able to play an increasingly active role in disaster relief in the time to come. As is common with most natural disasters, it is the infrastructure that is affected the worst, this leads to shortages in medicines and food. Using drone technology to help in this regard would only be beneficial to humanity.

Undoubtedly some of the best applications of autonomous Quadcopters are military. UAVs can give “instant battle overview” and other associated mission utility like fire control, range finders, laser targeting etc. Although they still have limited range (battery powered models), not directly exposing personnel to opposing forces cumulated with a low radar signature, low noise levels and small size (making them almost invisible to radar) makes them the ideal tool for urban reconnaissance missions. In cases where the deployment area is very far away, quadcopters can be deployed from airships or other platforms that can launch and retrieve them. Still equating in an overall reduction in human time spent in enemy airspace.

Surveillance missions can be performed in civilian environments for law enforcement purposes, although most types of operations can be covered by airship, which in contrast to Quadcopters benefit from an infinitely longer range allowing them to loiter above a designated area for long periods of time, much bigger carrying capacity (for larger weights simply use a bigger airship). In more fluid situations that requires higher mobility, the Quadcopters and airships can be associated for a faster response.

Maintenance of large structures like tall buildings, bridges, monuments, plants, stacks, infrastructure, can benefit from the advantages offered by the stable platform that a Quadcopter is. Bringing “an eye” (camera or other specialized inspection device) in close vicinity of the place to be inspected or maintained in a very short period of time, especially at higher altitudes, is an advantage that we cannot ignore. Reducing the risk of injury through eliminating direct human presence on high buildings or under bridges combined with the reduced time periods required to reach and inspect difficult places makes it an interesting and viable proposition.

Another area in which Quadcopters can be very useful is mapping radiation zones, in recent times (in part due to natural disasters increasing) the number of nuclear disasters has also gone up. Mapping the radiation in these zones can be a very dangerous task for biological organisms (high levels of radiation even interfere with electronic circuits) therefore Quadcopters can easily be retrofitted with radiation detection sensors and GPS modules to provide a risk-free and in-depth overview of radiation levels in disaster zones so as to guide relief efforts/workers. This would allow relief workers to plan ahead of time a safe route risk assessments of the area in question.

Mountain rescue is also an area where Quadcopters can make a huge impact. Based on a two part technology that involves a detecting device carried by the autonomous Quadcopter sending out a search signal and a reflective material worn by those in distress, which bounces back a directional signal. Although some detectors have a considerable size and weight, ninth generation Recco detectors have been designed to weigh less than 1 kg, and is the size of schoolbook. (The Recco System, 2014) [20]

In fact, such devices make a great platform for delivering small equipment and other small cargo on short distances to inaccessible but open places, be it a camera, emergency medication, sensors or other small telecommunications equipment. It does have its limitations in weight and range, but within their window of specifications, Quadcopters are good solution to a whole range of problems.

Task Definition

The general aerodynamics of flight

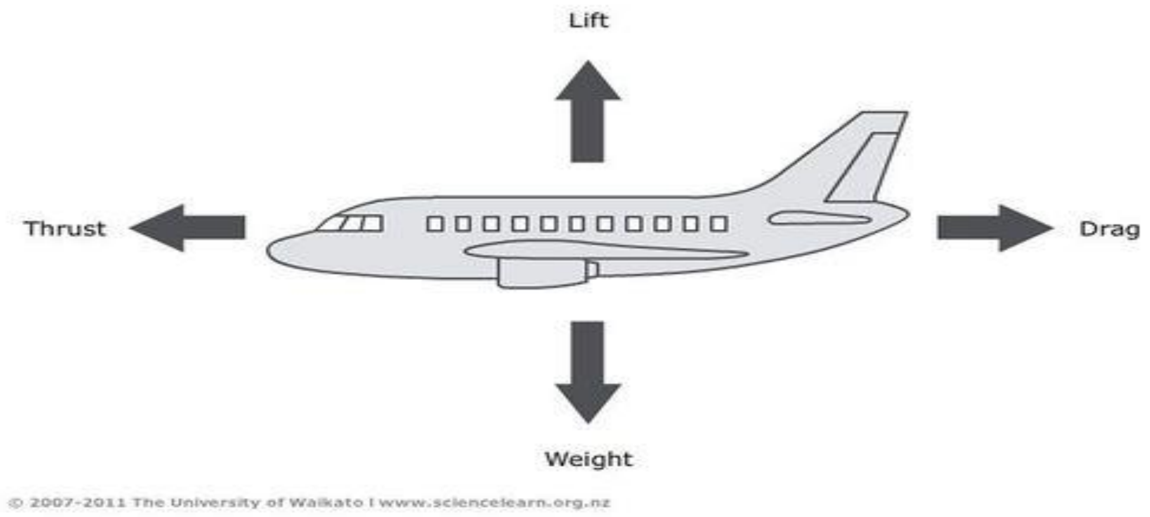


Figure 5- Main forces that apply to aircrafts [21]

As it can be seen in the picture above, when it comes to flight in general, there are 4 main forces that are always present: thrust, lift, drag and weight.

In every possible case, for the object to be able to maintain itself in the air and fly, the lift must be greater than the weight and the thrust must be greater than the drag.

What creates lift?

Well, the lift is created using Bernoulli's principle. The specific shape of any wing allows this principle to work as it will create a difference in air pressure that can allow the aircraft to stay in the air.

For the aircraft to be able to have lift, the air pressure above the wing/propeller must be less than the air pressure bellow the wing/propeller.

Lift must always be greater than the force of gravity in order for the aircraft to fly.

What is drag?

As an aircraft moves through air, it will create drag as air has a certain resistance to movement. The resistance to the movement of the aircraft is called drag.
Drag must be always less than thrust in order for the aircraft to move through air.

It also needs to be mentioned that an aircraft can have 3 basic motions that it can perform, as these 3 motions will be mentioned in the next chapters.

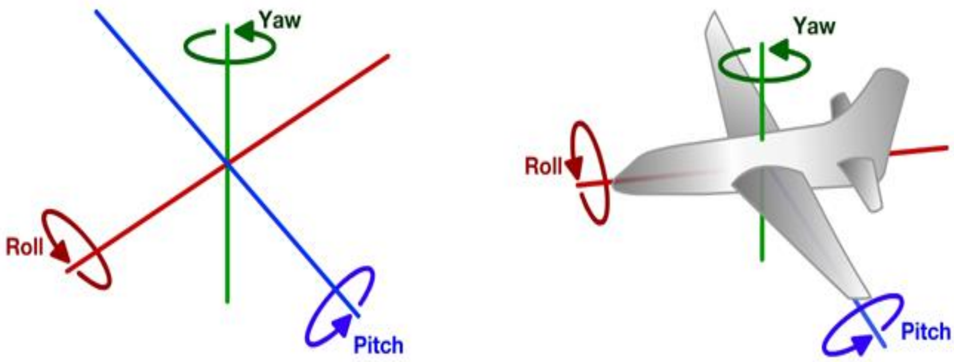


Figure 6- Main motions that [22]

When explaining these 3 motions, the Quadcopter will be mentioned as these apply to prototype built for this project.
These 3 motions are roll, pitch and yaw. The easiest way to explain these motions is shown in the picture above. Each movement is characterized by a certain axis that is fixed. For example, Roll uses the axis from the front to the end of the Quadcopter to perform this specific motion; yaw uses the axis from the top to the bottom of the Quadcopter and the Pitch uses the axis from the sides of the Quadcopter.

Principle of VTOL (Vertical Take Off and Landing)

Taking of vertically involves not only sufficient thrust to cancel out gravitational acceleration but also controlling thrust provided by each motor to keep the vehicle stable relative to the x-axis, while accelerating relative to the y-axis. Another factor to be considered is the torque effect. Various solutions have been developed involving:

Tandem rotors assembly

Rotor assembly rotating in opposite directions countering each other's torque out, or managing rotation around y-axis of the whole assembly by the difference of torque induced by the rotors (T_{total} = T_1 + T_2 + T_3 + T_4), a solution widely used by Kamov for military helicopters. Boeing adopted a similar concept for the CH-47, the difference being in the fact that the rotors are not coaxial, but working together on the same principle of cancelling out each other's induced torque. Other configurations are also possible, but the working principle is the same.

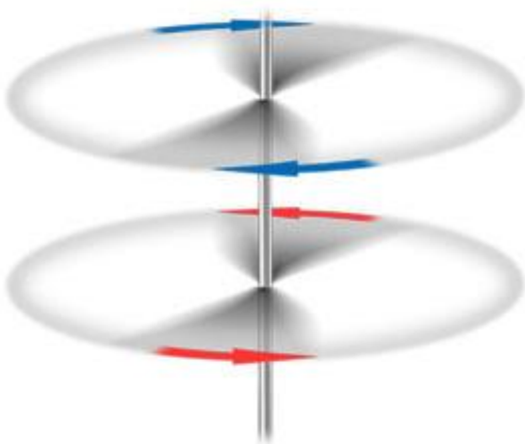


Figure 7- Tandem rotor assembly [23]

Tail rotor assembly

In the case of tail rotor assembly, the torque of the main horizontal rotor providing the vertical lift thrust is countered by a smaller rotor placed on the tail providing horizontal thrust. Varying the thrust on the smaller rotor allows the vehicle to rotate or remain at rest relative to the y-axis.

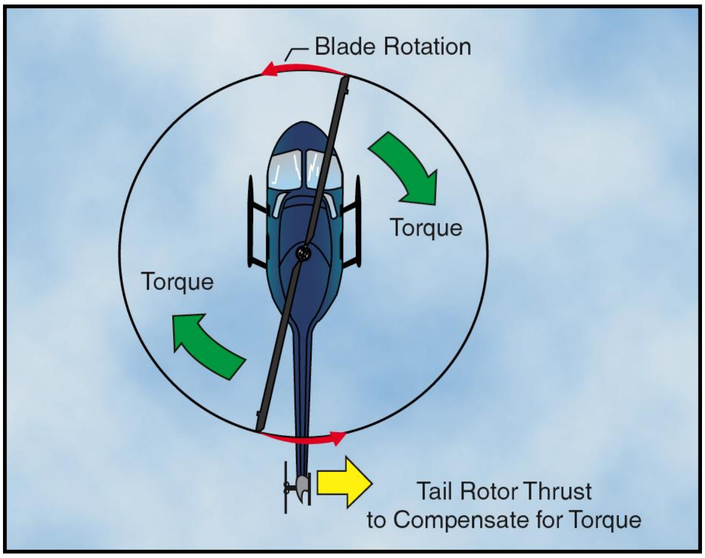


Figure 8- Anti Torque [24]

Notar system

The Notar system replaces the tail rotor assembly with high volume of ambient air to pressurize the composite tail boom produced by an enclosed variable-pitch composite blade fan that produces a low pressure creating a boundary layer of air along the tail boom utilizing the „Coanda Effect” creating thrust. [25]

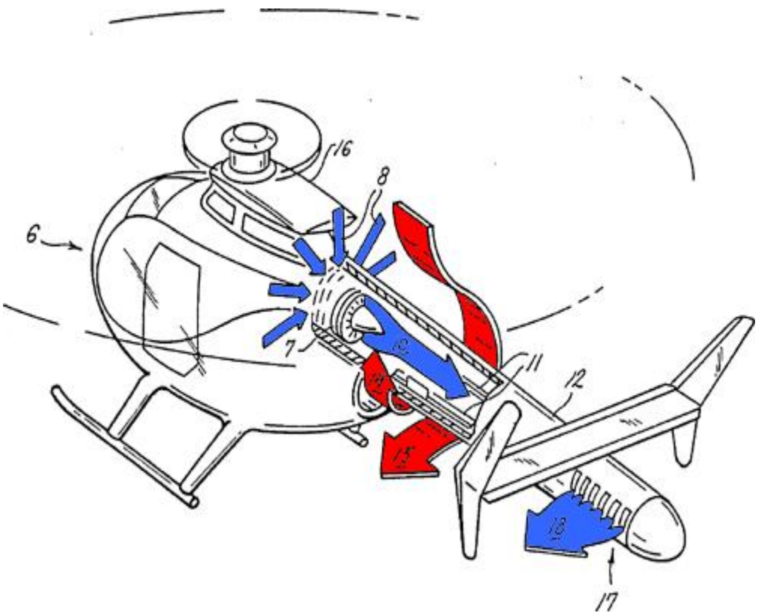


Figure 9- Notar System [26]

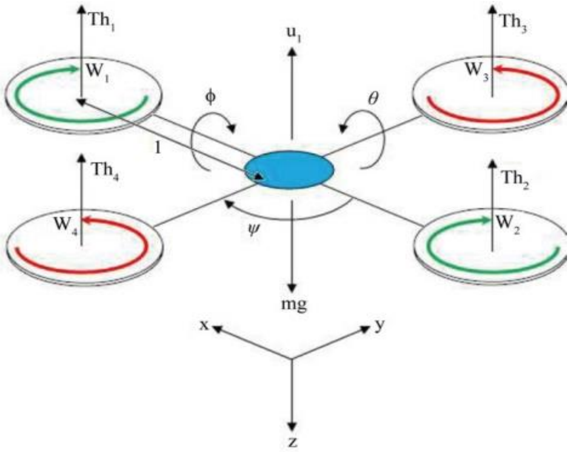


Figure 10- Axis reference frame - Hovering [27]

Multirotor assembly

Multirotor assemblies are different to other types of arrangement through their mechanical simplicity. Because they can change the pitch/roll angles just by varying the thrust of the motors, control can be exercised without the complicated mechanical assemblies that are required in single rotors or tandem rotor flying vehicles. Their inherent instability is exploited through the use of computers.

Principle of sustained flight and hovering at fixed point

Without going deep into studying induced torque which will depend on the type of battery, motor, blades and weight, assuming it together with conclusions of the blade theory, we can understand that forces acting on a powered Quadcopter are as follow:

1. **Gravity**, acting on the Center of Gravity (CG), also point zero of our axis of coordinate x-y-z, directly proportional to the mass of the vehicle, defined easily by G=m*g

2. **Thrust**, delivered by each motor, the sum of which in the case of a flying quadcopter has to match and overwhelm gravity giving the vehicle vertical movement. Thrust delivered by each motor play another very important role in the Quadcopter dynamics; by varying thrust delivered by each motor, the resultant thrust (considering that the thrust vector of each motor is always perpendicular on the rotational plane) acting together with gravity will rotate (known as roll and pitch movement) the entire assembly around the Center of Pressure, the resultant force being the force that drives the vehicle front/back/sideways, when it counters the forces induced by aerodynamic drag.

3. **Tangential force** induced by the resulting induced torque. As described, the quadcopter is configured with 2 pairs of opposite blades, each pair rotating in opposite direction with the resulting torque being zero (no yaw movement). Yaw movement is achieved by varying angular speed on one pair of blades or the other resulting in non-zero torque that will induce a tangential pair of forces that will rotate the whole assembly around the vertical axis (that contains both center of pressure and center of gravity in a good, stable or relatively stable design).

It needs to be mention that Center of Pressure (CP) is the point where all of the aerodynamic pressure field may be represented by a single force vector (in the case of this project, the resulting thrust vector) with no moment. Generally, depending on what is required from the Quadcopter, CP and CG in equilibrium are to be found on the same vertical axis, resulting in no moment acting on the whole assembly. However, when pitch/roll angle is different than 0 with gravity acting from CG and thrust vector acting from CP and because the thrust vector is perpendicular on the air foil and acting in the same direction with the assembly axis, motion on horizontal is induced by the resulting force vector between the thrust and gravity.

In hovering mode, a Quadcopters collective thrust, according to Newton's Law equals gravity

$$F_{total}= F_1 + F_2 + F_3 + F_4$$

Where,

$$F_{total} = m*g = F_1 + F_2 + F_3 + F_4$$

With F_1 to F_4 being nominal thrust of each motor, F_{total} being the collective thrust, m is the mass of the flying vehicle (and, when loaded, the mass of the whole vehicle plus the mass of the loaded cargo) and g – the gravitational acceleration. For the purpose of the project a thrust to weight ratio of 2:1 has been chosen, meaning that the payload should not exceed the weight of the flying vehicle.

When in motion, for each axis transformation matrices and the resultant rotation matrix can be written as:

$R = R_x*R_y*R_z =$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} * \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} * \begin{bmatrix} \cos\psi & -sin\psi & 0 \\ sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} =$$

$$\begin{bmatrix} \cos\psi\cos\theta & \cos\psi\sin\theta\sin\phi - \cos\phi\sin\psi & \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi \\ \sin\psi\cos\theta & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \sin\psi\sin\theta\cos\phi - \sin\phi\cos\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\theta\cos\phi \end{bmatrix}$$

For the brushless motors, the torque of each engine is given by the formula:

$$\tau = K_t * (I - I_0)$$

Where τ is the torque of the motor, K_t is the motor proportionality constant, I is the input current and I_0 is the current when there is no load on the motor.

The power developed by the motor is

P=I*V

Where V is $V=I*R_m+K_v*w$ (V is the voltage drop across the motor, R_m is the resistance of the motor, w is the angular velocity of the motor, and K_v a proportionality constant), resulting in Power being equal to

$$P = \frac{(\tau + K_t) * (K_t * I_0 * R_m + \tau * R_m + K_t * K_v * \omega)}{K_t^2}$$

And if the assumptions that the motor has a negligible resistance is made, the theoretical model for the power becomes

$$P \approx \frac{(\tau + K_t * I_0) * K_v * \omega}{K_t}$$

And if the assumption is extended to the fact that the current I_0 when no load is on the motor is negligible, then the equation becomes

$$P \approx \frac{K_v}{K_t} * \tau * \omega$$

Now, it is known that the energy the motor consumes is equal to the energy of the air being pushed by the propeller, resulting that

$$P = F\frac{dx}{dt}$$

Where $\frac{dx}{dt}$ is he velocity of the air v_h and F the thrust of the motor that it will be noted as T from now on.

Restricting momentum theory to a case where it is considered v_h the velocity of the air in hover mode and the velocity of the surrounding air to be equal to 0, the formula of the minimum air velocity needed for the vehicle to hover as a function of the thrust T

$$P = T * v_h$$

$$v_h = \sqrt{\frac{T}{2 * \rho * A}}$$

Where ρ is the density of the air and A is the area swept by one rotor.

Noting that torque is

$$\tau = \vec{r} \times \vec{T}$$

And restricting the cases to where torque τ is proportional to the thrust T times a proportional constantK_τ, thrust becomes

$$T = \left(\frac{K_v K_\tau \sqrt{2 * \rho * A}}{K_t} * \omega \right)^2 = k * \omega^2$$

Where k is a specific constant (if the density of air and the area swept by the motor are considered as constants).

The total thrust generated by all 4 motors in out theoretical model will be

$$T_B = \sum_{i=0}^{4} T_i = k * \sum_{i=0}^{4} \omega_i = k * \sum_{i=0}^{4} (\overrightarrow{\omega_i})$$

But because a restriction to hover mode only is made, the angular velocity has only one component on the vertical (z-axis) for each motor and the equation becomes

$$T_B = k * \begin{bmatrix} 0 \\ 0 \\ \sum_{i=0}^{4} \omega_i^2 \end{bmatrix}$$

While drag (in the case of this project a simplified perspective of friction forces) will be modelled as being proportional with a constant (k_f) times displacement vector and opposed direction to thrust.

$$F_f = -k_f * \begin{bmatrix} \vec{x} \\ \vec{y} \\ \vec{z} \end{bmatrix}$$

With the forces acting on the quadcopter the theoretical model will move to find the torques involved. As mentioned before the total torque will be sum of all torques induced, while the torque of a single engine has to be the sum of the torque necessary to overcome drag and the torque necessary to provide positive lift (positive displacement on the z-axis) according to the formula

$$\tau_z = b * \omega^2 + M * \alpha$$

Where b is an appropriately dimensioned constant derived from the drag equation ω is the angular velocity, M is the Moment of inertia of the motor around the z-axis and α the angular acceleration of the motor. Since, according to the drag equation

$$F_f = \frac{1}{2} * \rho * C_f * A * v^2$$

(C_f is a dimensionless friction coefficient, A is the area of cross section of the propeller, not the area swept by it, and v the velocity at the tip of the propeller), and

$$\vec{\tau} = \vec{r} \times \overrightarrow{F_f}$$

Then, considering that $v = \omega * R$, torque due to drag becomes

$$\tau_f = \frac{1}{2} * \rho * C_f * A * R * v^2 = \frac{1}{2} * \rho * C_f * A * (\omega * R)^2$$

And considering density, friction coefficient and area as constant and replaced with b, the following equation will be obtained

$$\tau_f = b * \omega^2$$

In addition, if it is considered that during steady flight (hovering) the necessary angular speed is constant, angular acceleration can be approximated$\alpha \approx 0$ then torque becomes dependent of the squared value of the angular velocity times a constant, according to the above formula.

For the whole assembly the total torque (yaw torque) is the sum of all torques given by each propeller and becomes

$$\vec{\tau}_{z-total} = \sum_{i=0}^{4} \vec{\tau}_i$$

$$\tau_{z-total} = \tau_1 - \tau_2 + \tau_3 - \tau_4 = b * (\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2)$$

The pitch and roll torque are given by classic mechanics. By inducing the same torque in motors 1 and 3 (roll axis – arbitrarily chosen) and varying torque in motors 2 and 4 (pitch axis – arbitrarily chosen) [28] we obtain for the roll axis

$$\tau_\varphi = \sum r \times T = L * k * (\omega_1^2 - \omega_3^2)$$

Analog, for the pitch axis

$$\tau_\theta = L * k * (\omega_2^2 - \omega_4^2)$$

Where L is the length from the CG (and in the ideal model we assume that coincides with CP). And now we have a model of torque on all axes, defined as

$$\tau_B = \begin{bmatrix} L * k * (\omega_1^2 - \omega_3^2) \\ L * k * (\omega_2^2 - \omega_4^2) \\ b * (\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2) \end{bmatrix}$$

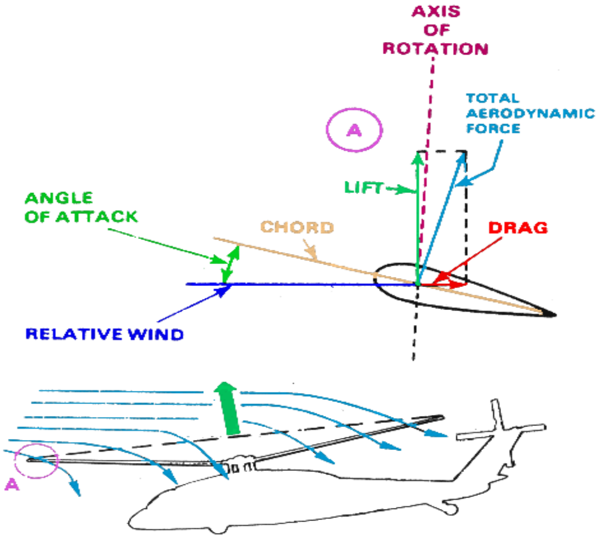


FIGURE 2-87. FORCE VECTORS IN LEVEL POWERED FLIGHT AT HIGH SPEED.

Figure 11-Force vectors in level powered flight at high speed [29]

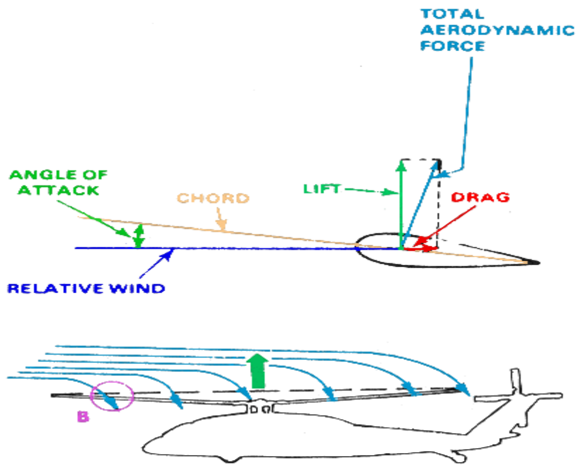


FIGURE 2-88. FORCE VECTORS AFTER POWER LOSS WITH REDUCED COLLECTIVE.

Figure 12-Force vectors after power loss with reduced collective [30]

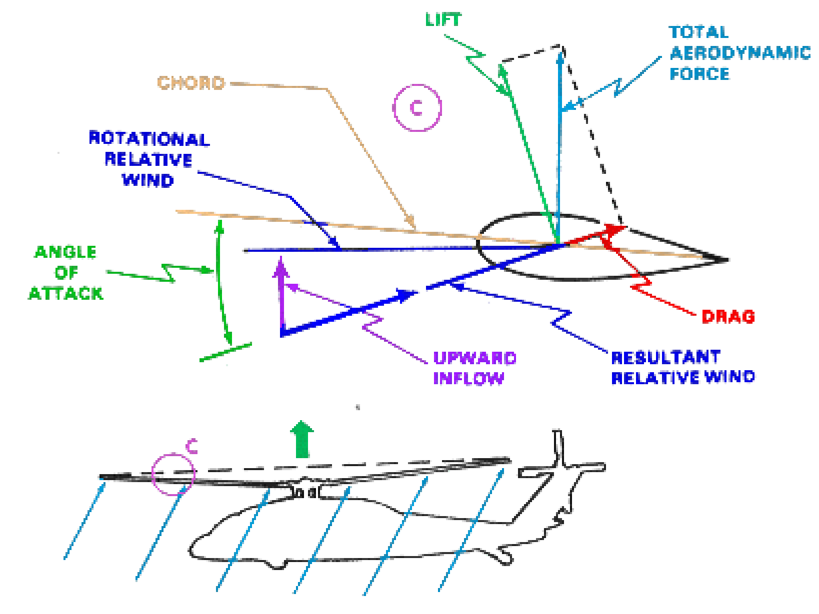


FIGURE 2-89. FORCE VECTORS IN AUTOROTATION STEADY STATE DESCENT.

Figure 13- Force vectors in autorotation steady state descent [31]

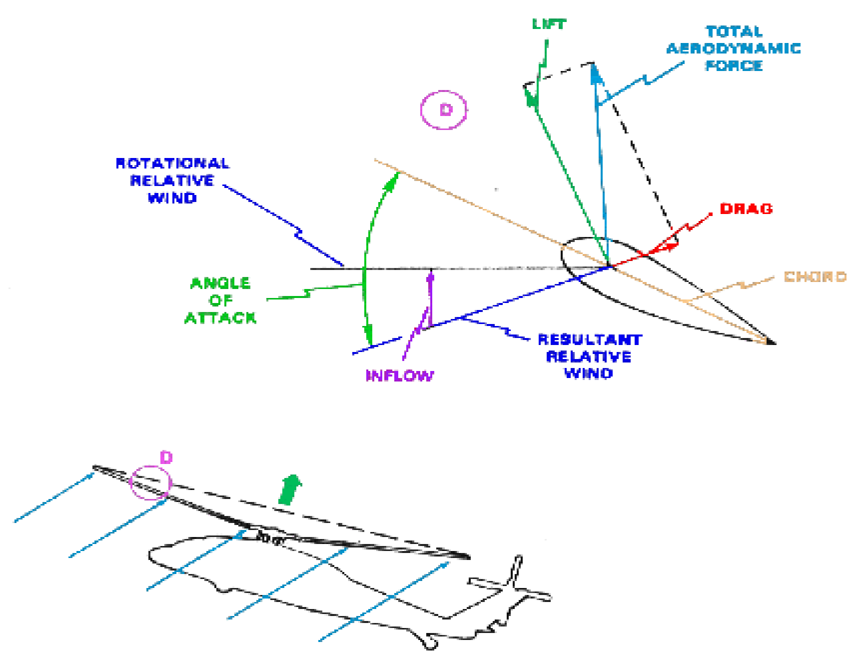


FIGURE 2-90. AUTOROTATIVE DECELERATION.

Figure 14-Autorotative deceleration [32]

Solution

In forming a set of specifications it has to be taken into account that the prototype that will be made for this semester project is a very simple and rudimentary version of an autonomous quadcopter design. Due to the complexity of flying, it will not be taken into consideration factors as aerodynamical drag, ground effect, the point being an educational exercise into the mechatronic aspects of such an autonomous flying platform. The ability to automate flight from point A to point B is the goal of the project. Another core requirement is to be able to detect and avoid obstacles autonomously while still mapping an efficient way to get between the points. An additional possibility is to include a memory map which makes the return of the Quadcopter far quicker than deployment as rudimentary obstacle avoidance requires some random false trials before the system is able to make its way to the designated location.

Diagram

Since the specifications refer to the capability of being operated remotely, a control interface with a radio transmitter is needed, transmitter that will basic control procedures from arming the vehicle to throttle, attitude, yaw, as well as preset flight modes. The transmitter (Tx) modulates those signals and broadcasts them on a 2,4 GHz link to the flying vehicle that should incorporate a receiver (Rx). The flight controller receives the digital signal as well as signals from the accelerometer, gyroscope and PWM to PPM converter, and according to the program stored in EEPROM communicates to the ESC the amount of power to be used by the motors. Additionally, other equipment can be attached to the frame and controlled by the flight controller, like video equipment, sensors, transmitters according to the diagram below

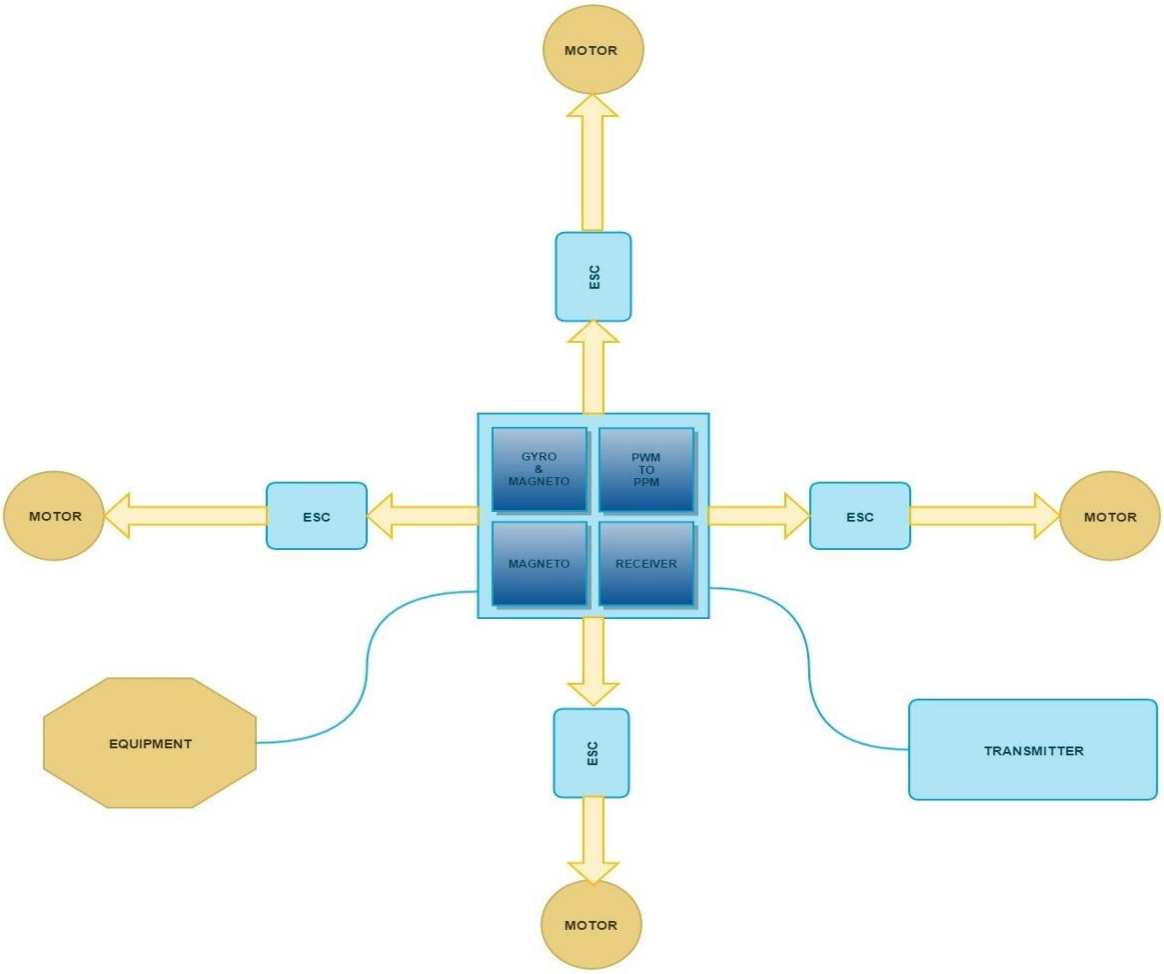


Figure 15- Diagram showing the components and data transmission

Components

Turnigy 9X 9Ch Transmitter w/ Module & 8Ch Receiver

Figure 16- Remote control [33]

In the website from where this remote control is bought (HobbyKing), it is stated that it is a ”reliable 2.4Ghz system suitable for beginners and pro pilots alike” and „Without a doubt, the best value 9Ch system available”. Of course, most of the statements shown on the website are written in such a manner that are appealing for the newcomer that wants to buy a reliable and good remote control. Leaving the marketing strategies aside, this remote control is suitable for the purposes of this project as it will be used to control the Quadcopter only in the case when it can be simply cannot be controlled or a flaw in the functionality of it occurs. In larger areas where the Quadcopter is our of the controllers sight (it is fully autonomous like the prototype built for this semester project) and a flaw occurs or any unpredicted events, it is really useful to have this kind of transmitter-receiver mechanism so that it can be controlled manually.

Technical specifications:

This remote control uses a frequency of 2.4 GHz. Why is this 2.4 GHz radio system so special?

Older models of remote controls use radio frequencies of 27 MHz to 72 MHz which are called „narrow-band” because „they work just like your regular AM or FM radio - sending out a signal that is picked up by the receiver and then sent to the servos.” as it is stated in a specialist website.

The reason why these „narrow-band” remote controls are not used anymore is because it is really easy to disrupt a „narrow-band” signal.

It is stated in the same technical website that „A noisy thermostat or electric drill can often cause massive amounts of electrical interference when listening to an AM broadcast and FM isn't always that much better.”, which is a good comparison to understand the basic functionality of older remote controls.

These remote controls need to have a frequency of their own if they want to avoid any interference with other similar signals with the same frequency, but this is not always possible due to poor planning or other reasons (different geographical locations can use the same frequency which can be a serious problem for more advanced systems). This usage of the same frequency is called CCI (co-channel interference). [34]

In the process of building the prototype, the CCI has been noticed when the 2.4GHz RC has been tested. Whenever the RC was turned on, the Internet connection was lost in that same period of time because the frequency of the signal from the RC interfered with the frequency of the signal from the Wi-Fi network.

In modern times, the CCI problem has been overcome and different signals with the same frequency can operate in the 2.4 GHz signal spectrum because there are different channels of transmission. For example, the RC (remote control) used for this project has a transmitter of 9 channels and a receiver of 8 channels.

There is still a main difference if we compare signals in the frequency of 27MHz to 72MHz and 2.4 GHz signals. The first ones mentioned are not affected by the objects they meet in their way so that means that they can go through object without affecting the signal, whereas the 2.4GHz signal behaves more like light(it has a smaller wavelength) and that means that the signal can interfere with the object it meets in the way. In this project, it is not a noticeable problem as it will be used only for close distances and without any major objects to interfere with the signal.

Glass fiber Quadcopter frame with an integrated PCB

Figure 17- Quadcopter fiber glass frame with integrated PCB [35]

Glass fiber or fiber glass is a type of material with a lot of good properties such as high textile strength, high thermal endurance, low moisture absorption, electrical insulation and last but not least cost effectiveness. [36]

- **High textile strength**

As it is stated on a website:„ Fiberglass yarns as twice as strong as steel wire". Nonetheless, it has a good strength-to-weight ratio.

- **Cost effectiveness**

„ Fiberglass fabrics offer cost advantage compared to other synthetic or natural fiber fabrics", is stated in the same website.

- **Electrical insulation**

Fiberglass has a high dielectric strength. As it is stated on a website, the dielectric strength is simply the insulation strength of the specific material. Fiberglass is a really good insulator so it doesn't allow any current to flow within it. [37]

- **High thermal endurance**

Fiber is a composite material which doesn't burn. Exposed to high temperatures it can still keep its internal properties.

Moreover, fiber glass is a lightweight material which makes it suitable for the purposes of this project. Besides the material advantages, this frame is suitable for the purposes of this project because it comes along with a PCB (Printed Circuit Board) which allows to solder wires directly on it.

HKPilot Mega 2.7 Flight Controller

Figure 18- Flight controller [38]

The functionality of this flight controller is best stated in the website it was bought from „This amazing flight controller allows the user to turn any fixed wing, rotary wing, or multi-rotor vehicle (even boats and cars) into a fully autonomous vehicle, capable of performing a wide range of tasks even programmed GPS missions with waypoints (with the optional GPS module).

This flight controller has included a lot of useful hardware parts as well such as telemetry radio, barometer, 3 axis gyroscope, accelerometer and a magnetometer. Moreover, it is Arduino compatible and its microcontroller is an ATMEGA2560, the microcontroller used on the Arduino Mega board.

- **Barometer**

The barometer is a sensor that measures the atmospheric pressure.

- **Accelerometer**

An accelerometer is a sensor that measure acceleration forces. There are 2 types of acceleration forces:

1. static (caused by the force of gravity)
2. dynamic (caused by moving or vibrating the accelerometer)

The accelerometer is a piece of technology that can show how a device is moving and in which direction. The way in which this is calculated varies however the general principal is to calculate the change in capacitance induced on two crystals by acceleration. [39]

- **Magnetometer**

A magnetometer is a sensor that can determine the strength or direction of a magnetic field. [40]

- **Gyroscope**

The Gyroscope is a rather complicated bit of machinery to understand, however its use is that it provides information regarding the orientation of an object. This has to do with angles of orientation relative to the axis of the objects designated rest position.

All these sensors are used to keep track of the Quadcopters altitude and keep it leveled as well as other function such as allow the pilot to know the internal state of the Quadcopter at all times and change settings in real time.

Turnigy Multistar 2216-800Kv 14Pole Multi-Rotor Outrunner

Figure 19-One of the 4 motors 42

In the picture it can be seen one of the 4 motors used in this project. The 4 motors have different rotations: 2 of them have clockwise motion and the other 2 have counterclockwise motion.

The reason why the motors have been selected with different rotations is because in order for the quadcopter to be able to hover, different rotation is needed on its axis. So on one axis there is clockwise motion and on the other one there is counterclockwise motion. Using motors with different rotation, when the quadcopter will hover, the reason why it doesn’t go on either one side or another is because he torque is equal to 0.

Basic functionality of electric motors:

These motors are composed of strong magnets and coil with an axle in middle. When the motors are connected to a battery, they coil simply becomes an electro-magnet with two poles (south and north) and the rest is simply electromagnetism. Because of the strong magnets that lay on the sides of the coil, they simply start to attract or repel each other causing the axle to move in a specific direction. [43]

Turnigy Nano-tech 6000mah 3S 25~50C Li-Po Pack

Figure 20- Battery [44]

On the website from where this battery was bought, it is stated that „ TURNIGY Nano-tech lithium polymer batteries are built with a Li-Co Nano-technology substrate complex greatly improving power transfer making the oxidation/reduction reaction more efficient, this helps electrons pass more freely from anode to cathode with less internal impedance.”

Advantages of Lithium Polymer batteries

- They have high discharge rate so that they can power up any demand motors.
- They are light weight and they have high capacity so they can store a lot of power.

Disadvantages of these types of batteries

- They have a lifespan of about 300-400 charge cycles. For the prototype built this semester, the battery could charge the motors for about 15 minutes, after that it is almost discharged.
- Such batteries can be dangerous: „because of the volatile electrolyte used in Li-Po’s, they can burst and/or catch fire when mistreated.”

Because of these batteries are light weight considering the power stored, they are suitable for the purposes of this project. [45]

12x4.5 SF Props 2pc Standard Rotation/2 pc RH Rotation

Figure 21- Propellers [46]

The propellers come in 2 pairs. One pair is clockwise oriented and the other is counterclockwise oriented.

IMAX B6 50W 5A Charger/Discharger 1-6 Cells (GENUINE)

Figure 22- Charger/Discharger [47]

This charger/discharger is a very advanced piece of technology. It is controlled by a microcontroller and is able to balance the charge on every single cell of a battery.

Turnigy Multistar 30 Amp Multi-rotor Brushless ESC 2-4S (OPTO)

Figure 23- Speed controller [48]

Speed controllers work on the PWM (pulse-width modulation) that allow them to control the power supplied to the electrical devices.

Advantages of the speed controller chosen for the purposes of the prototype (as described by the suppliers):

- It allows „very smooth yet linear throttle response, without sacrificing a rapid, crisp response to any throttle input".
- Safe arming.
- Signal loss shut-down.
- Bullet connectors installed.

Issues met while making the Prototype

The prototype for the 3rd semester was from more points of view more complex than the prototypes in the other two semesters. The prototype in this semester is the first prototype that can interact with the environment and can be affected by common natural phenomena such as wind and rain as it is the first dynamic prototype, whereas the other prototypes made were static, unable to move.

The prototype for this semester project is different from the others for another reason. It is the first attempt of automation of a dynamic prototype, so more parameters need to be taken into account when testing it (e.g. wind, rain) whereas in the previous semesters only the proper transmission of information from the microcontroller (Arduino Uno) to sensors or valves was taken into account.

The building of the actual device was slower than planned as a lot of components broke or were malfunctioning. A quick summary will be presented in the report regarding the issues met on the way, outcome and group work for building this prototype.

First issue met on the way was regarding the battery. The first position considered for the battery was on top of the frame. The only problem was that the battery was not fixed properly on the frame. In a testing session, it fell from the frame and the anode was completely cut off the battery. This was a major issue in the testing phase of the prototype as the group could not test the Quadcopter for another 2 weeks until a new battery has arrived.

After the new battery has arrived, a new issue occurred with the some components of the Quadcopter. These components were one of the motors and the adjacent speed controller.

These 2 components were malfunctioning even from the beginning and they didn’t last long until they completely broke so another 2 components were added on the shopping list.

Overall, the group could not test the Quadcopter for an entire month and this lack of progress is a huge drawback both mentally and technically when trying to build and program such a complex prototype.

This period of one month was not completely without any productive work as the group spent almost 1 day in total for designing and creating a proper landing gear for the Quadcopter.

After 2 failed attempt of creating a proper landing gear, a proper has been built. The first attempt of making a landing gear was with a frame using PVC where all the sensors would be positioned. This landing gear was very efficient but too heavy for the Quadcopter. The second attempt was using some wooden sticks. This attempt was the most inefficient of them all because there was no way to position them on the frame so that the Quadcopter would have maximum stability when it was landing, so the sticks were moving when it was landing.

The current landing gear is using PVC material like the first landing gear designed, but in smaller amounts. PVC has the property to become very malleable when boiled so it can be shaped. After the PVC is cooled down, it becomes hard again so it was the perfect material to shape and design a landing gear. This landing gear is very stable as the PVC is put on the arms of the Quadcopter.

Initial preparations

Propeller and motor calibration are an important part in the preparation for the construction of the prototype.

This calibration step is very important because weight is not evenly distributed in the surface of the propellers and motors and this can cause vibrations while the Quadcopter is hovering of flying. Although the difference in weight distribution in the surface of the wings and motors is insignificant at first sight, uneven weight distribution for 4 wings and 4 motors can make a big difference when flying the Quadcopter.

The calibration process is a pretty straightforward process which requires no experience and can be realized using two methods: weight addition (using duct tape on the lighter blade) or weight reduction (using sandpaper on the heavier blade).

Figure 24- Propellers calibrated with both weight reduction and weight addition methods

For wing calibration, a special support was used (the support was given to the group members by an acquaintance).

Figure 25- The support aforementioned

Figure 26- Screw and nut used to balance the propeller on the support

Figure 27- The screw and the nut fixed on the propeller

Figure 28- Perfectly calibrated propeller using the special support

Figure 29- Uneven mass distribution in the blades of one propeller

As it can be seen in Figure 30, one of the blades of the propeller is heavier than the other. Although some duct tape was used on the lighter blade to try making the mass distribution equal in the surface of the propeller, more adjustments are required.

The motor calibration follows the exact same procedure as in the propeller calibration. Motor calibration is important in order to reduce vibrations to a minimum amount on each of the four arms of the frame.

In order to measure the vibrations on each of the arms, a seismograph app for smartphones was used.

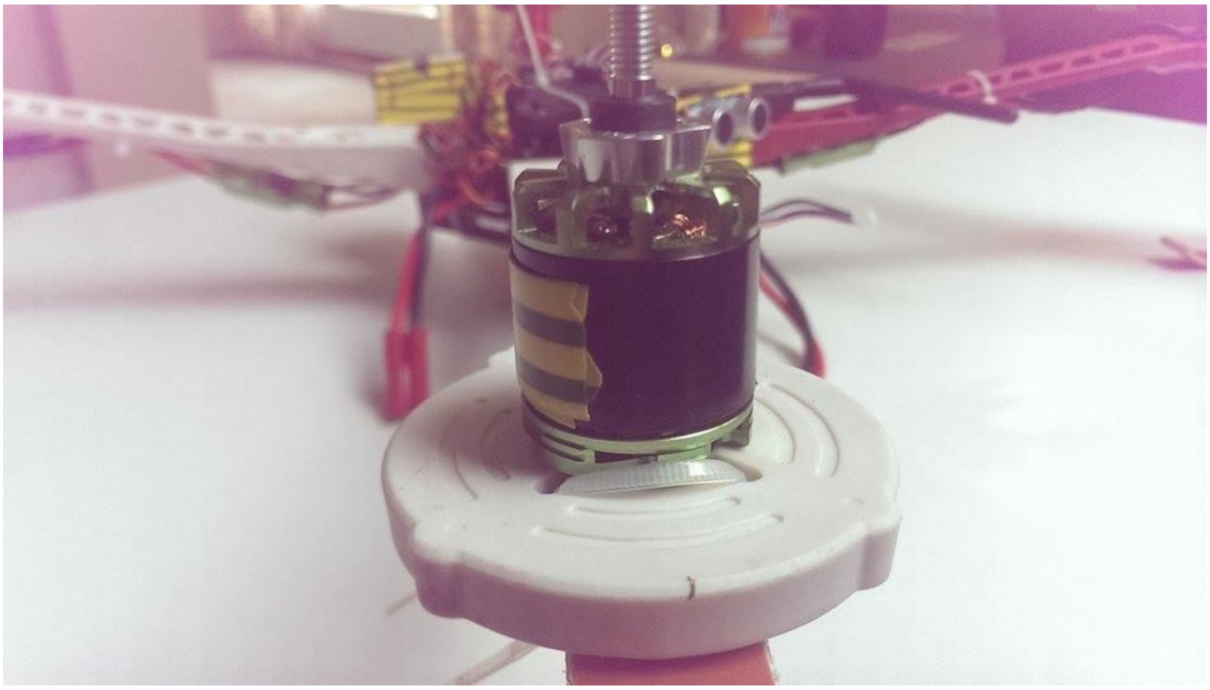


Figure 30 - Calibrated motor

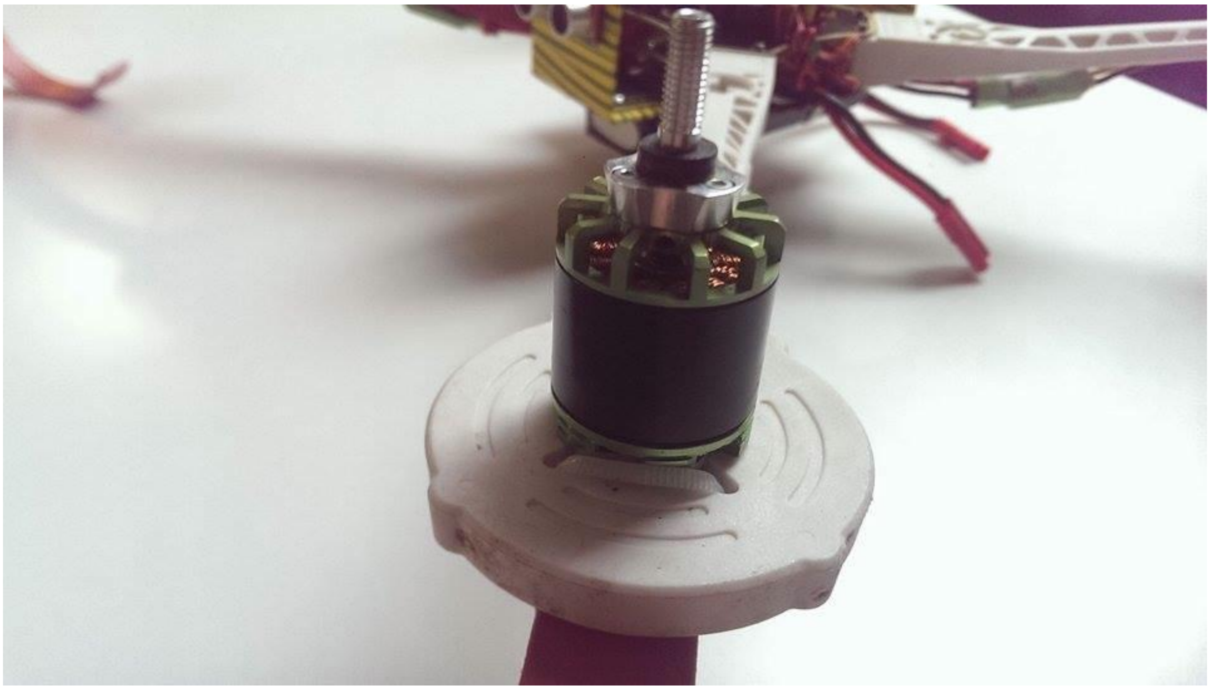


Figure 31 - Motor that hasn't been calibrated

Landing gear

In order to ensure a stable landing platform, several solutions have been considered. Initially, a basic configuration with 4 wooden legs has been considered, attached close to the center of gravity with the legs fanning out at 90° as seen in the figure below

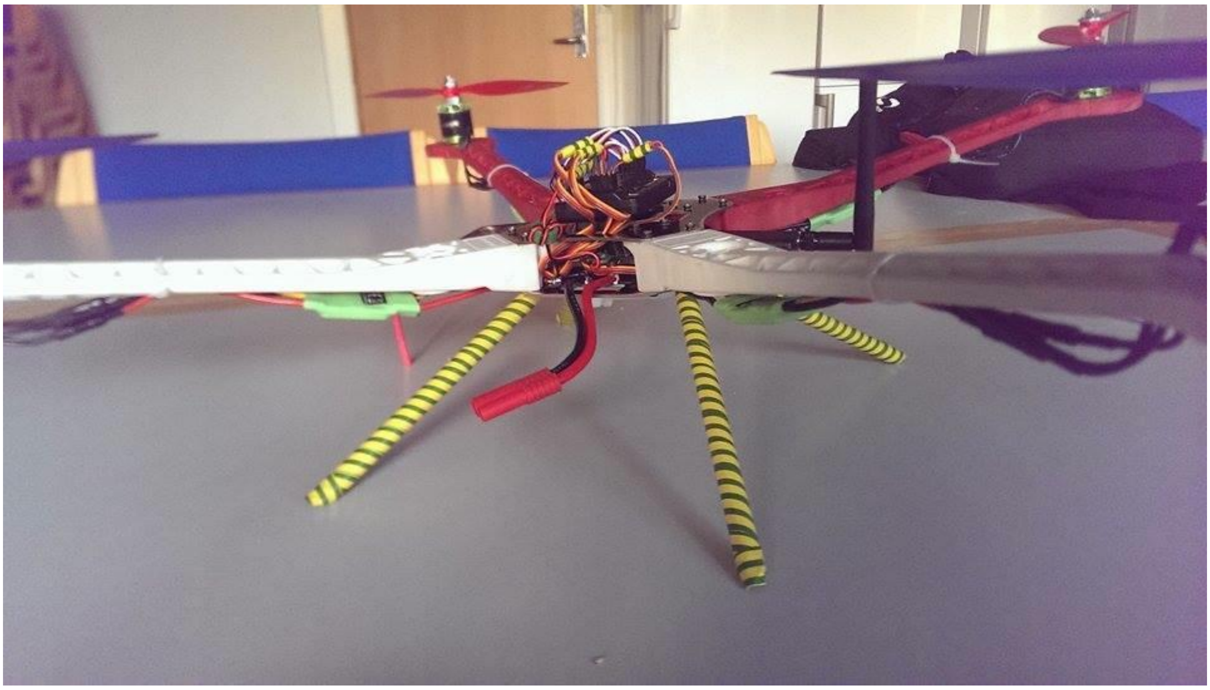


Figure 32 - First attempted solution for a landing gear

While easy to implement, and effectively dumping the shock of impact while landing vertically the solution proved unstable and flimsy, accounting for several incidents during testing resulting in damage to 2 propellers. The problem was caused while landing the vehicle under an angle during first throttle input tests and take off. When in close proximity to the ground, if a change in attitude was induced, the partial loss of the vertical component of the lift force would generate a decrease in altitude. Since a change in attitude also generates a lateral movement, the vehicle would roll on impact.

Considering these problems, another solution has been considered. In an attempt to increase the base of support moving the wooden legs into a vertical position towards the extremities of the frame has been considered, but the frame had no usable attaching points, reverting to a configuration closer to the center of gravity projection. To ensure damping the impact force, at the inferior extremity of each leg a polyethylene foam collar has been attached as seen in the figure below:

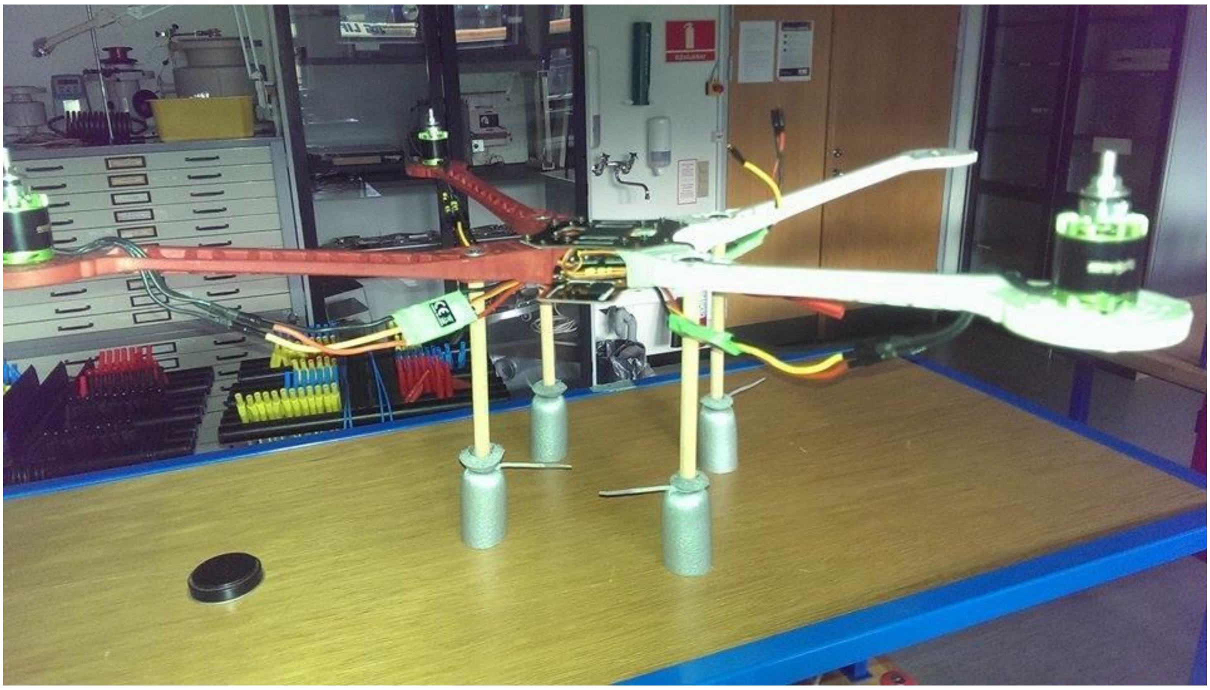


Figure 33 - Second attempted solution for landing gear

This solution has not solved the problems encountered with the previous configuration and the prototype kept the tendency to roll while touching down even under small angles of attitude.

It was time to have a more radical approach. The set specification for the landing gear would be extrapolated from the lessons of previous attempts:

1. Maximum support base possible, and the projection of the frame as a minimum
2. Simplicity
3. Capability to damp the force of impact.

During an ad-hoc brainstorm session in a local store, the idea put forward was to use some form of plastic bands with limited elasticity attached to the extremity of the frame, and that was easy to do with transversal sections of PVC pipes, that can be cut open and reshaped under high temperatures (see figure below). The transversal sections have been cut open, immersed in boiling water and re-modelled in an elliptical shape that was attached with plastic fasteners to the outer edge of the frames ensuring a maximum support base. Under tests, this solution proved to be very stable and reliable, the vehicle being able to safely touch down even under angles of 35°-40° in case of emergency or mishandling.

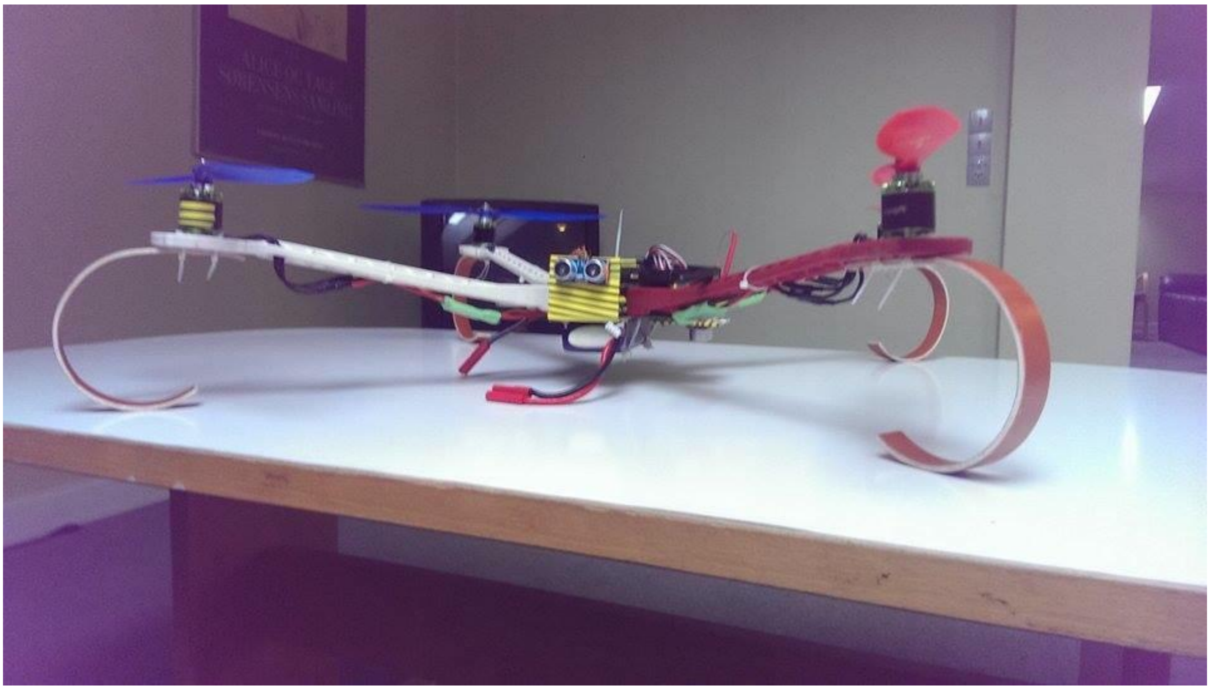


Figure 34- Quadcopter with final landing gear

Automation principle

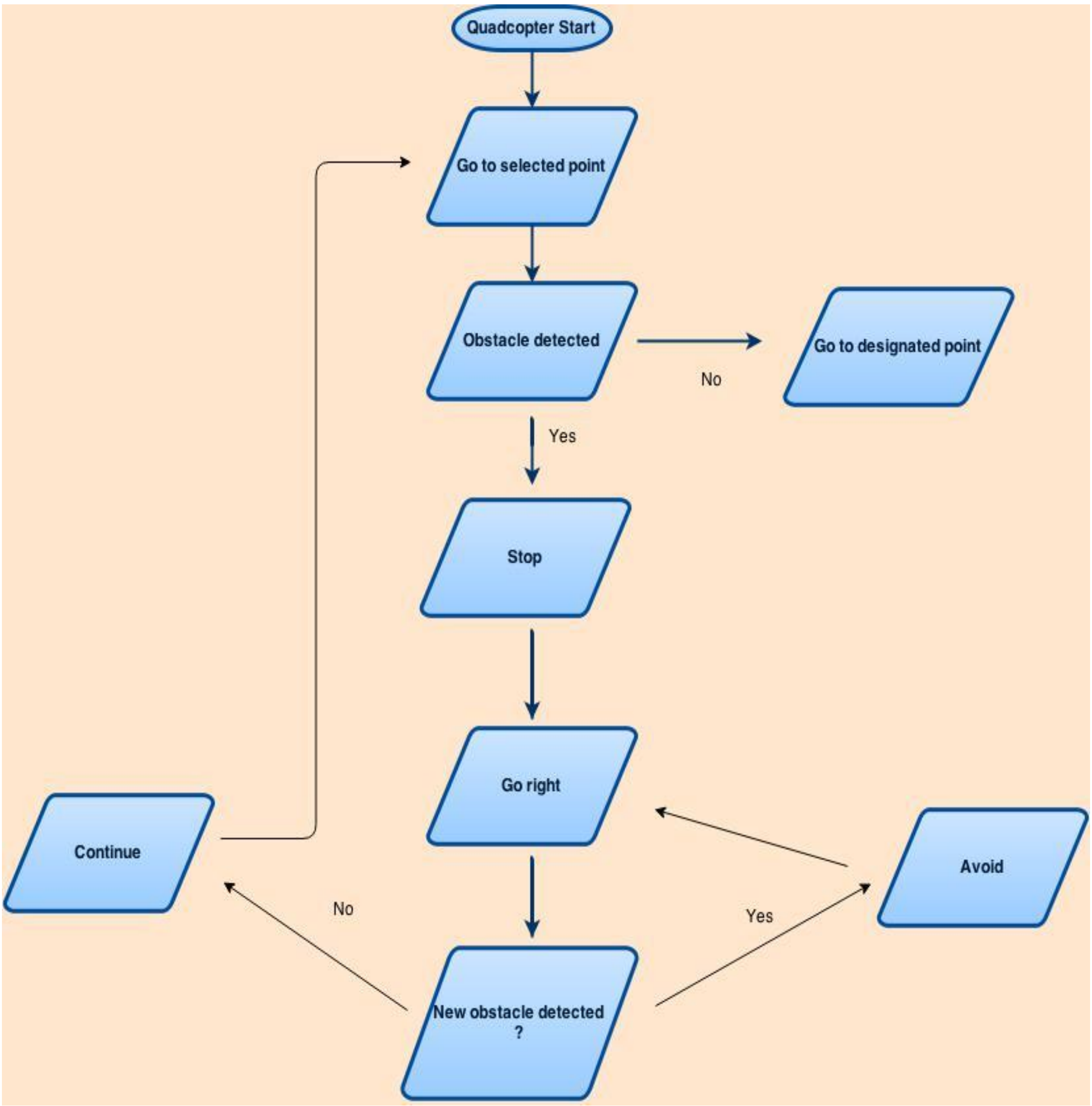


Figure 35-Automation Principle

As it can be seen in the diagram above, the principle of which the Quadcopter will follow when it will be set to go from one point to another is the following: Quadcopter will start from its initial position predefined by the pilot. As it will move along a certain path to go to the next location, if it meets an obstacle in its path it should stop and avoid it on a predefined direction which is again predefined in the code. If no object is met on the way as it avoids the obstacle, it will continue its direction to the desired location. If the Quadcopter meets an obstacle again, it should repeat the principle illustrated in the diagram above.

Due to repeated technical difficulties met during the creation and testing of the Quadcopter (crashes, parts malfunctioning and difficulties in designing a landing gear) and difficulties understanding the programming necessary for it to become autonomous, the way it reacts to different inputs from the pilot and general movement of it when it was flying, the automation part was practically impossible to realize. It can be stated that the automation of a dynamic prototype such as a Quadcopter is difficult to realize as a 3rd semester project as there are too many aspects that need to take into account and the knowledge required to realize such a project lacks.

A number of obstacle avoidance solutions had been considered, from LIDAR to using a camera with recognition software to see obstacles and judge the real time position of the quad. LIDAR is based on a laser beam that judges distance by lighting on a designated location and analyzing the beam that is reflected. These however is a very complicated technology and commercial components are without doubt too expensive and heavy for the purposes of this project (however with the ever increasing pace of technological progress this might become available in the near future for smaller aerial drones).

Another way to achieve this is a visual camera based solution, where advanced software can detect obstacles based on video footage in real time. This however is again out of the scope of this project; however it does provide a cheap and interesting solution for a rather complicated task. If the required processing power can be obtained or a fast enough transmission link established this could be done remotely and information relayed back to the drone (however this could have unwanted side effects w.r.t. transmission delays). Such a solution is described in a publication made by ETH Zurich researchers [49]; here they use a stereo camera with a laser range finder which transmits the data to a “computer cluster” which runs the required algorithm. [49] A drawback to this is that the system will crash if it loses connection to the cluster. This system is coupled with a GPS/INS solution for judging the location of the Quad. INS stands for inertial navigation system and is based on the principal of calculating current position based on a fixed point (using the dead reckoning principal). The sensor inputs are usually gyroscopes and accelerometers. A problem with these sensors is an accumulation of error that has to do with integration drift, which is the accumulation of small errors in measurements that can end up being a large problem. The GPS/INS solution incorporates data from both an INS and GPS, using the latter to calibrate the first during flight to offset the integration drift.

The problem with both of the above mentioned solutions are that they are way beyond our understanding. The complexity of the algorithms at hand is very high and would be best served as a stand alone project.

PID controller

PID (proportional-integral-derivative) is a close loop control system that is trying to set the final result closer to the desired result. The Quadcopters use this control system to achieve stability and fast responses based on the input, with one controller for each of the 3 axis of movement (roll, pitch and yaw).

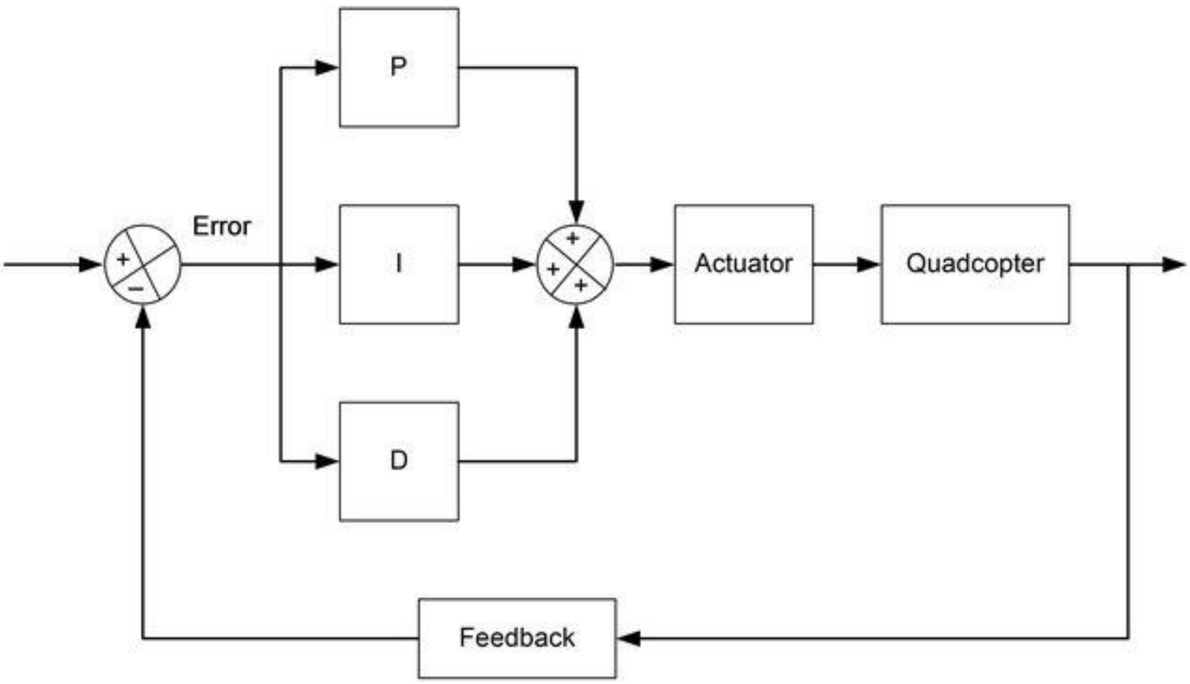


Figure 36-PID Controller [50]

The PID controller has 3 main components the P (Proportional), I (Integral) and D(Derivative).

$P_{OUT} = K_p e(t)$ (Proportional)

$I_{OUT} = K_i \int_0^t e(\tau) d\tau$ (Integral)

$D_{OUT} = K_d \frac{d}{dt} e(t)$(Derivative)

The final form of the PID controller looks like this:

$$K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t)$$

Where e is the error between the desire result and the final result, K_p is the gain of the proportional controller, K_i is the gain for the integral controller, $K_d$is the gain for the derivative controller. For tuning the controller the gain needs to be modified in such a way that the system that is controlled is behaving as close as possible to the desire result. Each part of the controller can be use separately and in this way different kind of controllers can be obtained, for example PD, PI, PID, or they can be used separately like P, I and D controller.

To obtaining a very good stability for a Quadcopter the PID values (the gains for each of the tree controllers) needs to be very well tuned. By modifying the D gain the Quadcopter can be more aggressive to the input commands.

While very important for stable flight, a PID controller (proportional – integral – derivative controller) has been integrated with the flight controller supplied. A PID controller is a control loop feedback mechanism, controlled by the formula:

$$\mathrm{u}(t) = \mathrm{MV}(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{d}{dt} e(t)$$

Where

K_p: Proportional gain, a tuning parameter

K_i: Integral gain, a tuning parameter

K_d: Derivative gain, a tuning parameter

e : Error $= SP - PV$

t : Time or instantaneous time (the present)

τ : Variable of integration; takes on values from time 0 to the present t.

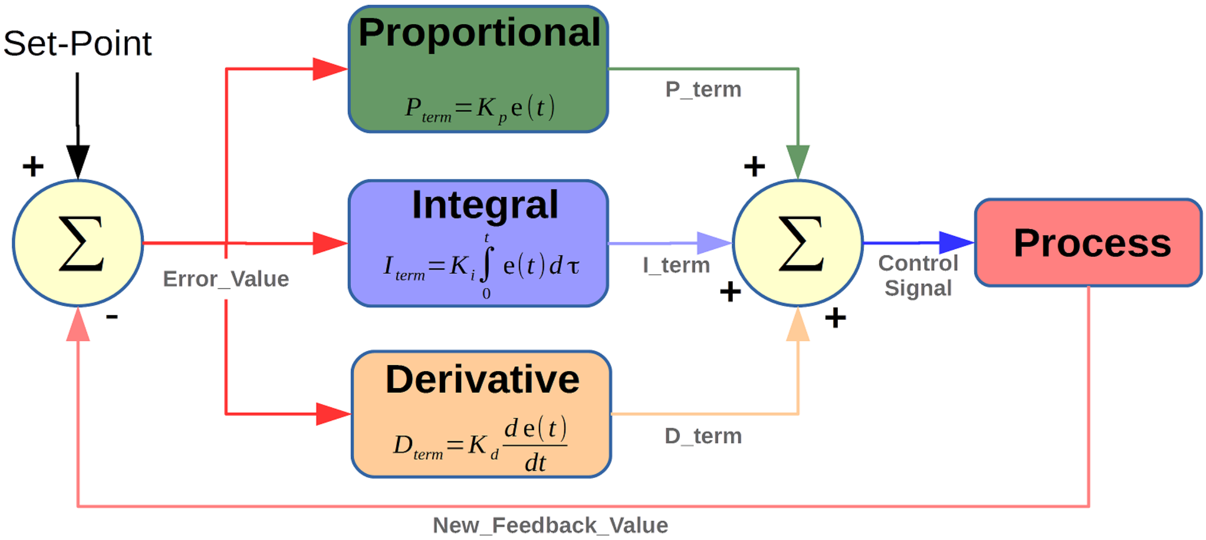


Figure 37- PID controller [51]

- The proportional controller acts as a high pass filter measuring and compensating the difference between the set point and point value. It is also considered the component that is based on an advanced hysteresis principle, because it acts on keeping the value between a range.

- The derivative controller acts as a low pass filter, measuring and compensating the rate of change of the point value

- The integral controller, also known as “Reset Controller” due to their unique ability to return the controlled variable to the exact set point following a disturbance. [52]

Pseudo-code for such an example could be:

"PID:
 Error = Setpoint - Actual
 Integral = Integral + (Error*dt)
 Derivative = (Error - Previous_error)/dt
 Drive = (Error*kP) + (Integral*kI) + (Derivative*kD)
 Previous_error = Error
 wait(dt)
GOTO PID" [53]

Considerations

During the present project several factors have not been taken into consideration for reasons ranging from having little relevance to this project or little impact over the flight characteristics to requiring a higher level of understanding of control algorithms and being integrated already in parts purchased for the scope of the project.
Aerodynamic drag. Since volume and static aerodynamic footprint of the assembly is small we will consider it negligible:

- Blade flapping
- Vortex impact
- Vortex wake
- Noise
- Dynamic stall
- Ground effect

A considerable obstacle in completing the project has been related to understanding the complexity of flying, and the phenomena influencing multirotor flying.
Project was marred by issues largely still not understood to the group, while the Arduino microcontroller that has been used to collect data from testing (with a code developed only for this purpose) behaved erratically, provoking further delays. For example, before executing a test, a quick check up of the test set-up revealed nothing

out of the ordinary, the sensor readings would be correctly transmitted to the computer through a wireless communication on a 433 MHz link. During actual testing however, data received from ultrasonic sensors would be either on extreme values, not read at all or the values would be completely random. During debugging sessions that revealed no problems with the code, problem persisted only to surprise the team with a problem free renewed checkup where sensors worked perfectly and correct readings would be transmitted to the computer, and have the same problems again during actual testing. Trying to isolate electromagnetically as much as possible the microcontroller, a temporary shield has been used from aluminum foil, with no improvement at all. Problems have delayed implementing the data acquisition code from external sensors (ultrasonic sensors).

For the 6^{th} and last test, a data gathering session has been scheduled to study the behavior of the vehicle flying remotely using only internal sensors (accelerometer, magnetometer, barometer and GPS), under changes of direction and elevation. The wind at ground level was at an estimated 2 m/s, and cloud cover was very high. Initial maneuvers went as predicted, with smooth lift-off and direction changes with a maximum altitude ceiling of 15 m. however, problems started appearing when the vehicle was taken to a higher altitude, where winds were stronger, maneuvers that ended with the vehicle crashing heavily. After a search that lasted 2 hours the prototype was found disintegrated in a parking lot.

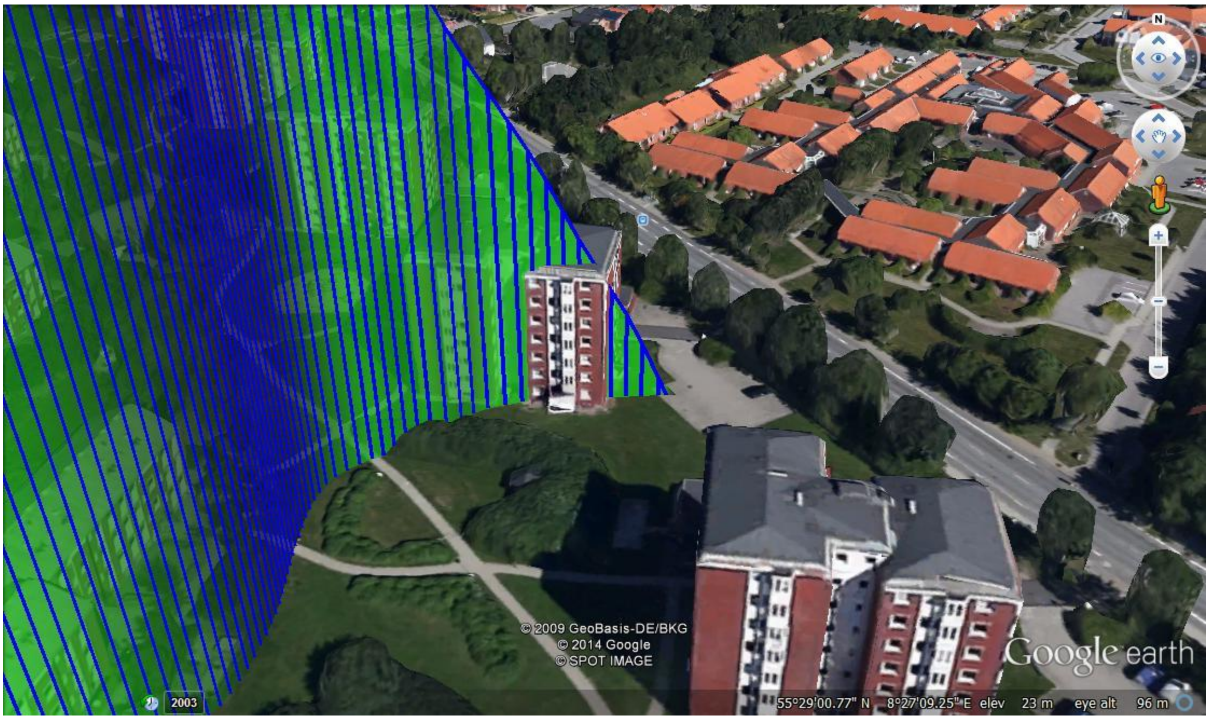


Figure 38- Data log from flight controller

Fortunately, no other material damage has been inflicted on private or public property, and no person has been injured during the crash, but better health and safety procedures should have been considered. At this point, having lost the prototype, the project switched focus from obstacle avoidance to investigating, analysis and understanding the circumstances of the incident, and ways to avoid such incidents in the future. A detailed analysis will be discussed in the next chapter.

Crash of the prototype

During the 6th test, an unfortunate event that will be described and analyzed in this chapter took place. In an attempt to acquire data about the behavior of the quadcopter in remotely controlled mode, during changes of heading, direction and elevation, the vehicle was lost having fallen from 110 m and crashing in a parking lot.

Parameters of the test:

- Maneuvers to be executed:

  Safe take-off

Hovering
Change of direction/heading
Climbing
Descent
Safe landing

- Maximum height: 50 m
- Maximum perimeter: 150 m*100 m
- Weather:
  Daylight is necessary for direct observation/piloting the prototype
  Wind – under 4m/s
  No rain conditions
- Location: large field relatively flat, unobstructed by trees or bushes to ensure good observation. In this scope the football field at Stormgade 200, Esbjerg was chosen. No person was observed on the field.

Goals of the test:

- Collecting telemetry data on the following parameters:
  desired vs actual roll, yaw, pitch and altitude values
  RC input vs Flight controller output
- Study the behavior of the prototype under mild wind and the influence outside factors have on the flight trajectory and control

Conducting the test

When all the parameters of the test have been met, the prototype has been taken to the test field, armed, and after GPS lock has been achieved, the pilot executed the take-off at a height of ≈4 m and after a short session of getting re-acquainted with the control the prototype has been kept in hover mode at a height of ≈6 m. Next step involved several runs across the field with changes in direction and heading at heights between 4 to 6 m. up to this point everything went smooth, the prototype seemed to be always under control, responsive and unaffected by wind.

However, next on the maneuvers list was elevation changes, and this is where problems started. The prototype climbed smoothly to around 40 m, where a slight deflection from the path has been visually observed.

Figure 39- Flight path in Google Earth

At that moment, the attitude parameters, specifically real pitch (Pitch) and desired pitch (DesPitch) showed a difference of 25 centi-degrees.

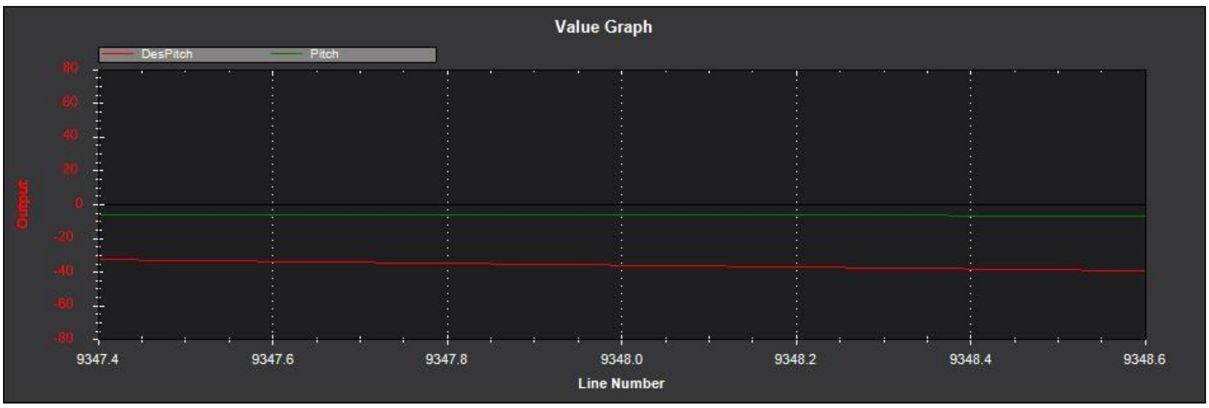
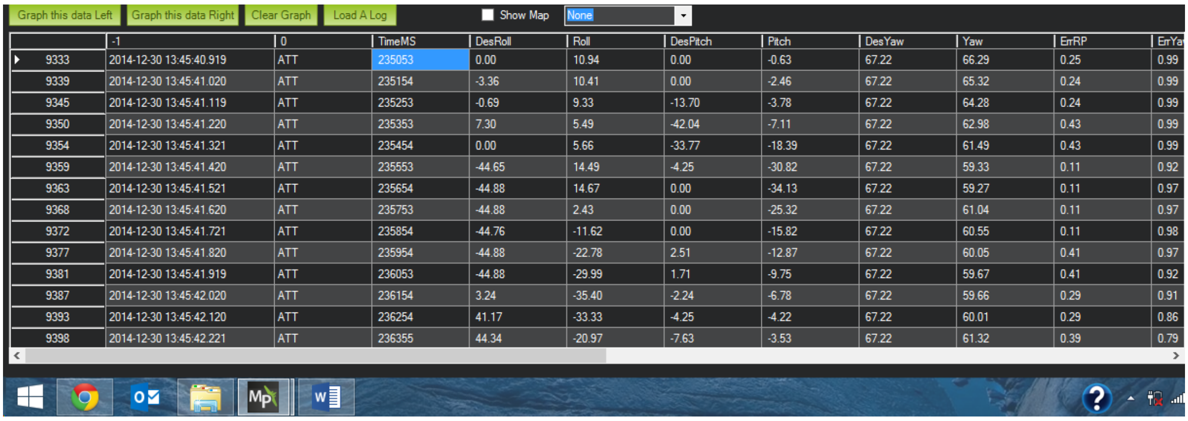


Figure 40 - Desired pitch vs. real pitch

Also, roll had a relative big difference between desired roll (DesRoll) and actual roll (Roll) as we can see in the data below, where it is noted that DesRoll is at -44.65 value, while Roll is at 14.49 rotated in the opposite side, situation that carried on from the time reference 235454 (in ms), indicating that either a problem has developed or outside factors interfered. Considering that yaw stayed relatively stable during this time, we can presume that a mechanical problem can be discarded, since a difference in angular speed of either engine could induce lower torque on that engine, influencing total torque and rotating the vehicle around the vertical z-axis, and that did not happen.



	-1	0	TimeMS	DesRoll	Roll	DesPitch	Pitch	DesYaw	Yaw	ErrRP	ErrYa
9333	2014-12-30 13:45:40.919	ATT	235053	0.00	10.94	0.00	-0.63	67.22	66.29	0.25	0.99
9339	2014-12-30 13:45:41.020	ATT	235154	-3.36	10.41	0.00	-2.46	67.22	65.32	0.24	0.99
9345	2014-12-30 13:45:41.119	ATT	235253	-0.69	9.33	-13.70	-3.78	67.22	64.28	0.24	0.99
9350	2014-12-30 13:45:41.220	ATT	235353	7.30	5.49	-42.04	-7.11	67.22	62.98	0.43	0.99
9354	2014-12-30 13:45:41.321	ATT	235454	0.00	5.66	-33.77	-18.39	67.22	61.49	0.43	0.99
9359	2014-12-30 13:45:41.420	ATT	235553	-44.65	14.49	-4.25	-30.82	67.22	59.33	0.11	0.92
9363	2014-12-30 13:45:41.521	ATT	235654	-44.88	14.67	0.00	-34.13	67.22	59.27	0.11	0.97
9368	2014-12-30 13:45:41.620	ATT	235753	-44.88	2.43	0.00	-25.32	67.22	61.04	0.11	0.97
9372	2014-12-30 13:45:41.721	ATT	235854	-44.76	-11.62	0.00	-15.82	67.22	60.55	0.11	0.98
9377	2014-12-30 13:45:41.820	ATT	235954	-44.88	-22.78	2.51	-12.87	67.22	60.05	0.41	0.97
9381	2014-12-30 13:45:41.919	ATT	236053	-44.88	-29.99	1.71	-9.75	67.22	59.67	0.41	0.92
9387	2014-12-30 13:45:42.020	ATT	236154	3.24	-35.40	-2.24	-6.78	67.22	59.66	0.29	0.91
9393	2014-12-30 13:45:42.120	ATT	236254	41.17	-33.33	-4.25	-4.22	67.22	60.01	0.29	0.86
9398	2014-12-30 13:45:42.221	ATT	236355	44.34	-20.97	-7.63	-3.53	67.22	61.32	0.39	0.79

Figure 411 - Data log at time reference 235454

As we can see later at time reference 26609, despite drops in the value of throttle, the altitude does not decrease, further suggesting that outside factors, and we suspect winds stronger than we expected, had an important role in controlling the prototype.

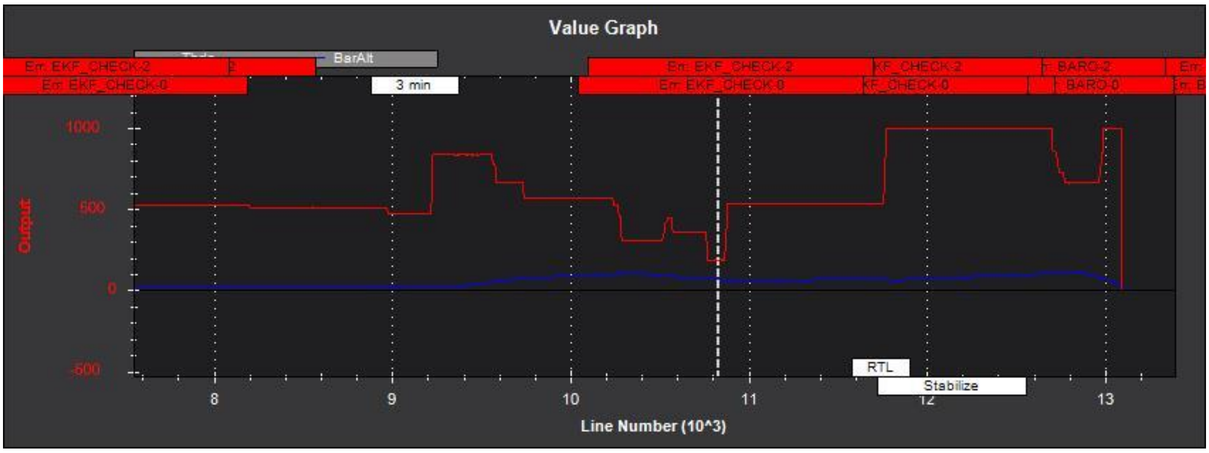


Figure 4242 - Throttle input vs. altitude

Having such behavior, and analyzing the attitude data, we can only conclude that wind was the cause of the prototype drifting away from the intended course, but it does not explain the crash. In trying to find out why, “google Earth” was employed to help, allowing views that modelled the path and elevation as well as being able to display attitude loaded from the log files saved from the last test. Going through the flight path from the moment of impact backwards towards the start of flight, we can identify at the altitude of around 100, at time reference point of 312449 ms a complete loss of throttle (ThrOut) despite a having an input for desired throttle (ThrIn), followed shortly by an error message. Studying the attitude of the craft with the help og google Earth, it is easily observable that from that point strange yaw movement has been induced, as if one motor stopped working.

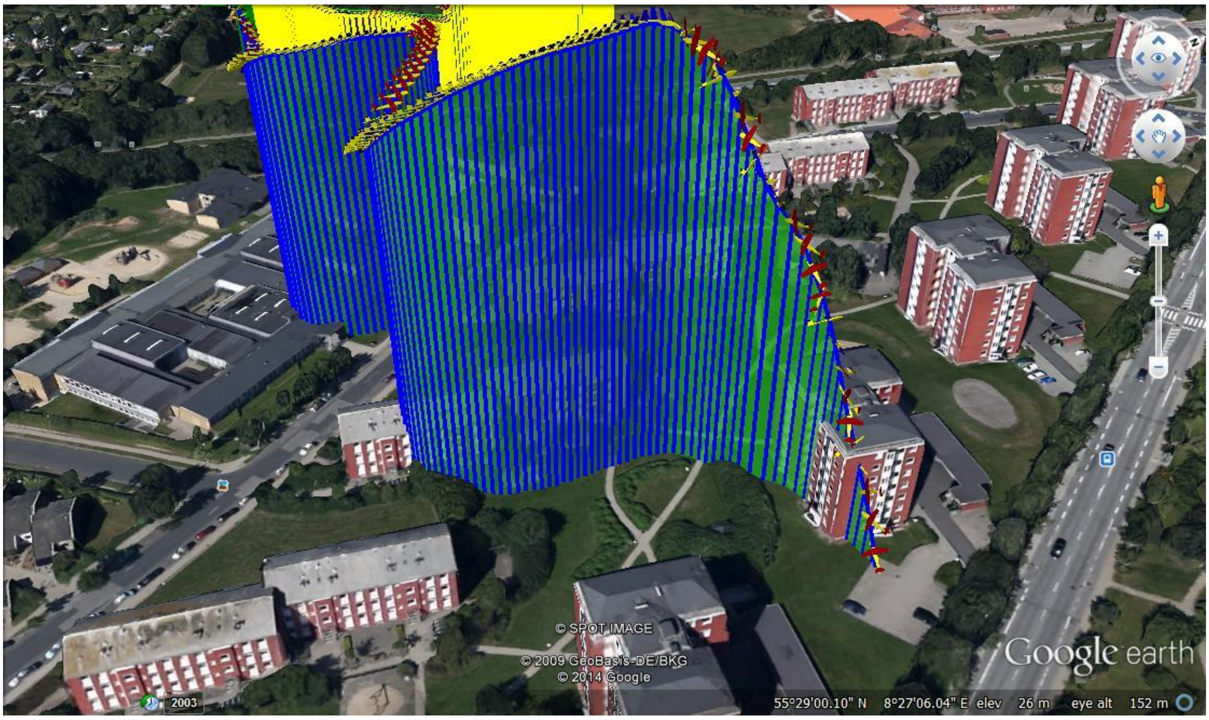


Figure 433 - Point of descent represented in Google Earth

Taking into consideration the high value for the desired throttle and the lack of response, we conclude that most probably a motor has simply stopped working, causing erratic yaw movement, causing the aircraft to lose altitude at a rate of 297 cm/s.

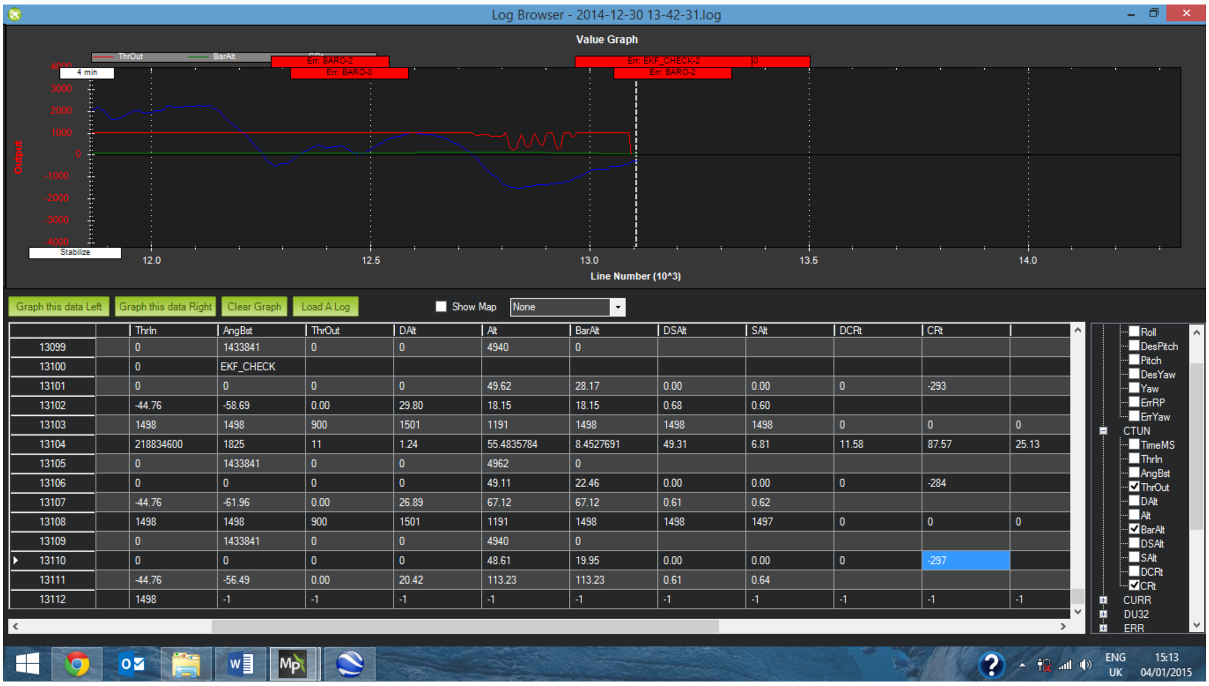
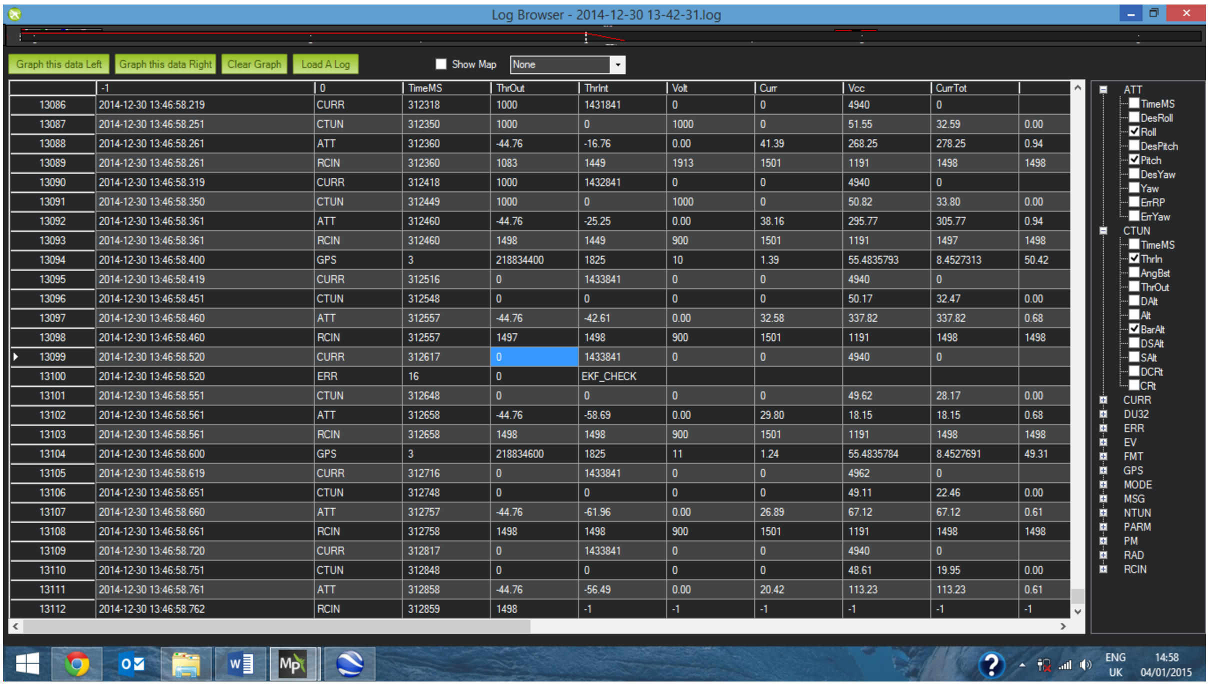


Figure 444 - Data log indicating rate of descent



	-1	0	TimeMS	ThrOut	ThrInt	Volt	Curr	Vcc	CurrTot	
13086	2014-12-30 13:46:58.219	CURR	312318	1000	1431841	0	0	4940	0	
13087	2014-12-30 13:46:58.251	CTUN	312350	1000	0	1000	0	51.55	32.59	0.00
13088	2014-12-30 13:46:58.261	ATT	312360	-44.76	-16.76	0.00	41.39	268.25	278.25	0.94
13089	2014-12-30 13:46:58.261	RCIN	312360	1083	1449	1913	1501	1191	1498	1498
13090	2014-12-30 13:46:58.319	CURR	312418	1000	1432841	0	0	4940	0	
13091	2014-12-30 13:46:58.350	CTUN	312449	1000	0	1000	0	50.82	33.80	0.00
13092	2014-12-30 13:46:58.361	ATT	312460	-44.76	-25.25	0.00	38.16	295.77	305.77	0.94
13093	2014-12-30 13:46:58.361	RCIN	312460	1498	1449	900	1501	1191	1497	1498
13094	2014-12-30 13:46:58.400	GPS	3	218834400	1825	10	1.39	55.4835793	8.4527313	50.42
13095	2014-12-30 13:46:58.419	CURR	312516	0	1433841	0	0	4940	0	
13096	2014-12-30 13:46:58.451	CTUN	312548	0	0	0	0	50.17	32.47	0.00
13097	2014-12-30 13:46:58.460	ATT	312557	-44.76	-42.61	0.00	32.58	337.82	337.82	0.68
13098	2014-12-30 13:46:58.460	RCIN	312557	1497	1498	900	1501	1191	1498	1498
13099	2014-12-30 13:46:58.520	CURR	312617	0	1433841	0	0	4940	0	
13100	2014-12-30 13:46:58.520	ERR	16	0	EKF_CHECK					
13101	2014-12-30 13:46:58.551	CTUN	312648	0	0	0	0	49.62	28.17	0.00
13102	2014-12-30 13:46:58.561	ATT	312658	-44.76	-58.69	0.00	29.80	18.15	18.15	0.68
13103	2014-12-30 13:46:58.561	RCIN	312658	1498	1498	900	1501	1191	1498	1498
13104	2014-12-30 13:46:58.600	GPS	3	218834600	1825	11	1.24	55.4835784	8.4527691	49.31
13105	2014-12-30 13:46:58.619	CURR	312716	0	1433841	0	0	4962	0	
13106	2014-12-30 13:46:58.651	CTUN	312748	0	0	0	0	49.11	22.46	0.00
13107	2014-12-30 13:46:58.660	ATT	312757	-44.76	-61.96	0.00	26.89	67.12	67.12	0.61
13108	2014-12-30 13:46:58.661	RCIN	312758	1498	1498	900	1501	1191	1498	1498
13109	2014-12-30 13:46:58.720	CURR	312817	0	1433841	0	0	4940	0	
13110	2014-12-30 13:46:58.751	CTUN	312848	0	0	0	0	48.61	19.95	0.00
13111	2014-12-30 13:46:58.761	ATT	312858	-44.76	-56.49	0.00	20.42	113.23	113.23	0.61
13112	2014-12-30 13:46:58.762	RCIN	312859	1498	-1	-1	-1	-1	-1	-1

Figure 455- Data log indicating difference between throttle input and throttle response

On the discovery of the crashed vehicle, at a distance of approximately 270 m from the take off point, debris was spread over an area of 25 m^2 with 2 motors still attached to the chassis (and still in working order, as proven at a later test), one of them having the propellers scratched but still in one piece, while the other had only parts of the propeller still attached. A third motor has been found at a distance of 3 m form the chassis, with a part of the glass fiber arm still attached, showing clear signs of damage having the rotor at an angle and the blades of the propeller broken off. The most interesting discovery was the 4^{th} engine that was found at approximately 6 meters away from the main wreckage site, with only a small part of the glass fiber arm attached to it, but with no propeller on. At a closer inspection of the motor, the bolt to which the propeller should be attached to the rotor of the motor had signs of mechanical abrasion, the nut was not found and no parts of the propeller still attached. Parts of propeller were found scattered in pieces of various sizes all around the wreckage site.

This discovery, correlated with the sudden change in attitude, and loss of altitude at a high rate despite a high throttle input coupled with erratic yaw angle change led us to believe that at the height of 113 m, while the prototype was drifting due to the wind in a semi-controlled flight, a propeller had come off either due to a mechanical failure improper mounting generating an torque and thrust imbalance that led to loss of control that brought down the prototype.

Annex

Algorithm – Algorithms is a procedure to process data and perform calculations

UAV - Unmanned Aerial Vehicle or RPA which stands for Remotely Piloted Aircraft

RC – Remote Control

VTOL – Vertical Takeoff and Landing

IMF – International Monetary Fund

PWM – Pulse-Width Modulation

PCB – Printed Circuit Board

PVC – Polyvinyl chloride

GPS – Global Positioning System

Li-Po – Lithium Polymer

PID – Proportional-Integral-Derivative

FAA – Federal Aviation Administration

CG – Center of Gravity

CP – Center of Pressure

PPM – Pulse-position modulation

EEPROM – Electrically Erasable Programmable Read-Only Memory

ESC – Electronic Speed Controller

FM – Frequency Modulation

CCI – co-channel interference

g - Gravitational acceleration

g=9.81 m/s^2

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