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Safety Mechanisms for the Reliable Operation of 3D Vehicles

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ABSTRACT

The safety and reliability of unmanned vehicles is a growing concern in our modern society. This work proposes and implements mechanisms to minimize risks in the operation of 3D vehicles. A brief analysis is performed to identify high priority risks and low complexity solutions are proposed in order to avoid or minimize their impact. To cope with critical power failures, an autonomous current monitoring system was studied and implemented after analyzing two different techniques: resistive and magnetic current sensing. Furthermore, a fall detection system capable of detecting rotational and free falls was developed and evaluated. Lastly, an obstacle detection and avoidance system relying on multiple smart sensors was proposed. Several simulation tests were performed for different velocities to obtain processing delays and stopping times and thus, the minimal safe flying distance for the avoidance of obstacles.

***Keywords*:** Unmanned vehicles, 3D vehicles, failsafe mechanisms, fault detection.

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RESUMO

A segurança na operação fiável de veículos não tripulados é uma preocupação crescente na nossa sociedade moderna. Este trabalho propõe e implementa mecanismos para minimizar os riscos no manuseamento destes veículos. Uma breve análise é realizada para identificar os componentes com maior risco de ocorrerem problemas e soluções de baixa complexidade são propostas a fim de evitar ou minimizar o seu impacto. Para lidar com falhas de energia críticas, um sistema de monitorização de corrente foi estudado e implementado após analisar duas técnicas diferentes: detecção de corrente resistiva e magnética. Além disso, foi desenvolvido e avaliado um sistema de detecção de quedas rotacionais e livres. Por último, foi proposto um sistema de detecção e anti-colisão de obstáculos baseado em múltiplos sensores inteligentes. Diversos testes de simulação foram realizados para obter atrasos de processamento e tempos de travagem. Deste modo foi possível calcular a distância de segurança mínima de travagem face à detecção de um obstáculo.

***Palavras-chave*:** Veículos não-tripulados, veículos 3D, mecanismos de segurança, deteção de falhas.

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Chapter 1
INTRODUCTION

This chapter presents the concepts behind this dissertation, an overview and the motivation to initiate this study, objectives and contributes, and is described the state of the art concerning this dissertation technology field. A dissertation structure is also present.

1.1 Overview

During the last decades, there was a great investment in unmanned vehicles due to its growing popularity and usefulness of their applications. The concept Unmanned Aerial Vehicle (UAV) defines an air vehicle that operates without the need for a human pilot. Its use began in military interventions in situations where the risk of having a human pilot was unacceptable to the type of mission conducted. UAVs are controlled by autopilots and /or remotely by human operators through a Control Station (CS). This allows to have a general solution for the control, First-Person View (FPV) and telemetry data, thus allowing a total autonomy in the flight. The term Unmanned Aerial System (UAS) [1] is a more comprehensive description that encapsulates the UAV, CS, and communications system that interconnects both of them.

Currently, UAVs are sufficiently developed to carry out a wide range of services for personal or commercial use. These have the ability to take off / land vertically, hover with great stability, move in all directions as well as change their direction of flight and even stop their movement abruptly. The side effect of this control malleability is that it can be automatically controlled, especially if equipped with Global Positioning System (GPS) and other positioning / locating sensors or other guidance systems. This technology is used in real-world applications such as photography and video, meteorology, photogrammetry and remote sensing [2], civil security operations [3] - fire detection, search and rescue operations, surveillance, police operations, and Engineering / Construction inspections, among others. Socially, this technology is increasingly part of our daily lives, involving companies and hobbyists who are dedicated to selling and exploring at sporting and cultural events and other areas of public interest.

1.2 Motivation

The first UAVs were controlled with the support of radio control (RC). However, handling an UAV with RC, in Line-of-sight (LOS), is not enough and limits the potential of this technology. In military situations, a satellite link is also often adopted although, it requires more complex hardware and has its limitations for civilian use in telemetry transmission - entailing higher costs. The use of packet network communications, such mobile communications is increasingly prevalent due to its wide coverage area. Mobile networks enables Beyond Line-of-sight (BLOS) communications, regardless of the operator location, maintaining high transmission rates and reduced latencies between the UAV and the control station.

The handling of UAVs carries risks in its use, which jeopardizes the safety and reliability of these systems. These air vehicles are capable of reaching distances far away from our line of sight which are only limited by the autonomy of the vehicle's battery. In vehicle control over long distances, there is a need to ensure that the vehicle has ensured certain mechanisms to recover from loss of connection - which can lead to a lack of vehicle control – or electrical/mechanical failures that may result in a number of undesirable situations.

For these reasons, a complex fault tolerant system incorporated in a UAV is very important and beneficial. In fact, users are increasingly concerned about the safety of their equipment in the handling of their UAVs and the possible danger of their use in civilian areas. A system able to tolerate faults helps minimize the costs of any possible impact of the UAV and reduces the risk of damaging the UAV components or even arm people or public/private property.

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1.3 Objectives

The main objective of this thesis is to understand the possible faults that can compromise the operation of a UAV and develop solutions to avoid possible undesirable situations. Using the results of a complete system analysis, the most likely failures to happen are prioritized and a fault tolerant system will be developed. Thus, several secondary objectives stand out:

- Define a general architecture of an UAS;
- Identify possible failures and classify them according to cause, effect and existing solutions;
- Select the most harmful failures that can be solved;
- Develop strategies to minimize the risk of selected failures:
  1. Current Sense Monitoring;
  2. Fall Detection System;
  3. Obstacle Collision and Avoidance.
- Implement the strategies in a real system;
- Test the strategies developed and analyze their efficiency.

The dissertation aims at the creation of several security mechanisms for the reliable operation of a UAV. It is intended to obtain a reliable and robust system to failures most likely to occur during UAV operation. The security mechanisms to be implemented will be tested and validated in real-world environment. The possible failures of the UAV can be simulated in order to verify if the different security mechanisms allow their reliability.

1.4 State of Art

There has been a great development in the area of UAVs. Numerous companies, academic groups and diverse hobbyists have developed numerous software and hardware solutions for UASs. The hardware includes the vehicle and all communication system for the control station, as well as any additional accessories denominated payload. At software level there are numerous platforms for stabilization, geolocation, failsafe mechanisms and command missions. The following sections describes the tools and scientific advances developed in the area of UAS, with a more detailed focus on the security mechanisms.

1.4.1 3D Vehicle Controllers - Open Source Projects

The vehicle controller is responsible for all system operation and is therefore the main component of 3D vehicles. They have the function of processing input signals, such as information from the transmitting radio and/or telemetry, which combined with the information gathered by the sensors output signals to the Electronic Speed Controllers (ESCs) - responsible for all transmission of commands for the vehicle's motors. They present basic vehicle control functions such as mapping of radio control channels to information for speed, direction and altitude change - vertical axis (Yaw), longitudinal axis (Roll) and lateral axis (Pitch). The combination of a vehicle controller with GPS module and Inertial Measurement Unit (IMU) sensors allows to introduce the concept of Flight Controller (FC), responsible for the control of the UAV.

There are several vehicle controllers in the market for different applications. The ArduPilot Mega (APM) and Pixhawk (PX4) are two open-source platforms for the operation of 3D vehicles, providing the tools for a developer configures the vehicle for his own applications.

The APM [4] was first developed by Chris Anderson and Jordi Muñoz of DIY Drones using the 16MHz ATmega1280, known as APM1 - 1280. The APM2.8 incorporates an ATmega2560 microprocessor and an ATMEGA32U-2 for USB functions. It includes 3-axis gyro and accelerometer along with a high-performance barometer and a 6-Degree of Freedom (DOF) accelerometer/gyroscope MPU-6000. Has 54 pins for digital input/output, which 15 of them can be used as Pulse Width Modulation (PWM) outputs, 16 analog inputs and 4 pins for serial communication. It is an open-source firmware, which supports 3D platforms such as: airplanes, multirotor, rovers, autonomous boats and helicopters.

PX4 [5] is a platform with the intention of implementing the command and automation of the Micro Air Vehicle Link (MAVLink) [6] protocol. The platform is made up of the PX4 autopilot, open-source. It consists of two boards, PX4FMU and PX4IO, running the firmware according to the configuration of the vehicle. It allows the use of fixed-wings, multi-rotors, helicopters, boats, cars and robots. A CS is provided for parameter setting and vehicle control as well as mission planning.

1.4.2 Fault Tolerance Mechanisms

There can be several safety mechanisms implemented on the firmware of the vehicle controllers: automatic return to the starting point of the UAV in case of loss of connection, altitude sensors (sonars) for take-off and landing, battery consumption monitoring, visual led alerts and audible warnings in case of failures, among others. In case of failure, what has already been developed is relatively little compared to the progress that has been made in the development of these complex systems. There are solutions such as the use of parachutes with IMU [7]. Other solutions includes obstacle sensors and current monitoring sensors.

1.4.3 Detection and Anti-Collision of Obstacles

The use of detection and anti-collision algorithms improves the safety and ensures a greater autonomy and safety in a UAV. The use of ultrasonic (UR) sensors [8] has its limitations, such as failures in the detection of human obstacles. These UR sensors do not detect surfaces with properties that absorb the sound and therefore do not allow to evaluate their distance to the obstacle. On the other hand, infrared (IR) sensors, which are optical sensors, do not have this problem even though they fail in conditions of poor visibility (fog, poor lighting, and smoke) or in the presence of obstacles that allow the passage of light (translucent obstacles). In [9], the combination of low cost ultrasonic sensors and infrared sensors allows to overcome the limitations presented above. This system allows us to avoid collisions with obstacles such as walls and people and to control their distance from them. Other solutions, equally effective but with limitations on weight and cost, could replace infrared sensors by laser sensors.

1.4.4 Safety Mechanisms for Power Supply

In the case of a failure in the power supply - cables and loose connectors, excessive discharges, short circuits, among others – the consequence is the inactivation of the whole system.

The existence of current measurement sensors is a possibility, although they are ineffective in that they are fed by the same power source being controlled. The PX4 has a configuration [10], using a voltage and current measurement sensor, which allows communication with the FC for possible future missions in case of power failure, for example: Return to Home / Land (RTH or RTL). A similar configuration [11], using an embedded intelligent sensor, can detect current-level faults in the power supply (with an excellent accuracy of 0.01mA). This configuration of low cost and consumption and of great precision and reliability later allows the treatment of information and notification, per example, for a CS.

Another power supply solution is the introduction of an additional battery. As it has been proved in [12], it was possible to create a supplementary battery mechanism in UAVs through an automatically battery change. An online algorithm for information treatment and monitoring of the conditions of the batteries would inform a low battery level to proceed to the exchange of the battery after a safety landing. After the automatic exchange of the battery, the UAV would proceed its flight. One of the limitations of this system is that it is not a solution to a fault in mid-flight when there is a cut in the power supply but rather as a system to guarantee a greater autonomy of the UAV. A simpler configuration is the use of two batteries in parallel. This does not ensure a considerable increase of the flight-time but could fix a failure in a single battery when the UAV is in flight mode.

1.4.5 Propulsion System Redundancy

Possible propulsion system failure is recognized as a critical problem in a UAV. There are solutions that allow an analysis of their control and decision making in order to avoid possible problems both in the motors and in the control system. A control system has been developed [13] to detect local faults in the control units of the motors and rotors. These faults can be caused by the wear and aging of the rotors which have negative effects on the performance on the flight control system. In short, this system has the capability of producing torque higher than those used in order to compensate for the above-mentioned wear effects on the rotors. This solution acts at the electrical and mechanical level and was implemented in a multirotor in a controlled environment.

1.4.6 Micro Air Vehicle Link

MAVLink is a communication protocol for MAVs that has now been extended to all types of non-airplanes (both aerial and terrestrial). The MAVLink package is basically a sequence of bytes encoded and sent through a transducer (via USB serial, radio frequency, Wi-Fi, Cellular Networks, etc.). By encoding, information is intelligently ordered in a data structure by adding a checksum, sequence number and sent through the byte-to-byte channel.

1.5 Contributions

This dissertation proposed a fail-safe security system for the reliable operation of 3D vehicles. The focus of this work consists of three different mechanisms implemented: a current sense monitoring system, a fall detection system and an obstacle collision and avoidance system. All the mechanisms developed are implemented on a platform independent of the vehicle to ensure its autonomy in the case of a failure.

In the current sense system implemented, two different techniques are tested to detect the flow of the current between the battery and the flight controller: resistive and magnetic current sensing. The two techniques are studied, implemented and tested providing different results.

The fall detection system is implemented through the use of an IMU sensor. Firstly, it is developed a software to test the sensor. The software allows to represent the orientation and the behavior of the UAV through the IMU sensor data collected. The data collected allows to implement an algorithm to detect a free fall and a rotational fall – and still able to differentiate between a single flip and a rotational fall.

The obstacle collision and avoidance system is divided into two sections. The obstacle collision uses an interface of the fall detection system implemented. The IMU sensor provides the orientation of the UAV, detecting its direction of movement and activating the nearest obstacle sensors to detect obstacles. The avoidance system is a physical interface connected to the vehicle controller transmitting an alert message to an emergency stop to avoid the obstacle. This was tested on simulated environment with an open-source 3D environment simulator. The use of this simulator is intended to simulate the time that a UAV takes to completely reverse its movement to avoid an obstacle and the maximum distance it travels in the course of this braking. Data collected from the simulation will correspond to the minimal safety distance, at a certain speed, on which the obstacle is able to be detected and the collision avoided.

ICUAS'17 - The 2017 International Conference on Unmanned Aircraft Systems: A paper was submitted for this conference that takes place in Miami Marriott Biscayne Bay, Miami, Florida, United States of America, from June 13th to June 16th of 2017;

1.6 Dissertation Structure

The dissertation contains five chapters and a final section with appendixes.

Chapter 1 concerns the dissertation motivation and defines the proposed objectives. It also describes the state of the art in this field of study.

Chapter 2 presents an overview about UASs, which includes all components to remotely control an UAV, such has the control station, the communication system, the vehicle and its transport and support.

Chapter 3 is divided into two sections. The first section is a risk analysis and introduces the fault-tolerant proposed solution. The second section concerns all concepts required for the implementation of this dissertation: classic current sensing strategies, basic concepts for the detection of a free and rotation fall and an introduction to the obstacle avoidance work developed so far.

Chapter 4 is the core of this dissertation. It describes the failsafe mechanisms and discusses the results of the experiments developed.

Chapter 5 presents overall conclusions achieved with this dissertation and proposes possible future work to improve and create more fail-safe mechanisms.

This dissertation ends with appendixes with subjects addressed during the dissertation.

Chapter 2
UNMANNED AERIAL SYSTEM

This chapter introduces the components and functionalities of an UAS architecture.

2.1 UAS MAIN MODULES

An UAS is more than just the aircraft itself. It is a complex system which comprises a number of sub-systems which work together as one. These sub-systems may be able to operate with some autonomy from each other in some applications, although they must work together to achieve the performance of an only working system. An example of these sub-systems working as one is the communications radio subsystem acting like an interface between the CS and the aircraft: it must operate the same protocols and have the same radio frequencies and security to establish a communication between these sub-systems. The whole system must be properly designed from the beginning to be part of a complex system, which comprises the following sub-systems:

- Unmanned Aerial Vehicle;
- Control station;
- Communication Systems;
- Transport and Support.

2.2 UNMANNED AERIAL VEHICLES

UAVs are usually confused with model aircraft or drones. A model aircraft is a radio-controlled model usually kept within LOS and manually controlled by an operator. A drone will have the possibility to fly BLOS, but has no artificial intelligence (AI) embedded in the system. It is pre-programmed to do a mission and only returns the mission status and data collected, when returns to base. An UAV requires some minimal AI depending on the UAV desired application. It must have a communication link and a control station to transmit payload, telemetry data and other flying data parameters.

UAVs are distinguished from manned vehicles for a reason: the vehicles operate without an on-board human presence. These vehicles ensure the safety of the pilot in dangerous missions. Either this can be an important advantage or a disadvantage depending on the role of the mission. It depends on what the task is however unmanned technologies are starting to prove themselves as a major necessity for different tasks.

2.2.1 Unmanned aircrafts

Unmanned Aircrafts can be classified by different parameters. They can differ in weight, autonomy, range and structure. Massive UAVs tends to have more mass and reach a higher altitude. This also depends on their structure, as fixed-wings are more aerodynamic then rotary-wings. Their range is becoming global as the network communications for UAVs are capable of providing more telemetry range with, per example, cellular networks. Table 2.1 summarizes characteristics of aircrafts according to [14-15].

Category	Mass [kg]	Altitude [m]	Autonomy	Range [km]	Structure
HALE	450-13500	>15000	>Day	Trans-global	Fixed Wing
MALE	450-13500	<15000	<Day	500	Fixed Wing
TUAV	15-450	<5500	<day	100-300	Fixed-Wing Rotary-Wing
Close-Range UAV	<50	<3000	>Hour	<100	Fixed-Wing Rotary-Wing
Mini UAV	<20	<3000	<Hour	<30	Fixed-Wing Rotary-Wing
Micro UAV	<2	<1500	<Hour	<20	Fixed-Wing Rotary-Wing
Nano UAV	<0.025	<100	Minutes	Short Range	Fixed-Wing Rotary-Wing

Table 2.1 - UAV Category Specifications

2.2.2 UAV applications

Unmanned Systems technology has been used in diverse commercial applications. The most common being the following:

- Water management: pollution monitoring, temperature and flow measurement, monitoring rivers, flood alerts;
- Security: law enforcement, border and coastal, monitoring surveillance [16], poaching patrol;
- Transportation: of good, of people;
- Air monitoring: ground traffic monitoring, air traffic control support;

- Forestry: tree disease monitoring and inspection, cutting and harvesting trees, fire detection;
- Photography and videography: advertising, public events, private use;
- Media resources: news, entertainment broadcasting;
- Communications: communication and broadband services, satellite augmentation system, radio relay;
- Climate monitoring: hurricane hunters, meteorology;
- Military applications: security and control, aerial reconnaissance, terrain search and rescue, transport, destruction.

2.2.3 UAV components

Manned and unmanned aircrafts usually have similar physical components. An UAV can be decomposed into four main groups:

- Electronic Processing System: the flight controller and communication modules;
- Propulsion System: actuators (motors and propellers) and ESCs;
- Power Supply: at least a power source for powering up the electronic processing system and the propulsion system;
- Mechanical Structure: a frame supporting all the UAV components;
- Payload: all unnecessary components on-board the UAV.

Electronic Processing System

The electronic processing system is divided in two main components: the FC and a communication module. The flight controller is mainly responsible for controlling the UAV and the communication module is responsible for the communication with the CS. Other solutions can be used for establishing this communication but it is still a requirement to have this bridge connecting the FC to the CS.

There are several flight controllers available. For controlling the UAV the FC requires some navigation sensors, such as gyroscope, accelerometers, magnetometers, altitude pressure (barometer). It is also used a GPS to provide accurate positioning. . FCs also include extra pins for external sensors, serial ports, analog to digital converters, microcontrollers and pulse-position modulation encoders. The firmware running on the processing system uses all information data from sensors and other devices to perform the operator requests from the CS. There is also a RC receiver for radio control.

The communication between the operator and the UAV is commonly made in civilian applications using RC. In this case it is only required a RC receiver and transmitter to communicate. For a complex communication to a control station using wireless networks a different configuration has to be used. One solution is the use of a Raspberry PI. This is a small computer based on a Linux operating system. The Raspberry PI operates as a bridge between an USB dongle, such as a Wi-Fi or 3G/4G communication module, and the CS.

Propulsion System

The propulsion system are a combination of motors and propellers, or actuators, and the ESCs. The main objective of this sub-system is to generate force that leads to UAV movement.

ESCs are the interface between the actuator, power supply and the FC. They are connected to the power distribution board (PDB), which is connected to the battery. An additional battery elimination circuit (BEC) is included to limit maximum power output for the UAV motor and, in some systems, provide power for the FC to avoid the use of additional power supplies. ESCs have the task to receive PWM signal and transmit the phase to the actuators. BECs accepts a range of voltage and current and provide direct current (DC) electric power to UAV motors. This makes possible to control the UAV, redirecting it for a desired position.

Actuator is the combination of a motor and respective propeller. The most common is the use of Brushless DC (BLDC) motors, which are responsible for converting electrical energy into mechanical energy. A propeller is a blade responsible to convert rotary motion into propulsive force when attached to an electric motor.

Actuators, ESCs and power supply must be dimensioned to achieve maximum efficiency. The power input is a good indicator of the mechanical power output of a motor. Also, a motor draws more current as it delivers more output torque, which is only limited by the power supply capacity. The size of propellers is normally defined in the motor specifications. All components must be dimensioned to work together to perform a stable and controlled flight.

Mechanical Structure

The physical structure that supports the UAV components is denominated frame. It is responsible for holding the propulsion system, landing gear, the electronic processing system and the payload.

A decisive factor when choosing the frame is the configuration: more motors lead to a more stable flight but highly increases the energy consumption reducing the UAV autonomy. For Vertical Take-Off and Landing (VTOL) vehicles, it ranges from one rotor to multi-rotor. Single rotors are common in helicopters. Multi-rotors ranges from tri-copters to octocopters. Some aircrafts use co-axial rotors to carry more payload weight without the necessity to have a larger frame. There are configurations in Horizontal Take-Off and Landing (HTOL), such as the flying-wind and delta wing.

Power Supply

All electrical components in the UAV system need to be connected to a power supply. Most UAVs use lithium-polymer (LI-PO) batteries, but there are other ways to power the UAV.

Some systems use solar cells attached on the wings, providing and storing power to the battery even in flight mode. This approach has its limitations and depends on the energy provided by the sun. Another approach is a hydrogen fuel cell. This fuel cell can take the UAV for a flight for about two hours while traditional LI-PO batteries last for about 20 minutes. A more dangerous method is the use of gasoline engines. The UAV is powered by a combustion engine and although it requires a tank with a flammable gas it provides more power than the usual LI-PO batteries.

In either situations, there is a trade-off between the payload and the available flying time. The weight of the UAV substantially decreases the autonomy. This requires the UAV to come down and replace the battery or recharge the battery quite often. The most common batteries for UAVs are LI-PO batteries. These batteries have high energy capacity, high discharge rates and reduced size.

Power supply is a critical and dangerous point in the UAV system. Depending on the type of battery supply, different approaches have to be made to ensure a safe flight. Regular visual inspections to the batteries are crucial and monitoring the voltage cells levels is a pre-requirement before each flight.

Payload

The main task of an UAV is to carry the payload to a destination point. Payload is defined as the equipment carried that is not required for flight, control and navigation of the UAV. In sum, all items that are not essential for controlling the UAV are considered payload. This a considerable factor on the UAV autonomy, has it can considerably reduce its flying time.

As referred above, the payload depends on the role of the UAV. Hence, there are no limits for the type of existing payload [17]. The most common in civil applications is the use of a gimbal attached to the frame with a camera for aerial photography. The frame can also support any type of cargo for transportation, such as: medical care, delivery food, package delivering, among others. A more robust system can also include external sensors for specific tasks. These sensors can be used for detecting surfaces (radars, ultrasonic and infrared sensors) or collecting physical quantities in the environment (temperature, light, pressure, sound, humidity and others). The data obtained by the sensors can be processed and transmitted via the down-link to the CS. Safety mechanisms are also considered payload, such as parachutes and other on-board equipment for detection of failures.

2.2.4 Launch and recovery

There are two critical phases during the UAV flight: launch and recovery [18-19]. Regarding to the launch process it is possible to distinguish three types:

- Horizontal take-off and landing:

Take-off and landing requires a long and straight space available. The vehicle accelerates along an available surface until sufficient lift is generated for take-off. The landing is the reverse process, it only requires space and time to the aircraft to slow down.

- Catapulted or zero-length rocket-powered launch:

This method requires sufficient acceleration and catapult throw length for the aircraft to achieve flight speed on release. Some UAVs can execute a catapult launch but require space for an automatic landing.

- Vertical take-off and landing:

This is more common in multi-rotors and helicopters. The space required for take-off and landing only depends on the aircraft size. Landing and taking-off is done by a vertical flight.

The recovery procedure consists not only on a safe landing, but the return of the UAV to the launch position or a new location. The recovery process can be assisted depending on the aircraft. For long-range and medium-range aircrafts, the use of the GPS and the precise differential GPS are tools for an automated landing. This reduces the occurrence of accidents with manual control. For manual landing, vehicles without a landing gear or critical landing situations there are other solutions: parachute, recovery net or belly landing.

2.3 TRANSPORT AND SUPPORT (MAINTENANCE)

Unmanned vehicles needs transport and maintenance for utility purposes. Transportation can require more than the carrying the vehicle. It can also mean transport of the control station, payload, fuel or batteries or landing gears. On the other side, maintenance englobes visual inspection (mechanical and electrical) and repairing off the vehicle and the control station updates (software and hardware). The transport entirely depends on the dimension of the vehicle. From Table 2.1 it is understandable that some aircrafts can be carried by a single person, such as Micro and Nano UAVs. These vehicles can be controlled with a RC which can be carried in a single backpack or even carried by humans. On the contrary, larger aircrafts require another level of transportation. Close-range system such as micro-UAVs and heavier UAVs have control station and support equipment. This equipment is most likely heavy and large to be transported by humans. In such cases, there is a need to use motor vehicles capable of carrying heavy machinery. These vehicles can be cars, trucks or even planes. A complex system may require three or four vehicles for transportation. This include a CS, fuel, additional equipment and for some aircrafts a landing/take-off gear. The maintenance requires all support equipment and normally occurs on the ground. Mechanical and electronic system requires equipment to support its operation. Some components may have an occasional need for replacement due to their vulnerability to be damaged. Other equipment may need lubrication and adjustment from time to time. A visual inspection is as important as testing the communication between the CS and the UAV. This avoids undesirable situations and possible crashes. The control station needs to be updated and tested before each flight.

2.4 CONTROL STATION

A CS [20] is the man-machine interface responsible for aircraft operation. In some situations, a control station can be also part of a complex network-centric system, when interfaced with other components, sharing and receiving information with a larger system.

From the CS, the operator communicates to the aircraft via the communications system up-link to transmit the various types of missions to the aircraft. Similarly, the aircraft returns all type of information to the operator via the communication downlink, either in real-time or by pre-programmed missions with commands. This information can be navigation data, information about the sub-systems of the aircraft and data from the payloads. In more complex systems, the information transmitted can be shared with other external systems for different applications. A CS must ensure the following requisites:

- Mission planning, control and monitoring;
- Bidirectional communication link: telemetry and video visualization for real time operation or storing data. Transmission of commands for its operation;
- Safety and Security: activate warning alarms if the system enters an unsafe operating mode. Provide a reliable communication link between the CS and the aircraft. Protect its communication and data link against possible intruders;
- Storing and configuration data: storing data from save logs and telemetry and configuration of the flight controller’s parameters.

2.4.1 Control Stations Platforms

The operation of aircrafts is commonly associated to a ground station. However, the aircraft can be controlled by air and by sea. These are less used by civilians by the costs and complex systems required. Therefore, CSs are divided into three different subgroups:

- Ground Control Station (GCS):

The must-use CS by hobbyists. In such cases it can be installed in laptops and other electronic devices and is easily transported. Medium and long-range GCS are usually fixed in airfield bases for the operation of robust aircrafts.

- Sea Control Station (SCS):

The aircraft can be initially launched from land or aboard the ship. The UAV system control may be totally or partially integrated within the ship. Either cases, the UAV system radio integration alongside the ship radio and radar antenna may rise some interference considerations. Launch and recovery on-board may be limited for some vehicles.

- Air Control Station (ACS):

The aircraft is launched from another aircraft, off-ground or off-board launched. The communication system, such as the antenna mounting and the control system for the aircraft operation, is limited to the confines of a large manned aircraft. Beside the complex communication system embedded on the aircraft, the launch and recovery on-board has to be precise and calculated.

2.5 COMMNUNICATION SYSTEMS

Communication between UAVs [21] can be divided into radio frequency LOS and BLOS. LOS operations refer to a directly communication by radio, Wi-Fi or even Bluetooth. For BLOS operations, wireless communication links are used, such as: cellular networks, radio communications via satellites or other means of radio relay. Radio communications in BLOS operations are also used, when RC transmitters and receivers allow communications BLOS.

The main objective in having a communication system is to provide the data links between the aircraft and the CS. It consists of an uplink, transmitting command and control from the operators to the aircraft (or multiple aircrafts), and a downlink from the aircraft to the CS or other receiving stations (remote stations). The downlink is usually more demanding for the communication system due to the data transmitted: payload (sensors data, image/video, etc.) and telemetry data ("housekeeping" data) from the UAV.

2.5.1 Radio Communication and Wireless Networks

Satellite Communication

Satellite communication can be used, although they require more complex hardware and has limitations for civilian use in telemetry transmission - which entails higher costs. A possible solution is through the RockBLOCK [22]. This allows the communication between the UAV and the CS, but restrains the communication messages sent through the communication link. A maximum of 340 bytes for the up-link and 270 bytes for the downlink only makes it possible to send navigation and control commands for the UAV. Another complex situation do deal is the delay caused by the communication link through satellite, which makes impracticable to control the UAV in real-time.

Radio Control

The most common communication link used is by conventional RC. In this situation, at least a transmitter and a receiver radio system are required for transferring the pilot signals to the vehicle. Additionally, a different transmitter can be used for FPV or transmitting payload. The use of a FPV system is useful for control and navigation, mainly on situations where it is not possible to have eye contact with the UAV.

Microwave frequencies between 3 GHz (Super-high frequency – SHF) and 300 GHz (extremely-high frequency – EHF) are not refracted in the atmosphere. Frequencies between 3 Hz (Extremely Low Frequency – ELF) to 3 GHz (Ultra-high frequency – UHF) are considered true radio frequencies as they are refracted in the atmosphere. There must be a compromise when selecting an operating frequency to the UAV operation. Lower frequencies offer a better and reliable propagation but have a reduced data-rate. On the other hand, higher frequencies are capable of carrying high data rates but require a direct LOS between the transmitting and receiving antennas and consumes more power to propagate the signal. In typical UAV applications, two different frequencies are typically used: 2.4 GHz and 5.8 GHz. The DJI Phantom 1 Quadcopter operates at 2.4 GHz requiring a different frequency for FPV. The phantom FC40 operates at 5.8 GHz and uses a separate 3.4 GHz system to transmit video and photos.

Cellular Networks

RC communication has coverage limitations, although it is possible to control it within several kilometers of the operator. A more comprehensive solution is the use of mobile communications. This communication allows that regardless of where the operator is, provided there is mobile coverage, the UAV communication is always operational. The evolution of mobile networks increasingly allows higher transmission speeds to be achieved, up to 100Mbps in motion in the case of 4G coverage, while maintaining Quality of Service (QOS) point-to-point at any time and place.

However, there are also problems associated with the use of such mobile networks such as handovers, data transmission limitations, lack of coverage, data transmission problems at high speeds and delays. In order to enable transparent communication on mobile networks, a dynamic follow-up of user mobility is required. The handover is related to access, radio resource and control of the network allowing to modify the allocation of radio channels to users without losing the connection between different geographic locations. The limitations in data transmission depend on the mobile network used. There are other issues associated with mobile networks that go beyond coverage. Latency, which corresponds to the time a packet takes to reach a destination. Jitter, which consist of the variation of the delay between packets. Packet loss, which can be dropped mainly for a congested network buffer.

2.5.2 MavLink Protocol

The communication between a CS and the UAV requires an application level communication protocol for transmission of the information over a wired or wireless link. The MAVLink Communication Protocol defines a set of telemetry messages for all the communication required for the control of 3D vehicles.

Figure 2.1 represents the MAVLink packet. The package has a minimum of 8 bytes without any payload associated to a maximum of 17 bytes. The header has 6 bytes equally distributed by 6 different fields. The message header indicates the start of a new packet: 0xFE for the MAVLink version 1.0. The message length indicates the length of the payload. The sequence number allows MAVLink to continuously provide feedback about the packet drop rate and thus allows the aircraft or control station to take action. The system ID (1 byte for a maximum of 255 different possible ids) is aimed at supporting multi vehicles through the same CS. The component id is reserved for all components or just for a specific component within the same flight controller, such as: GPS, Mission Planner [23], and IMU. The message id defines the type of message included in the payload and how it should be decoded. A variable sized payload contains the essential data carried. The payload is responsible for carrying all the UAV information, from telemetry messages to FPV video. The checksum ensures the integrity of the content transmitted. The checksum is two bytes in the end of each MAVLink packet and is calculated using the header – except the Message Header Field, and data from payload. The minimum packet length is 8 bytes for acknowledgment (0 bytes of payload) and the maximum packet length is 263 bytes for full payload.

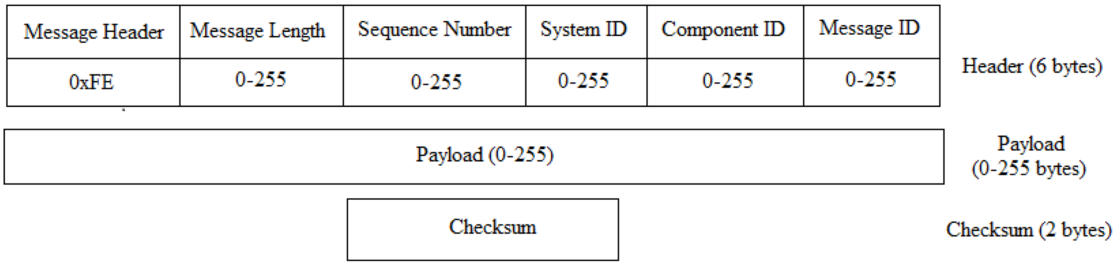


Figure 2.1 - MAVLink Frame Fields

2.5.3 Communication Problems

The communication link is a critical point in UAS operations. Without communication, the UAS is just a drone system and loses the versatility and mobility of the UAS. The communication link may fail under certain circumstances, such as:

- Partial or total system failure;
- Loss of LOS due to interferences, or geographic features blocking the signal:

An interference, a system failure or loss of signal can lead to a loss of communication. This can be temporary or permanent. In complex systems, both antennas can scan for each other by recording the last position off a successful established communication. In cases of permanent loss of communication the UAV can be programmed to return to base;

- Multi-path propagation:

This can occur if the transmission is reflected off nearby obstacles. Thereby, two signals displaced in time by microseconds are received. The solution is to use sophisticated processing to overcome this problem;

- Weakening or loss of power due to the distance to the CS:

This is directly influenced by the transmitter power output and receiver sensitivity. The loss of power that occurs to the signal as it propagates is referred to as path loss. Several factors must be taken into account: the distance the radio wave travels, the operating frequency and the height of the transmitting and receiving antennas. Either the system hardware is capable of dealing with larger distances or is required to minimize the distance between the transmitter and receiver;

- Intentional jamming of signals:

The radio transmission may be subject to inadvertent or intentional jamming of the signal. The downlink signal from aircraft or from satellites are more open to detection unless a sophisticated airborne detection system patrols the communication area. The risk of this happening depends on the available anti-jam measures. Using high power transmission to increase the signal-noise ratio of the signal to out-power a dedicated jammer system. This preventive measure can highly reduce the UAV autonomy and it is not recommended in some applications.

Chapter 3
RISK ANALYSIS AND CONCEPTS

The implementation of a fault tolerant system is preceded by an analysis of system risks that may arise in the components of an UAV. This chapter starts with a section about risk analysis with a compilation of the most common UAS failures that can compromise the UAV safe operation. Then, it presents the solutions developed in this thesis in order to ensure a more robust and reliable system. A second section introduces all needed concepts for the absolute understanding of how the system is built up and how it works. Therefore, this chapter builds the basis for the next steps of this thesis.

3.1 RISK ANALYSIS FOR UAVs

3.1.1 UAS Functional Block Description

This section presents the overall logic operation of an UAV system. This scheme simplifies and demonstrates all interactions between the system components. This has extreme importance to understand where the source of the high priority risks is and to analyze possible solutions to the implementation of safety mechanisms.

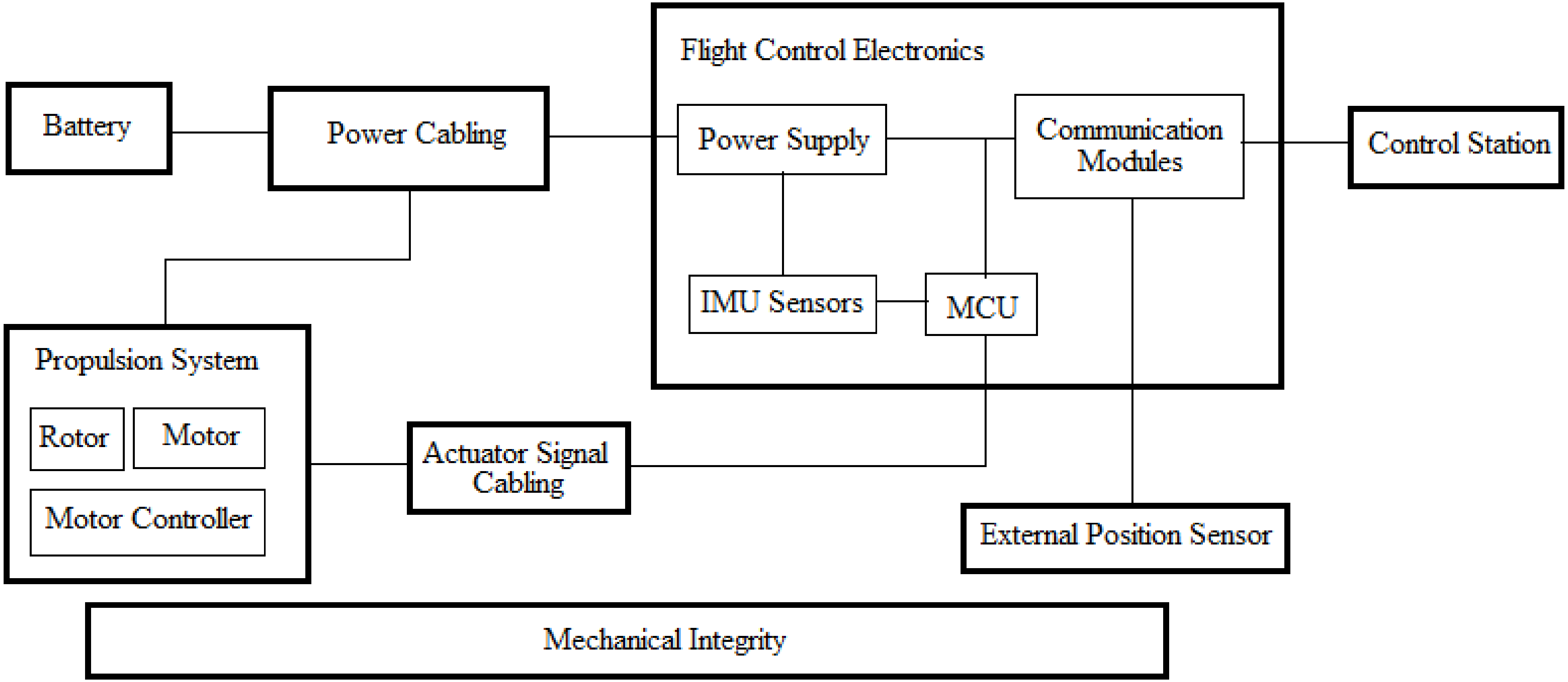


Figure 3.1 - UAV Functional Block Diagram

3.1.2 Identified High Priority Risks

In order to identify the components that present a higher risk in a UAV system, several factors are analyzed such as: effects, causes, current controls and the main function in the global system. Taking has reference [13], which has a very detailed analysis of this problem, it is performed a brief analysis of the components with higher risks - Table 3.1. The following risk groups have been defined to englobe the higher priority risks:

- Flight Control Electronics;
- Battery & Power Cabling;
- Propulsion System/ Propulsion Unit;
- BLDC Controller;
- BLDC – Rotor.

Flight Control Electronics:

This subsystem is responsible for powering the different components. It is responsible for the communication modules, IMU sensors and the Mission Control Unit (MCU).

Regarding the failures that might occur, stands out problems such as power supply failure, loss of communication, partial or total failures at the level of the IMU and MCU and problems in the Printed Circuit Board (PCB). The effects that may result from these faults can cause irreparable damage to the UAV system. The present checks are currently non-existent and are only detected by the responsibility of a visual inspection before each flight.

Battery & Power Cabling:

A power supply connected to a distributed system for all components with different levels of consumption. These components are vital to the system.

There can be many causes for the malfunction ranging from human failure where the user does not check the level of battery or low battery warnings, to electrical failures: damage to the battery, short circuit and overheating, bad or damaged wires, among others.

The consequences can be quite serious. A loss of power could lead to idle system, which results in physical damage in case of a fall or with a crash against obstacles that may damage the system. There are solutions to some of the problems. More robust cables and better materials allow for greater longevity and lower maintenance. The choice of the battery, depending on the requirements of the system, in accordance with the required levels of consumption and the constant monitoring of their voltage levels.

Propulsion System & Motor Communication:

The propulsion system has the function to generate the momentum and torque to stabilize, control and lift the system. The UAV may have different propulsion units associated with the system - among which the more common are: quadcopters (4 units), hexacopters (6 units) and Octocopters (8 units). At the mechanical level several failures may occur on motors, ranging from physical failures of propellers or motors to failures in the communication between the FC and the drivers of the motors. At the electrical level, failures in the bus communication can be detected and circumvented. Otherwise, the consequences in a situation in which the UAV is in flight mode are immediate. Any failure of an engine system causes a lack of stability of the system and hence immediate drop.

Part Interface Process	Component	Description	Failures	Current Controls
Power Supply and Cabling	Power Supply	Provides the energy needed to power up all system	Discharges, battery failure, exceeding maximum current, electrical connection failure, short circuit, physically broken/damaged wire	Measuring the voltage level, respect the minimal and maximum system power requirements
	Power Cabling	Distributes the energy for all system components		Visual inspection before flight
	Actuator Signal Cabling	Communications between the flight controller and the motor controller	Signal cable broken, short circuit, transmission errors	Visual inspection and testing connection before flights
Propulsion System	Rotor	Converts Rotational Power to Thrust	Total/partial damage, loss of rotor	None
	Motor	Converts Electrical Power to Mechanical Power	Electrical or mechanical failure, overheating	None
	Motor Controller	Control and Drive the Motor	Communication bus error, overheating	Checksums
	Propulsion Unit	Generates Thrust	Loss of power, overloading, communications bus failure	None
Navigation	MCU	Runs the software, reads the sensors, commands the motors	MCU freeze/reset/damage.	None

	IMU Sensors	Sensors Responsible for attitude information (Gyroscope, Accelerometers, Magnetometers, Pressure Sensors)	Noise, no signal, faulty signal, biased signal, external disturbances,	Data filtering, calibration
Mechanical Integrity	Physical Frame	Holds all of the parts together	Frame structural damage	Visual inspection before flight
	Physical Components	Mechanically connect different parts	Loose screws / attachments	
			Mechanical Failure, structural damage	
Communication Modules	Data Channel	Communication with user	No connetion	None
			Corrupted data	Checksums to ensure data validity
	RC (Manual Control)	Manual Control of the UAV	No connection	None
			Corrupted data	Checksum

Table 3.1 – High Priority Risk Analysis for UAS

3.1.3 Fault-Tolerant Proposed Solution

Figure 3.2 represents a system architecture which provides a solution for data processing and real time decisions for improving the UAV safety mechanisms. With this configuration it is possible to avoid failures which may occur in:

- Flight Control Electronics and Power Supply: monitoring the current which powers all system prevents a general battery failure.
- Mechanical Integrity: an obstacle avoidance system to prevent possible accidents on UAVs.

This system also incorporates a preventive method for detecting a collision of an UAV. When the system has a critical fail, or even a small failure, the fall detection system will detect a fall. This part consist on the detection of a fall to activate a self-rescue mechanism, such as a parachute.

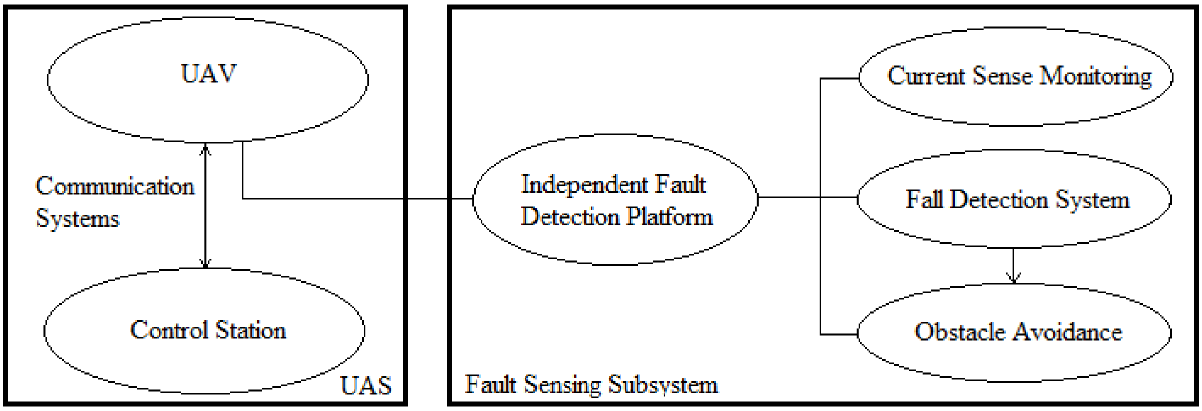


Figure 3.2 - Proposed System Architecture

UAS

It englobes the UAV, the control station and communications between both. The UAV is a representation of the 3D vehicle used for the implementation of the failsafe mechanisms developed in this thesis.

Fault Sensing Subsystem

This module consists of a fault detection platform interfacing the UAV system and the safety mechanism system implemented. It includes an Arduino Uno microprocessor and all accessory

Arduino components for the development of the security mechanisms. The Arduino is connected to a power source, independent of the UAV power supply. Hence, a power failure in the UAV does not affect the implemented system.

The safety mechanism system consists of three subsystems: current sense monitoring, fall detection mechanism and an obstacle avoidance system. These are the three units that will be implemented in this system as failsafe mechanisms. The fall detection system has a communication interface with the obstacle avoidance. This interface is derived from the fact that the sensor used to detect falls also allows to obtain the UAV movement direction, which will help in the decision to avoid obstacles.

3.2 Literature Review

Section 3.3-3.5 describe all concepts found in literature that are related to this work. For more information about the theoretical concepts one can find very comprehensive information with detailed descriptions in the following works:

- Current Sensing [24-29];
- Fall Detection [30-32];
- Obstacle Avoidance [33-47].

3.3 Classic Current Sensing Strategies

3.3.1 Resistive Current Sensing

Ohm's First Law states that an ohmic conductor (constant resistance), kept at a constant temperature, provides a directly proportional relationship between the current and the voltage at its terminals. Thus, it is possible to detect the current introducing a low-valued sense resistor in series with a current path. This produces a small voltage drop, which is proportional to the current flowing through the load. This voltage needs to be properly amplified and delivered to the control/monitor circuit.

Current Sensing Effects

The voltage across the resistor needs to be properly amplified and delivered to a monitoring system. This technique can create various challenges for the current sensing circuit. Table 1 defines, in summary, a number of problems likely to be found in those circuits.

Voltage Drop	Voltage drop created by the sense resistor could interfere with the circuits operation. This requires a balanced decision between the voltage needed to measure/detect the voltage drop in the resistor and the voltage drop tolerated by the application.
Power Dissipation	Current flow generates heat in the sense resistor, where the power dissipated is $P = I^2 * R$. Resistors tend to fail when operated in certain circumstances: at maximum power or temperature ratings and near rated power without proper heat sinking.
Parasitic Series Resistance	According to Ed Ramsden [24]: *"Low-value resistors (<1 Ω) often have lead resistances that are a substantial fraction (1% or more) of their rated resistance. This makes the resistor's value a function of the lead length."*
Parasitic Parallel Resistance	According to Ed Ramsden [24]: *"With high-value sense resistors (> 1 M Ω), current leaking around the resistor can degrade de device's effective accuracy. Contamination from solder flux residues, fingerprints, and similar sources is the primary culprit."*
Self-Heating Effects	Resistors value slightly changes as a function of temperature. Thus, the voltage across the resistor no longer be a linear function described by the Ohm's Law. Changes in temperature are not instantaneous and are unpredictable, so on proper thermal design and heat sinking should be used by current sense resistors.
Dynamic Effects	All real resistors exhibit parasitic capacitance, which appears across the terminals, and parasitic inductance, which manifest itself in series with the resistor. These effects can be ignored at DC or low frequencies but at AC circuits is often an unwanted side-effect. Inductive effects are usually common in low-value sense resistors and for high-value resistors, the capacitive effect dominates. Those effects influences the resistor's impedance as a function of frequency.

Table 3.2 - Resistive Sensing Effects

High-Side or Low-Side Sensing

In current sense applications a decision must be made as where to place the current sense resistor. This decision usually considers two possible configurations: high-side and low-side current measurement. In a low-side measurement (Figure 3.3 a.) the sense resistor connects in series between the load and the common ground. Alternatively, the sense resistor could be connected between the power supply and the load (Figure 3.3 b.).

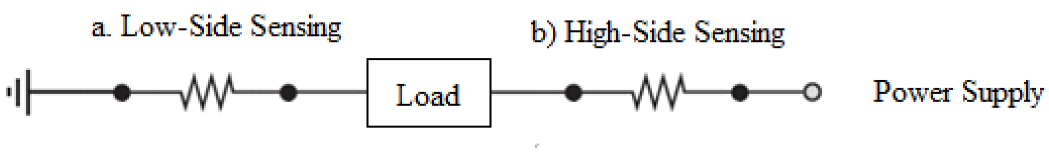


Figure 3.3 – Low/High-Side Sensing

Low-side sensing is defined by a resistor in the load's path to ground. This configuration results in the load's ground floating at a higher voltage than the system ground, which can introduce ground-path disturbance by the sense resistor. If other loads in the system - whose ground potential is unchanged - share the same ground, ground loop problems could occur. This could cause an audible noise or produce interference within the UAV. For this reason, low side sensing makes sense when dealing with large currents, one isolated load, or other situations where the system is immune to fluctuations in the ground path.

Advantages of Low-side Sensing:

- Sense amplifier handles a common-mode low voltage that is referenced to ground;
- Simplicity and low cost: a resistor in the load's path to ground means the voltage across the resistor can be amplified by a simple operational amplifier referencing the same system ground;
- Attractive for applications in which short-circuit protection isn't necessary, and where ground disturbances can be tolerated.

Disadvantages of Low-side Sensing:

- With a single load to monitor, it will no longer have direct connection to the ground due to the sense resistor;

- Fault conditions, such as a short or open circuit in the ground path, due to connections problems or interferences cannot be detected;
- The low-side resistor adds undesirable resistance in the ground path.

On opposition, a high-side sensing is a sense resistor placed in series between the system power source and the load. A resumed list of the advantages and disadvantages is listed below:

Advantages:

- This configuration is more responsive to changes in the current;
- Not only does this placement eliminate the ground disturbances found in low-side sensing, it also allows the detection of accidental battery shorts to system ground;
- High-side current sensing amplifiers has the ability to handle large common-mode voltages.

Disadvantages:

- Because shunt resistor is not at system ground, a differential voltage must be measured which requires the precise matching of the proper differential amplifier;
- Demands that the sense amplifier handle a common-mode voltage that is close to the supply voltage;
- Input resistance is relatively low;
- Inputs usually exhibit a large difference in input resistance;
- Resistors must be very well matched to obtain an acceptable Common-Mode Rejection Ratio (CMRR).

Current Shunt Monitors: Amplifiers

Current sense monitoring is just not only a decision as to whether to place the sense resistor. The voltage across the resistor needs to be properly amplified. Current sense amplifiers accurately measure the tiny voltages across the terminal of the sense resistor. In a first approach, several factors have to be considered in the selection of a current sense amplifier:

- Common mode range:

This defines the DC voltage range at the input of the amplifier with respect to ground. Normally, common mode voltages are above the chip supply voltage. For a low-side sensing the differential sense signal across the sense resistor is close to ground (0V), but for high-side sensing is close to the supply. The common-mode range must take in consideration this two different configurations for a correct voltage amplifying.

- Offset voltage and CMRR:

An operational amplifier, amplifies the difference between voltages at its two inputs. When both inputs are at the same voltage, the output should be zero. In practice, this does not occur and a small voltage appears at the output even when the input signals are equal – offset voltage. To specify the amplifier's ability to detect and reject signals in the given condition without amplifying them there is the term CMRR.

In high-side sensing, the shunt resistor is between the load and the supply. Therefore, it has to handle a common-mode voltage close to the supply voltage. In applications operating with a 5V supply, the high-side sense amplifier can be an instrumentation amplifier. Although, it has some limitations such as the input common-mode range which tends to be more expensive at higher voltages. Another approach for high-side measurements is the differential amplifier, which acts as a gain amplifier and a level shifter from the low side of the supply to the ground.

In opposition to high-side sensing, the low-side sensing is close to ground. The voltage difference across the resistor may not require the use of an amplifier (Figure 3.4 c.) as it is referencing the same system ground. However, in applications which require the measurement of small currents, the first method is not practicable: a small current with a low-valued resistor turns into a small drop voltage across the shunt resistor, which may be not possible to detect. In such cases, it is necessary the use of an amplifier to achieve better measurements and to compensate for the fuzzy nature of ground. Low-side sensing supports the use of a simple, low-cost and low-voltage amplifier since its common-mode voltage is close to ground. Another solution is the use of a differential amplifier to measure the voltage across the sense resistor.

For the amplification of the voltage two different schemes can be employed: the differential amplifier (Figure 3.4 a.) and the non-inverting amplifier (Figure 3.4 b.). In a high-side measurement, the differential amplifier is used to measure the voltage difference across the resistor and report the measurement as a ground-referenced signal. In a low-side measurement and because the common-mode range is close to ground, the current sense voltage can be amplified by a simple non-inverting amplifier.

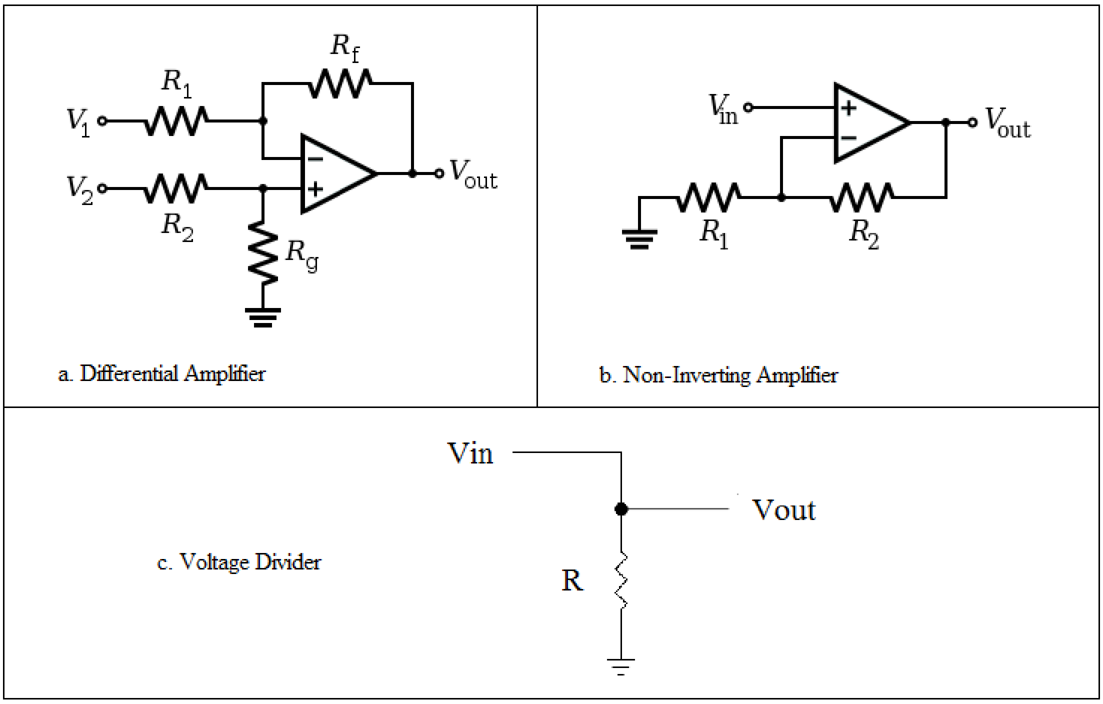


Figure 3.4 - Current Sensing Circuits

3.3.2 Magnetic Current Sensing

All magnetic fragments, regardless of their shape, have two regions called magnetic poles. Magnetic poles are always present in pairs, there is always a region defined by the North-pole and the opposite region defined by the South-pole. Earth's magnetic field is always pointing to magnetic North-pole. Magnetic fields are described as lines of force that give a definite pole at each end of the material where the flux lines are denser and concentrated. These lines, commonly referred as magnetic flux, represent the direction and intensity of the magnetic field.

When a current passes through a conductor, a circular electromagnetic field is produced around it. A current passing through a wire, a magnet or even the Earth's magnetic field produces a magnetic field. Electric current can be detected by the magnetic field it induces. When using magnetic current sensing, the sensing circuit does not need direct electrical connection with the current being sensed – due to their non-contact wear free operation.

An important application of the Biot and Savart law consists of determining the magnetic field from a straight conductor carrying a current. This is an important result because in almost all electrical and electronic devices, there are straight wires carrying currents. Considering a long and rectilinear conductor that carries current, the magnetic field in free space is given by:

$$B = \frac{\mu_0 I}{2\pi r} \quad (3.1)$$

Where *I* is the current in amperes, *r* the distance from the center of the conductor in meters, μ_0 the permeability of free space ($1.26 * 10^{-6}$H/m) and *B* the magnetic field in Tesla.

Two factors which are directly responsible for the intensity of the magnetic field are the current and the distance from the measuring point. The magnetic field is directly proportional to the current flowing through the wire: as it increases, the magnetic field increases as well. On the other hand, it is inversely proportional to the distance from the wire: the magnetic field decreases as it increases its distance.

Inductors as magnetic amplifiers

In electronic applications, an inductor is an electrical conductor wire wound on itself or around a well conductive surface. When an electric current flows through a winding wire it generates a magnetic field. Due to the fact that the magnetic field around a wire is circular and perpendicular to this, an easy way to amplify the magnetic field produced is winding the wire as a coil. However, for small currents, the magnetic field produced can be very weak.

As shown on Figure 3.5 a., a current *i(t)* is flowing through the wire. A wire of length *l* forming a loop of area *A* generates a magnetic field *B*. The current flowing in an inductor can be also used to generate a magnetic field. Figure 3.5 b. shows an inductor carrying a current *I* generating a magnetic field *B*. Each coil provides the same contribution to the magnetic field and the total field is *N* times the pitch of one coil. The factor *N* is the reason why one uses an inductor rather than a single coil to obtain a strong magnetic field. Also, as we move away from the center, the magnetic field module decreases.

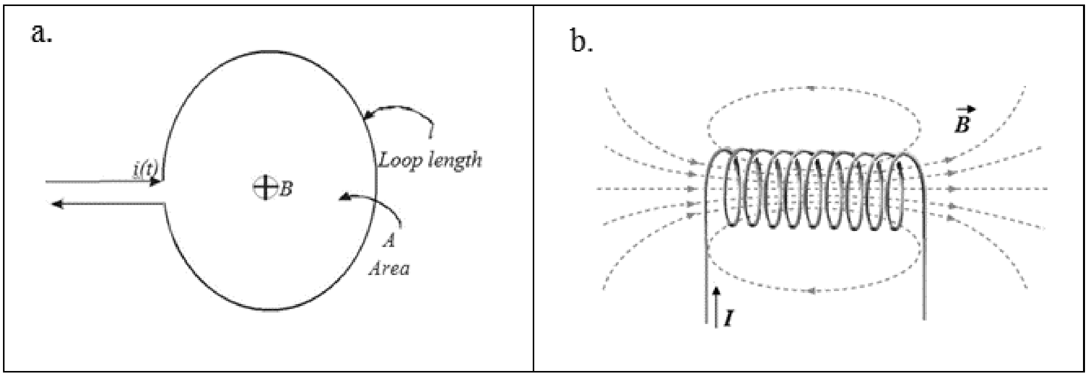


Figure 3.5 - Generated Magnetic Field Through: a. Single Circular Wire, b. Inductor

Hall Effect

Before introducing the Hall Effect, another concept must be explored. It is important to understand the Hall Effect is a consequence of the Lorentz Force. Lorentz Force equation describes the force experienced by a charged particle moving in a magnetic field. This force is perpendicular to both velocity and magnetic field and generates an acceleration perpendicular to the velocity of the charged particle; as consequence and in absence of other forces, this charge follows a curved path in the magnetic field.

When a voltage is applied from one end of a semiconductor material to the other end, charge carriers start to flow. In a presence of a perpendicular magnetic field, the current carriers are deflected to the side - Lorentz Force. This charges builds up along the side until the resulting electrical field creates a force sufficient to cancel out the Lorentz Force. Then, the current carriers no longer are deflected. This electrical field produces a transverse potential difference voltage between the opposite ends, denominated Hall Voltage. It is derived by the potential difference measured perpendicularly to the direction of current flowing in a conductor placed in a magnetic field. The Hall voltage is determined by the condition that the electric force associated equals the magnetic force acting on the moving charges.

Hall Effect Sensors

Magnetic sensors converts magnetic fields into electrical signals for processing by electronic circuits. These are designed to respond to a wide range of positive and negative magnetic fields in diverse applications. This sensors can be used in proximity sensors. It can be used instead of optical and light sensors in adverse environmental conditions such as water, vibration, dirt or oil (automotive applications). Hall Effect devices can also be used for current sensing.

A Hall sensor can measure electrical currents from a few milliamps into thousands of amperes. Magnetic Sensors can be divided in three different categories according to their field sensing range. For fields with less than micro gauss (10-3G or 10T, notice that 1G is equals to 10-4T) it is classified as low field sensors. Magnetic fields of 10T order occur inside atoms and are important in the analysis of atomic spectrum. Between 1 micro gauss to 10 gauss it is classified as Earth's field sensors; earth's magnetic field are in the order of 1 G. At last, fields above 10 gauss are classified as bias magnet field sensors. Some pulsating electromagnets can produce magnetic fields of 120T time intervals of one millisecond. The magnetic field on the surface of a neutron star is estimated at 108T.

The Hall Effect sensor outputs an electrical signal as a function of the magnetic field density around it. When the magnetic flux density cross the sensor and exceeds a certain threshold, the sensor detects it and converts it to an electric signal. To ensure maximum sensitivity, the magnetic field must be perpendicular to the sensing area of the device.

The A1324 Hall effect sensor [29] presents a sensitivity of 5mV/Gauss. In this type of sensor the value of the output voltage varies according to the intensity of the detected magnetic field. The Hall Effect sensor has several advantages: it has a lower price, does not require additional hardware, and has high reliability. The main drawback of the use of this sensor is that it not only detects the magnetic field created by a single source, but also detects the magnetic field generated around all nearby components, which may cause incorrect readings from the sensor. These sensors are relatively inaccurate (their sensitivity to magnetic field can vary within 20%). If there is no magnetic field applied, the sensor outputs approximately half of the supply voltage, typically 2.5V, assuming the supply is 5V. The output drops towards 0V or rises towards 5V, according to magnetic polarity, at a rate of 5mv/Gauss.

3.4 FALL DETECTION

3.4.1 Introduction

Our planet Earth has the inherent property of attracting objects towards it. This attractive force is taken for granted, even though is what keeps each of us from floating off into space. A fall is defined as a downward motion triggered by an attractive force acting upon an object:

gravitational force. The most commonly used value for gravity is 9.8m/sec^2 in System International (SI) units. For practical purposes, it is considered constant at all places of Earth but has slightly differences as it approaches the North and South Pole or at higher altitudes.

Newton first law states that every object will remain at rest or in uniform motion in a straight line, unless compelled to change its state by the action of an external force. If there is no forces acting upon an object, then the object will maintain a constant velocity or remain at rest - if initial velocity is null. If an additional external force is applied, the velocity will change. An object falling through the sky is a valid example. Initially, the velocity is zero (at rest) because the weight is compensated by an opposite force with the same magnitude. When this opposite force is null, the object is subjected to a single force, gravity. Since the object has no initial air resistance, it begins to accelerate into a downward movement. As the object velocity increases, air resistance is more effective. Such resistance opposes the downward motion movement. At a certain point, this opposite force equals the weight of the object and the acceleration goes to zero making the object fall at a constant velocity. This terminal velocity will depend on the weight, resistance to air, air density and the size/shape of the object.

Literature defines three types of fall: linear, rotational and projectile (see Figure 3.6). A linear fall it is a linear translation of an object falling from any orientation, where the orientation does not change. A rotational fall is a linear translation of an object falling from any orientation, where the orientation changes by rotation of the object on any axis. A projectile fall is a two dimension translation, vertical and horizontal, where the object has an initial horizontal direction making the object fall in a vertical direction afterward.

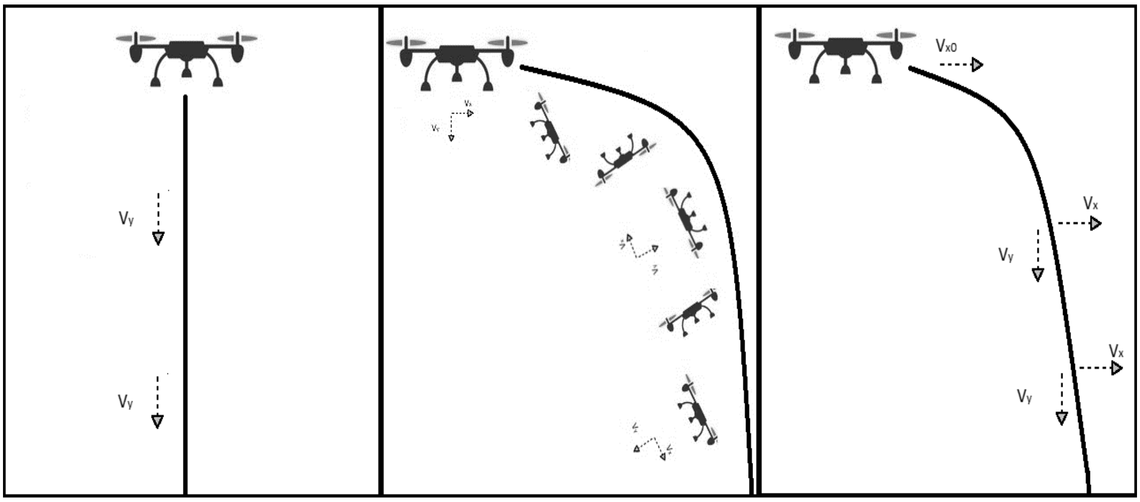


Figure 3.6 - Left to Right: Free Fall, Rotational Fall and Projectile Fall

Rotational motion is only applied for rigid bodies. The particles of a rigid body remain in the same position relative to one another, like a wheel or a rotor of a motor. It retains its overall shape over time. An UAV is considered a rigid body and a vertical rotational fall is a common type of uniform circular motion.

A uniform circular motion occurs when a rigid body moves in a circular path around a line called the axis of rotations, which cuts through the center of mass. A force acts perpendicular to a moving object making the object move in a circular path at a constant speed.

A linear fall is described as a free fall, since it is a vertical component only. A projectile fall, as mention above, is a two dimensional translation. It can be simplified just for a vertical motion for free fall detecting purposes. In next section is described the free fall motion with more details.

3.4.2 Free Fall Overview

An object that falls through vacuum is subjected to only one external force, the gravitational force. In such cases, the acceleration of the object equals the gravitational acceleration. For this reason, free fall acceleration is also known as acceleration due to gravity.

The main feature of free fall is that all objects, regardless of their mass, experience the same acceleration. Newton's second law states that the acceleration of an object is directly related to the net force and inversely related to its mass. All objects experience the same acceleration when in a state of free fall. A heavier object experiences a greater force, a thin object experiences a weaker force just to maintain the same acceleration as the heavier object. It is the force/mass ratio which determines the acceleration, and for two objects on free falling the force/mass ratio is the same. Resuming, two objects with different masses, falling from the same height, hit the ground at the same time. The mass, size, and shape of objects are not a factor in describing a free fall motion. So all objects, regardless of size or shape or weight, free fall with the same acceleration.

In fact, it is not realistic to ignore the influence of air resistance. Free fall equations bypasses air resistance, which has dramatic effects on objects at higher distances. The effect of air resistance depends on the size and geometry of the falling object – for example, a feather has low mass but offers a large resistance to the air but a hammer as higher mass but offers less resistance to the air. This would not be a problem in the absence of an atmosphere because all objects fall at the same rate, like astronaut David Scott demonstrated on the Moon. The equations of free fall also ignore the rotation of the Earth, failing to describe the Coriolis Effect. Nevertheless, considering UAVs as a dense and compact object operating over medium heights and ignoring air resistance and rotation of Earth, it is usually accurate enough to use of free fall equations principles in the detection of falling object. The following equation describes the motion of an object under the influence of free fall.

$$d = vi * t + \frac{1}{2} * a * t^2 \tag{2}$$

3.4.3 Representation of 3D Objects in Space

In order to control the attitude or orientation of objects it is necessary to define a coordinate system in all three dimensions. Any object will rotate about its center of gravity, which normally corresponds to the average location of his mass. Therefore, a three dimensional coordinate system through its center of gravity can be defined – as long as each axis is perpendicular to the other two axes. The orientation or attitude of the object is defined by the amount of rotation of his parts along these axes.

Most UAVs are symmetric about a line from the center of gravity to each of the three defined axis represented on the image below. In order to represent its attitude and orientation it is normal to define three different angles: yaw, pitch and roll. A vertical line aligned with UAV altitude is represented as the yaw axis. Motion about this axis is called a yaw motion and center of gravity of the UAV lies along it. Yaw is simple the deviation/rotation angle of the UAV head either to right or left. For a full representation in all three dimensions, two more axes are required. These are perpendicular to each other and to the yaw axis. On the figure, it is defined a longitudinal roll axis along the Y axis and a transversal pitch axis along the X axis. Pitch is represented as the movement of UAV either forward or backward. Roll is making the UAV fly sideward, either to left or right.

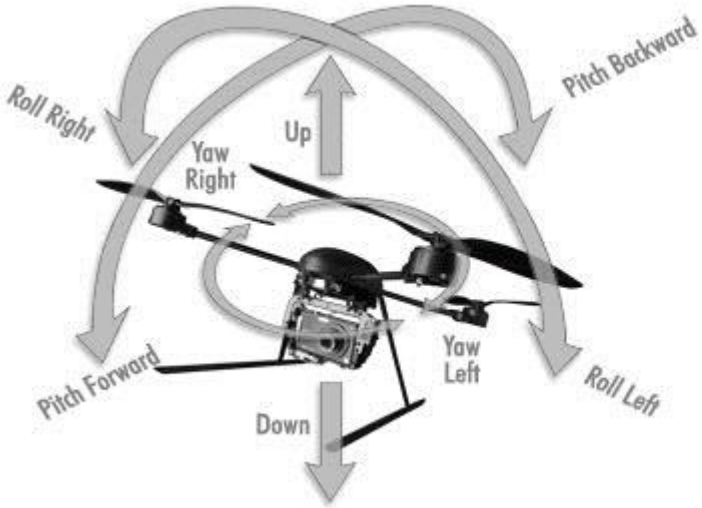


Figure 3.7 - UAV: Yaw, Pitch and Roll Representations. Source: [44].

3.4.4 An Overview of Inertial Sensing Technology

Sensors used in electronic devices are microscopic mechanical devices embedded in silicon microscopic chips – Micro-Electromechanical Systems (MEMS). MEMS technology provides the components needed to build devices such as gyroscopes, accelerometers and magnetometers at a tiny scale. There is a tinier technology designed by Nano-electromechanical systems (NEMS), a more recent technology with a smaller scale into the domain of Nano technology.

Magnetometers are devices capable of measuring the magnetic field. Earth has a significant magnetic field hence magnetometer can act as a compass - by detecting Earth magnetic field, which always points to magnetic North, it is possible to determine which direction it is facing. Some Magnetometers works with permanent magnets and others use electromagnets. In either case, when a magnetic field perturbs the material inside it, it is possible to detect the magnitude and direction of this disturbance.

An accelerometer measure the magnitude of acceleration along an axis. The accelerometer responds to vibrations associated to movement, this is useful to measure changes in velocity and position. A multiple-axis accelerometer can also be used as an absolute orientation sensor in a vertical plane considering that gravity acts like a continuous acceleration downward. On the other hand, it is not possible to measure the lateral orientation because there is only one vertical reference (gravity force) and not a horizontal reference. It fails to represent lateral rotations in objects, like UAVs, since there is no lateral forces applied to the device.

A gyroscope is an electronic device that can be used to calculate orientation, measuring either changes in orientation or changes in rotational velocity. A tri-axial gyroscope – also known as Inertial Reference Unit (IRU) - provides orientation in a 3D space and it helps to stick to a particular orientation or to make sure you have changed to the right one. This sensor maintains a high level of effectiveness measuring the rate of rotation around an axis. In comparison, a gyroscope measures angular acceleration while an accelerometer measures linear acceleration based on vibration.

These sensors allow us to translate movement to the virtual world measuring motion and direction in a dimensional space. Orientation data collected from this sensors is prone to drift significantly over time. A magnetometer has poor accuracy for fast movement but has low drift over time. On the other hand, gyroscopes reacts quickly and accurately to changes but accumulates errors over time when measuring the orientation of the device – also it requires to start with a known orientation in order to calculate his final position. Magnetometers are also susceptible to errors: beside the fact of the necessity of a properly calibration, it is strongly influenced by environmental variations in magnetic field – soft iron effects – responsible for errors in the calculation of the relative position of the Magnetic North.

The number of sensors inputs are referred to as Degrees of Freedom. To cover all degrees of motion for an object, in tri-dimensional space, it is necessary to achieve a six degrees of freedom (6-DOF) with the combination of different sensors. As explained before, sensors itself are prone to drift over time. The combination of sensors, known as IMU sensors, allow precise data collecting with low drift error over time. An IRU with the functionality to measure acceleration, through the combination of a three-axis accelerometer, it is referred as a 6-DOF IMU. Connecting an IMU to a processor capable of processing the signal, results on an Inertial Navigation System (INS) – a system that provides data speed, positioning for attitude control and direction.

3.4.5 6-DOF IMU Sensors

The MPU6050 Sensor [30] contains a MEMS accelerometer and a MEMS gyroscope. It combines a 3-axis gyroscope, 3-axis accelerometer, digital-output temperature sensor and a Digital Motion Processor (DMP). DMP acquires data from accelerometers, gyroscopes and other sensors linked to it and processes the data within the chip. Its purpose is to offload both timing requirements and processing power form the host processor. This sensor features three 16-bit analog-to-digital converters for the gyroscope outputs and another three ADCs for the accelerometers outputs. Therefore, it collects accurate both data at the same time. It is also designed to interface with non-inertial digital sensors, such as pressure sensors or another MPU-60X0 (where X represents the model of the MPU sensor), on its auxiliary I2C port. For this connection, AD0 pin allows two MPU-60X0s to be connected to the same I2C bus. When used in this configuration, the address of the one of the devices should be set as low – pin AD0 is logic low - and the other should be set as high. The sensor uses the I2C-bus to interface with the Arduino. There are more models of this sensor, like MPU-9150, which combines the MPU-6050 with a magnetometer.

The LSM303DLHC [31] contains a MEMS accelerometer and a MEMS magnetometer. It combines a 3-axis magnetometer, 3-axis accelerometer for applications such as free-fall detection, gaming and virtual reality and map rotation. Two independent interrupts can be configured to generate an interrupt signal in cases of inertial wakeup/free-fall events or detecting different position/orientation of the device itself. It includes an I2C serial bus to interface with the Arduino. It has a normal mode, which guarantees high resolution, and a low-power mode, which reduces the current consumption but lowers the resolution. A two data-ready signals indicates when a new set of measured data are available. Therefore, it simplifies the synchronization in the digital system that uses this device.

3.5 OBSTACLE AVOIDANCE

The use of systems to avoid collisions allows greater autonomy and security in a UAV. The process of avoid a collision has two different processes: the obstacle detection and the collision avoidance. Firstly, there must be physical sensors to perform an area inspection looking for any object in the way. The second module consists in an algorithm capable of using data from this sensors to avoid obstacles. This can be a simple algorithm to avoid obstacles by just going in the opposite direction [33]-[37] or complex algorithms like has the Simultaneous Localization and Mapping (SLAM) algorithm [38]-[42].

The physical sensors can be divided into different categories: ultrasonic sensors, infrared sensors and laser scanners. The use of UR sensors has its limitations. These sensors do not detect surfaces with properties that absorb sound and therefore are not completely reliable for detecting the available distance from them. IR and laser scanners are optical sensors. IR sensors can detect sound absorbing surfaces yet fail in poor visibility conditions - fog, poor lighting or smoking - or in the presence of obstacles that block the passage of light (translucent obstacles). The combination of ultrasonic sensors and low-cost infrared sensors can overcome the limitations presented above. Further leading approaches use laser scanners for a complex 3D reconstruction of close environments [43]. This solutions has more limitations, mainly in terms of weight and cost, and are still sensitive to light and diaphanous environment. Table 3.3 represents some commercial sensors in the market, along with their minimum and maximum range for the detection of obstacles.

Description	Function Mode	Range (cm)
Maxbotix LV-EZ2	Ultrasonic	91-645
MB1260	Ultrasonic	25-1068
Seeedstudio sensor	Ultrasonic	3-400
HC-SR04	Ultrasonic	2-400
GP2Y0A710K0F	Infrared	100-550
GP2Y0A21YK	Infrared	10-80
RPLIDAR 360°	Laser	20-600

Table 3.3 - Obstacle Detection Sensors

Chapter 4
TEST PLATFORM AND RESULTS

This chapter describes the three different failsafe mechanisms developed and discusses the experiments that have been performed to assess the behavior and performance of the system under potential faults. The following experiments have been performed:

- Current Sensing Monitoring
- Fall Detection System
- Obstacle Detection and Avoidance

4.1 CURRENT SENSING MONITORING

4.1.1 Monitoring System Architecture

Figure 4.1 represents the system implemented to monitor the FC from the battery. One of wires which powers-up the FC is connected to the current monitoring module for testing. It is intended to perform several tests, with different options for testing the best way to monitor the current, in a simple and effective manner.

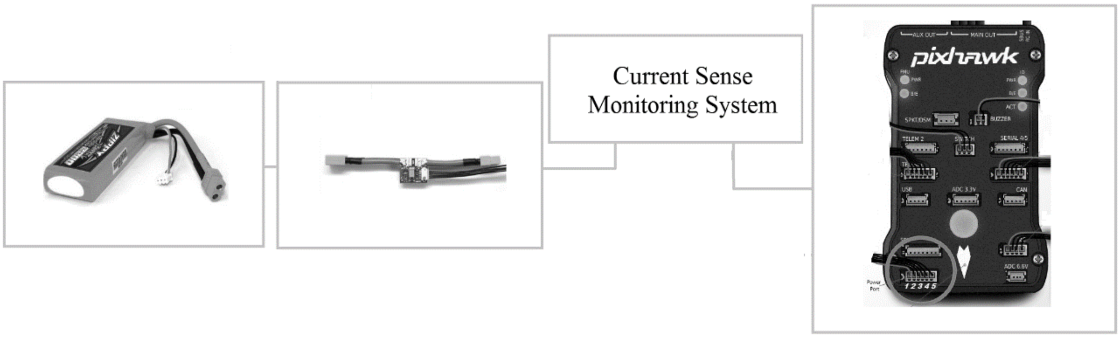
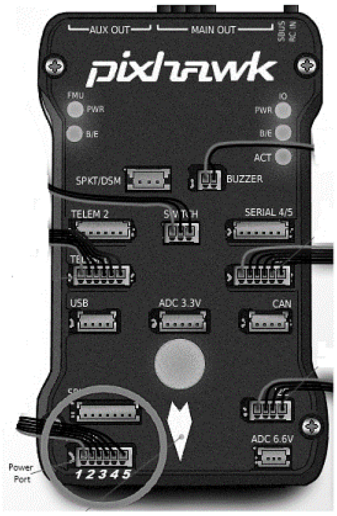


Figure 4.1 - Monitoring System Architecture

According to the analysis described in Section 3.1, the communication between the power supply and the FC is a critical point. The ideal solution is monitoring the current of each vital component to the functioning of the UAV system. In this section, it is monitored the current between the FC and the battery. The main goal is not to supervise the exact current values but verify that the system is actually being fed properly.

4.1.2 FC Current Monitoring

To be able to monitor the flight controller, it is first necessary to conduct performance tests to check the range of the current values. The flight controller tested corresponds to Pixhawk. In Figure 4.2, it is shown a DF13 connector with 6 pins, which establishes the communication between the Pixhawk and the power supply, and a table with the corresponding assignment of the power cabling connections.



Pin	Signal	VOLT
1 (Red)	VCC	5V
2 (Black)	VCC	5V
3 (Black)	CURRENT	3.3V
4 (Black)	VOLTAGE	3.3V
5 (Black)	GROUND	0V
6 (Black)	GROUND	0V

Figure 4.2 - Pixhawk Power Connector Pins

To check the current value of Pixhawk, one of the connections (Pin 1 or 2) was removed. Then, it was connected to an ammeter (to measure current values) and again connected to the battery. Figure 4.3 is a graphical representation of the described process.

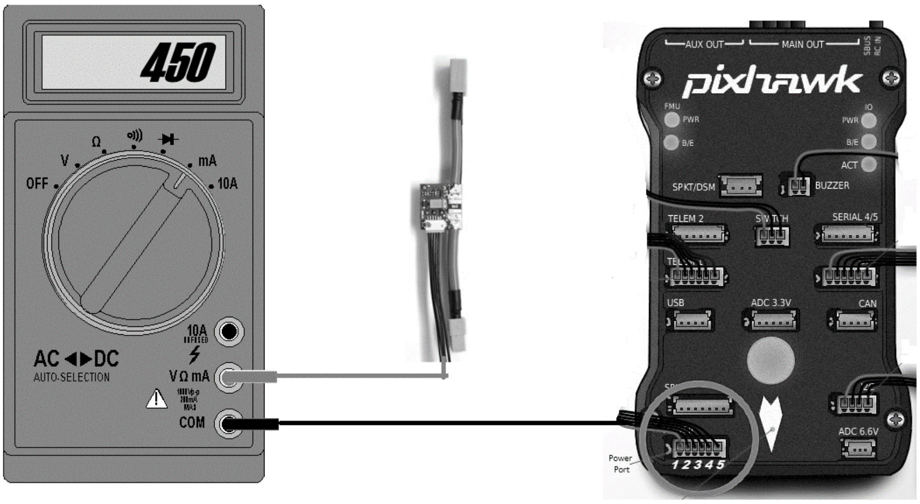


Figure 4.3 - Pixhawk Current Monitoring

According to the process described, it was recorded a minimal operating current value for PX4 - 35mA. The following experimental values obtained (Figure 4.4) allow to have a perception of the maximum operating values of PX4 connected with the different accessories (GPS, 433MHz telemetry, among others):

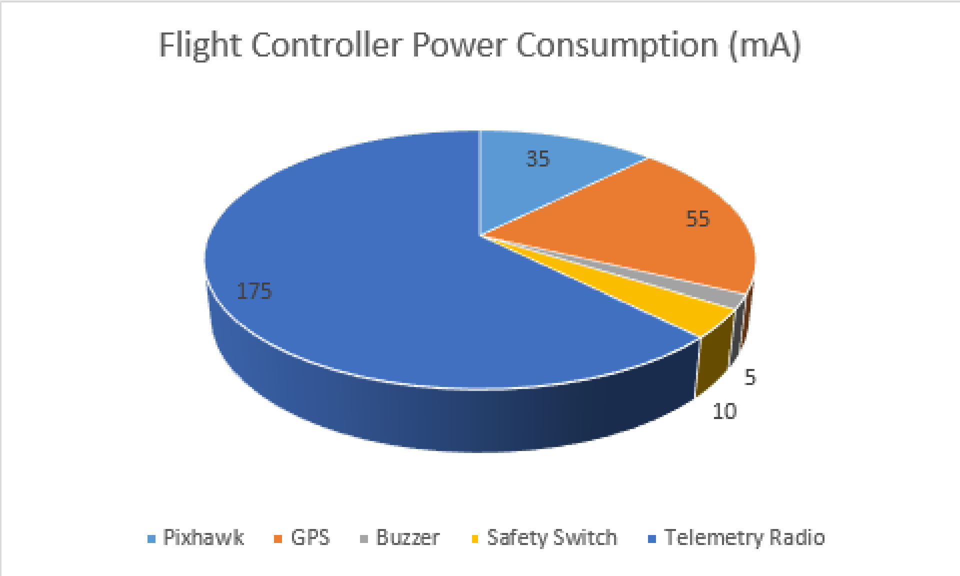


Figure 4.4 - Pixhawk Power Consumption (mA)

The PX4 has several accessories to be used together. To monitor the current that feeds Pixhawk, three different configurations were selected:

- Complete Configuration: PX4 with all its components (280mA).
- Medium Configuration: PX4 with compass, safety switch and GPS (105mA).
- Minimal Configuration: PX4 (35mA).

The three configurations used have different purposes. The minimal configuration corresponds to the decision threshold for detecting a FC power failure or for inactivity. Thus, a detected current lower than the minimum configuration corresponds to the system being in imminent failure. The medium configuration includes the accessories required for the UAV to be remotely controlled (except the telemetry radio which is only required for controlling the UAV BLOS. The complete configuration is for the FC with all accessories connected. The two last configurations are for the experimental tests in the implemented current detection mechanisms, simulating the FC current in flight situations.

4.1.3 Arduino ADC Configuration

The configuration of the processing platform is fundamental to achieve better results. The Arduino Uno ADC is preconfigured with a reference voltage of 5V, and comprises 10 bits of resolution which result in 1024 quantization levels. The change of the ADC reference voltage to 1.1V allows us to obtain better results by increasing its voltage resolution from 4.88mV per level to 1.7mV per level.

ADC Reference (V)	5	3	1,1
Voltage Resolution (mv)	4,88	2,93	1,07

Table 4.1 - Arduino ADC Sensibility

The output of the sensors used can easily exceed the value of 1.1V. In such case, two different solutions are applied. Or it is assumed that the read value is the maximum value that the sensor can achieve, or a solution is used to limit the input value to the ADC. In the second solution, a voltage divider is employed between the output of the sensor and the input of Arduino. Figure 4.5 shows the schematic of a simple voltage divider with two resistors of commercial value. This is to adjust the output value of the sensor to the Arduino ADC, without decreasing its voltage resolution. Equation 4.1 is the formula applied for the calculation of the output (V_{out}).

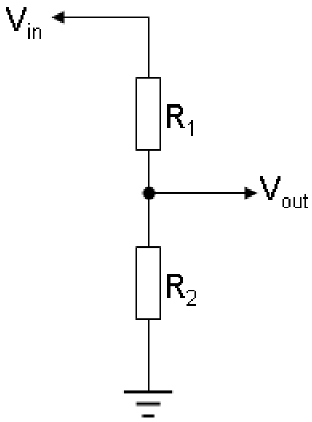


Figure 4.5 - Voltage Divider

$$V_{out} = \frac{R_2}{R_1 + R_2} V_{in} \tag{4.3}$$

4.1.4 Magnetic Sensing Monitoring Circuit

Test Platform and Conditions

The first scenario involves a hall sensor for the FC current monitoring. The Hall sensor is placed near the circuit that feeds the FC (Fig 4.1), measuring the produced magnetic field and transmitting the result to the Arduino Uno for further treatment of the data collected. Figure 4.6 represents the links between the Arduino and the Hall sensor used: A1324.

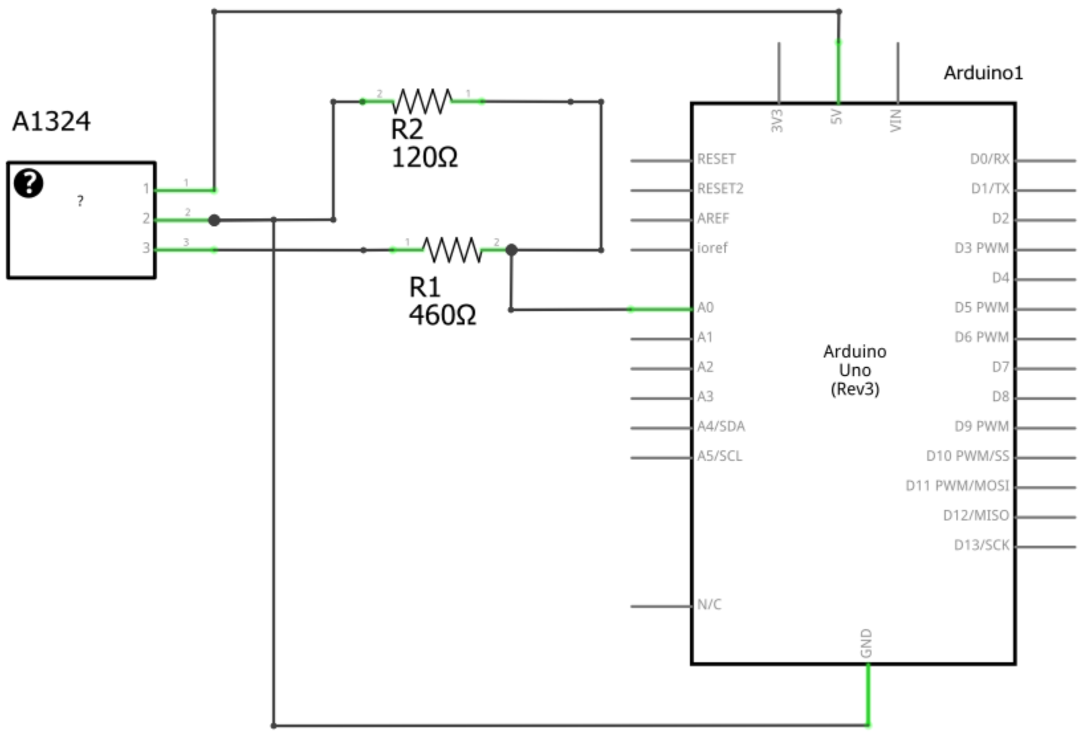


Figure 4.6 - Communication between Arduino and Hall Sensor A1324

As the sensor floats its output between 0 and 5V, one proceeds to the use of a voltage divider. This in order to convert this value into a voltage within the range of the ADC reference value (1.1V). Equation 4.1 is used to calculate the value of resistances R1 and R2.

V_{in} (V)	R_1 (Ω)	R_2 (Ω)	V_{out} (V)
0 - 5	460	120	0 – 1.034

Table 4.2 - Calculation of the Voltage Divider Resistors

Experimental Results

Table 4.3 represents the experimental results from this experience for the three simulated currents. V_0 and V_{out} represents, respectively, the value obtained from the sensor when there is no current and when there is current powering the FC. It is perceptible that the magnetic field applied to the hall sensor is too low to be detected, even with a higher current applied in case a). The data collected from the sensor, which corresponds to V_{out}, is processed by the Arduino software developed. The values obtained a), b) and c) are too close to each other to even allow to monitor the current.

ADC Arduino (1.1V)			
Test	I (mA)	V_0 (mV)	V_{out} (mV)
a)	280	478	476
b)	105	479	479
c)	35	478	478

Table 4.3 - Hall Effect Sensor: Experimental Results

Hall Effect Sensor with an Inductor

The results from the previous experience have shown the difficulty to detect magnetic fields with small currents. The principle is correct but there is the need to amplify the magnetic field to be properly sensed by the hall sensor. This solution involves the same previous method with the inclusion of a new component: an inductor. There are three different factors which can directly influence the magnetic field: the current, the inductance and the distance between the inductor and the hall sensor. As the current is predefined and the distance applied is less than 1cm, the only factor passible to change is the inductance. In this experience it is applied an inductor with 1mH. Figure 4.7 is a representation of the circuit tested, which is similar to Figure 4.6, with an inductor close to the Hall sensor.

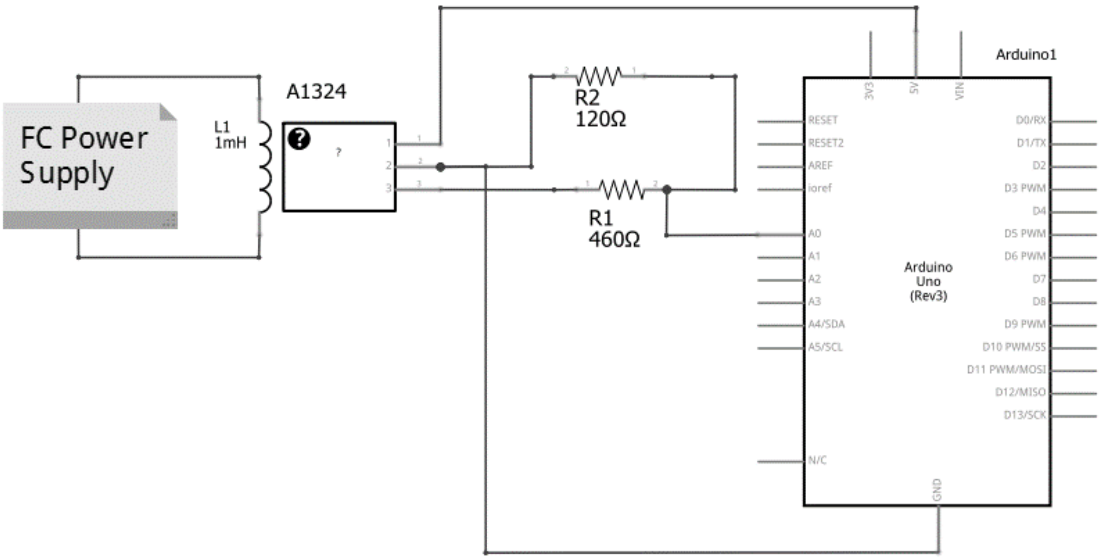


Figure 4.7 - Communication between Arduino and Hall of Sensor with an Inductor

In this experience, the hall sensor detects the magnetic field applied when the current passes through the wire. As it increases the current to the FC, the sensor's output provides more significant results. Table 4.4 represents the values read from the hall sensor. V_0 and V_{out} represents, respectively, the value obtained from the sensor when there is no current and when there is no current powering the FC.

ADC Arduino (1.1V)			
Test	Current (mA)	V_0 (V)	V_{out} (V)
a)	0,28	475	426
b)	0,105	477	458
c)	0,35	479	473

Table 4.4 - Hall Effect Sensor with Inductor: Experimental Results

4.1.5 Resistive Current Sensing

This experience presents another solution for the detection of the FC current. Firstly, it is explained the selection of the resistor, which takes in consideration some restrictions before testing and simulating them. Two different types of circuits are tested: non inverting amplifier and differential amplifier. The circuits tested provided different types of results, which represent the difference between the expected results (from theoretical equations), the simulated results (with software simulation tool *NI MultiSim* [45]) and the practical results (tested in an experimental circuit). This sections ends with a comparison between the circuits tested, taking into account the position of the sense resistor: low-side and high-side.

Selecting the Sense Resistor

As referred in literature (Section 3.3.1), there are several aspects to be considered. The selection of the sense resistor takes into consideration factors such as Voltage Drop, Power Dissipation, Parasitic Effects, and other effects described in Table 3.2.

Table 4.4 resumes some specifications of the resistor selected. Using the currents tested, it is calculated the power dissipation and the voltage drop in the resistor (Table 4.5). The main function of a resistor is to resist current flow through a specific circuit. This is done by dissipating the unwanted power as heat. Selecting a small wattage value resistor when high power dissipation is expected will cause the resistor to overheat, destroying both the resistor and the circuit. According to the specifications of the resistor, the power dissipated is above the maximum dissipated power rating. The voltage drop is an important factor to have in consideration because it can interfere with the circuits operation. On one hand, a low voltage drop makes the detection of the current an unworkable process. On the other hand, a high voltage drop can interfere with the tolerated application voltage for its normal operation. This situation needs to be simulated with the amplifying circuit to gather more information for further conclusions.

R (Ω)	Maximum Dissipated Power Rating (W)
1	5

Table 4.5 - Sense Resistor Specifications

I (mA)	Power Dissipation (mW)	Voltage Drop (V)
35	1,225	0,035
110	12,1	0,11
280	78,4	0,28

Table 4.6 - Sense Resistor Power Dissipation and Voltage Drop

Multisim Simulations

This sections represents the circuit simulations using the software NI Multisim. *I* represents the currents tested (35, 110, 280mA) and the *RLoad* represents the Pixhawk which works with a 5V supply voltage. Figure 4.8-4.10 represents simulations for configuration a), 35mA. In Annex A are shown simulations for configuration b) and c), 100 and 280mA respectively. The results provide two important simulated data: V_{in} and V_{out}.

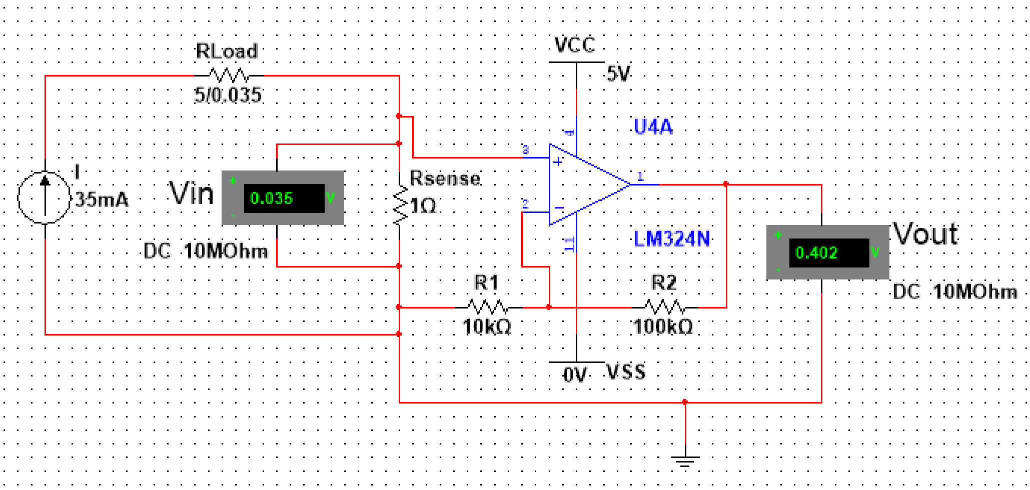


Figure 4.8 - Low-Side Non Inverting Amplifier

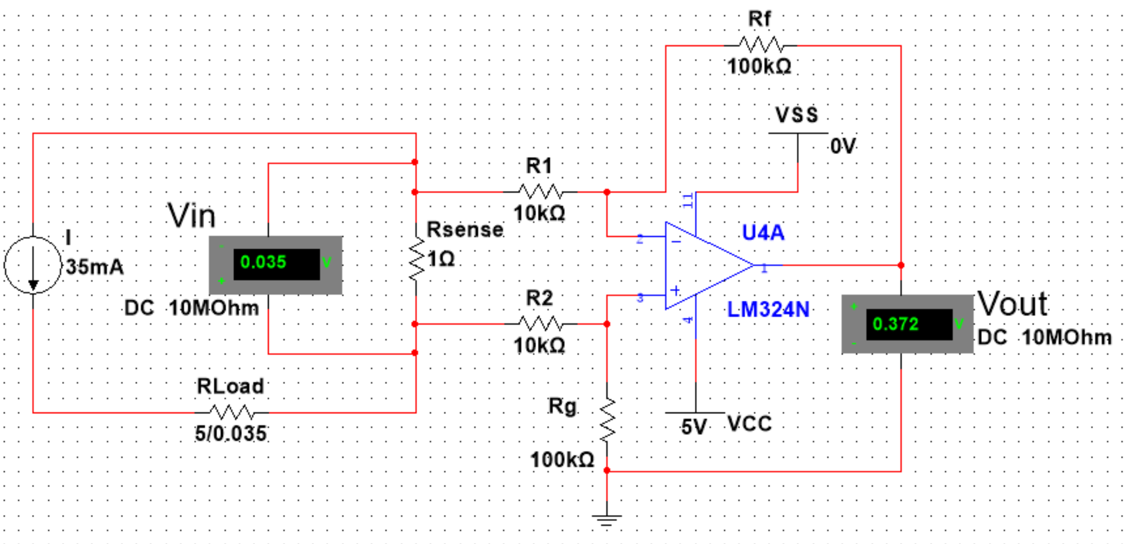


Figure 4.9 - Low-Side Differential Amplifier

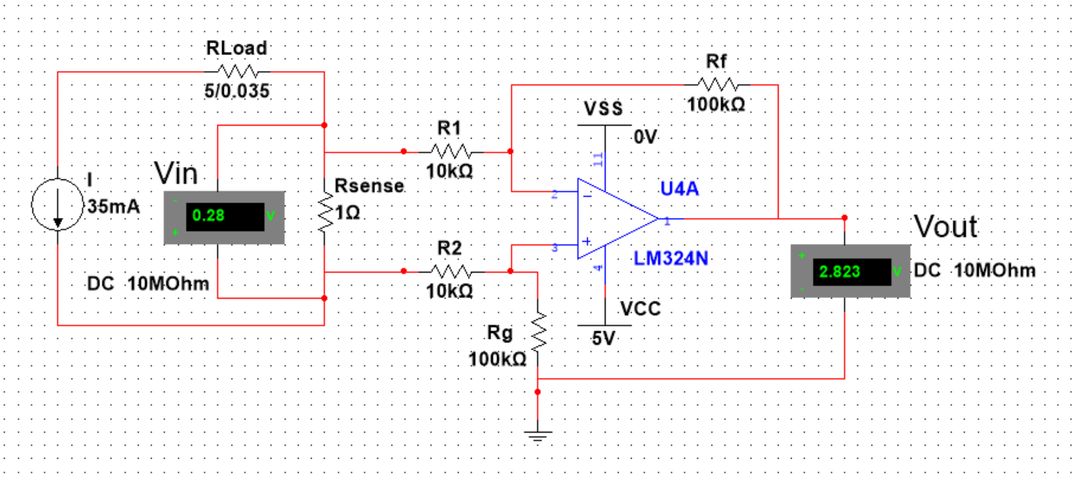


Figure 4.10 - High-Side Differential Amplifier

Theoretical Simulations

This simulations represents the results expected from theoretical equations of the circuits analyzed. This results normally differ from the experimental results due to the fact that the components used are not ideal. For the Non Inverting amplifier is used equation 4.2 and for the differential amplifier is used equation 4.3.

$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in} \tag{4.4}$$

$$V_{out} = \frac{R_f}{R_1} V_{in}\,, \qquad if\ R_1 = R_2\ and\ R_f = R_g \tag{4.5}$$

Experimental Results

Multisim Simulations		Theoretical results		Experimental results		ADC 5V	ADC 1.1V
V_{in} (V)	V_{out} (V)	V_{in} (V)	V_{out} (V)	V_{in} (V)	V_{out} (V)	ADC (V_{out})	ADC (V_{out})
0,035	0,385	0,035	0,402	0,035	0,414	89	404
0,11	1,21	0,11	1,227	0,11	1,305	278	1023
0,28	3,08	0,28	3,097	0,28	3,565	739	1023

Table 4.7 - Low-Side Non Inverting Amplifier Results

Multisim Simulations		Theoretical results		Experimental results		ADC 5V	ADC 1.1V
V_{in} (V)	V_{out} (V)	V_{in} (V)	V_{out} (V)	V_{in} (V)	V_{out} (V)	ADC (V_{out})	ADC (V_{out})
0,035	0,372	0,035	0,35	0,035	0,348	73	319
0,11	1,122	0,11	1,1	0,11	1,385	285	1023
0,28	2,823	0,28	2,8	0,28	3,209	652	1023

Table 4.8 - Low and High-Side Differential Amplifier Results

To prevent the sense amplifier from interfering with the voltage being measured, these integrated circuit (IC) amplifiers have a very high input impedance. The maximum value registered was 280mV (V_{in}), which can be considered an acceptable voltage drop. This means the interference caused by the amplifying circuit has no significant interference with the circuit's application. Analyzing Tables 4.7 and 4.8, it is possible to conclude that the non-inverting amplifier has better experimental results. Applying the same nominal resistors to the different circuits, the differential amplifier has lower gain in comparison to the non-inverting amplifier. The differential amplifier also requires more electronic components. However, the application is suitable for both circuits tested.

4.2 FALL DETECTION SYSTEM

4.2.1 Introduction

Regardless of multiple failsafe mechanisms in a UAS, a fall detection system is the last resource to prevent damage on the UAVs structure. This safety mechanism corresponds to a last resort generic solution for any problem that may occur: connection failure, electrical/mechanical failure and even in cases of human error, such as UAV handling by inexperienced operators. The fall detection system aims to trigger the activation of an UAV self-rescue system: a parachute. Figure 4.11 represents the logic behind the detection system. Firstly, accelerometer and gyroscope output signals are sampled. Then, if a free fall or a rotational fall is detected the rescue system is activated.

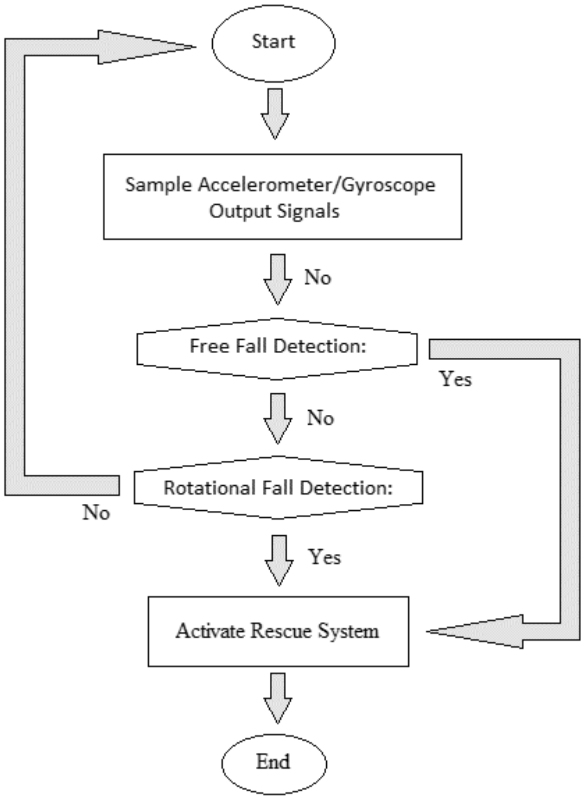


Figure 4.11 - Fall Detection Block Diagram

4.2.2 Test Platform Development

Simulation allows to rapidly prototype and test the fail-safe mechanism to be implemented during the development process. Hence, an application was developed to gather and visualize data from experimental tests. The application was developed in the open source programming language and environment denominated *Processing [46]*. Figure 4.12 represents the communication between two *XBee [47]* radios. To ensure the communication between the UAV and the ground platform, the system uses the following configuration:

- *XBee* Radio linked to a GCS: a GCS, with the developed application developed, for data analyses.
- *XBee* Radio linked to the UAV: an UAV with an IMU Sensor for collecting and transmitting data.

Figure 4.12 - XBee Communication Platform

This communication allows to get experimental data from the sensor data collected. First, this platform makes it possible to verify if the sensor is calibrated and if values read from the sensor correspond to the UAV orientation. Second, it allows to collect data to verify the behavior of the UAV when is on a state of rotational or free fall. At last, and after the implementation of the detection system, it sends confirmation of the detection of rotations or in the occurrence of a free fall.

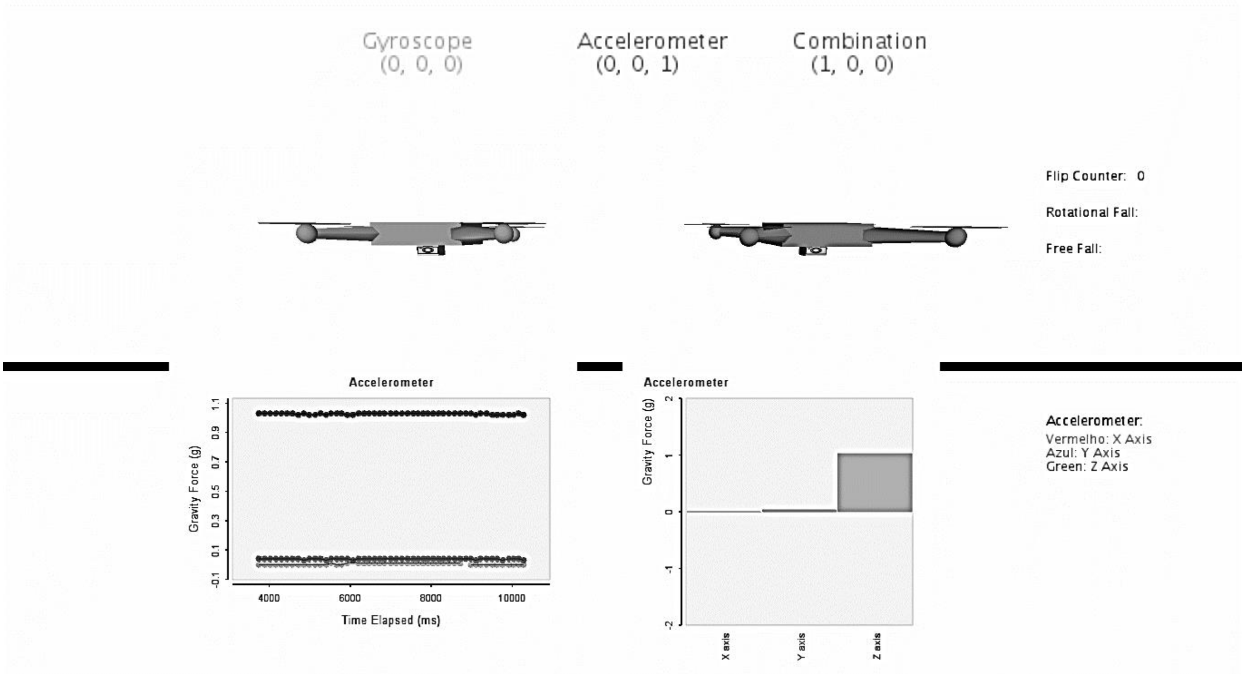


Figure 4.13 - UAV Simulation Application

Figure 4.13 represents the visual aspect of the platform. The images of the UAV give a three dimensional representation of the orientation and on the top is shown the corresponding numerical data. On the top-right corner, there are two parameters to signalize when a rotational or free fall is detected. It also incorporates a rotational counter for the detection of a 360º rotation of the UAV. The graphics represented in the bottom side, show data collected by the sensor in real time. It has also two graphics for the gyroscope data, which are not shown in the image.

4.2.3 IMU Sensor Configuration

The IMU sensor used for the detecting system was the MPU-6050, gyroscope and accelerometer. Figure 4.14 represents the wiring between the sensor and the Arduino. The sensors voltage regulator can take either 3.3V or 5V. According to MPU-6050 datasheet, for more precise data the sensor should be connected to 5V. The transmission of serial data to Arduino is made by the I2C bus, so a connection between Signals Serial Data (SDA) and Serial Clock (SCL) and the defined Arduino Pins A4 and A5 are necessary. As no extra sensor is wired to MPU-6050, the AD0 can be either set to low or high. In this configuration it is set to low (wired to the ground).

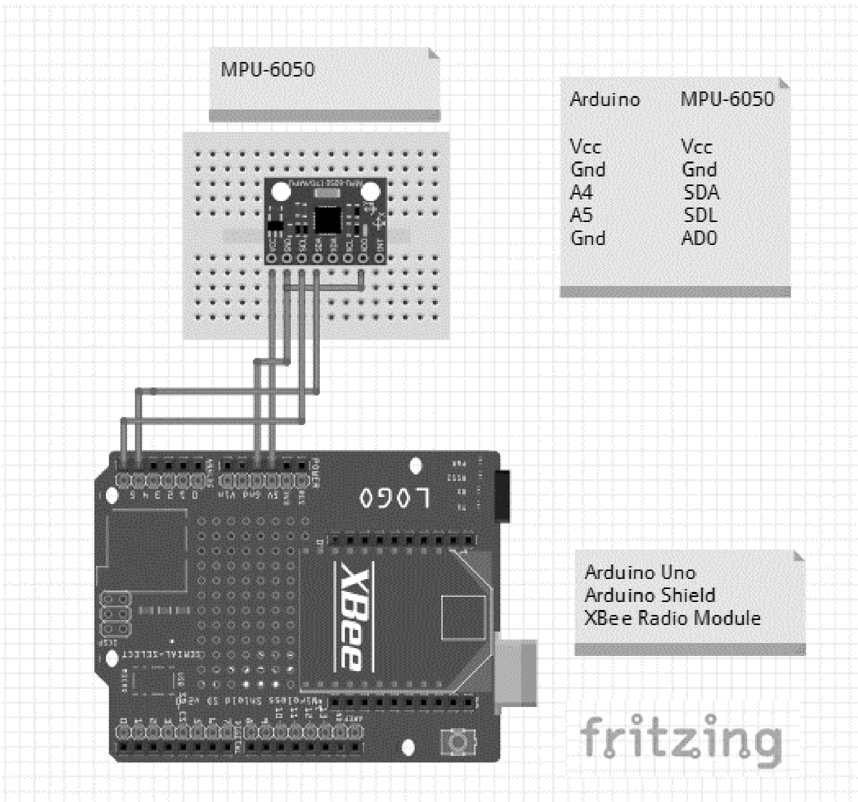


Figure 4.14 - MPU-6050 Communication with Arduino

Next step was to set up the accelerometer and gyroscope parameters. Gyroscope includes angular rate sensors with a full-scale range of ±250*º/s* up to ±2000*º/s*. It means this model will be able to detect how many degrees per second of a rotation it is doing around a particular axis. Accelerometer includes a full scale range of ±2*g* up to ±16*g*. It measures the acceleration forces around each axis. There is a trade-off: the sensitivity will be decreasing as it increases the full scale range of the sensor. Essentially, the goal is to select the most optimal range for this particularly project. To prevent the gyroscope and accelerometer signals from clipping and giving unreliable results, without forgetting the importance of the sensitivity for the detection of spontaneous moving, we selected the ±500*º/s* and ±8*g* configuration (Table 4.9).

Gyroscope		Accelerometer	
Full Scale Range (± *º/s*)	LSB Sensitivity (LSB/*º/s*)	Full Scale Range (±*g*)	LSB Sensitivity (LSB/*g*)
250	131	2	16384
500	65.5	4	8192
1000	32.8	8	4096
2000	16.4	16	2048

Table 4.9 - MPU-6050 Parameters Setup

4.2.4 UAV Orientation

The MPU-6050 has a gyroscope and an accelerometer. Firstly, a method to calculate the orientation with the accelerometer is analyzed. Right on through, it is explained the logic behind the calculation of the orientation with the gyroscope. At last, the combination of the two sensors allows a combined solution for a more precise calculation of the UAV orientation.

Orientation with an accelerometer

Accelerometer measures the magnitude of the acceleration detected. The calculation of the UAV orientation relies on the fact it has a moveable center of mass, which has a constant gravitational pull of 1g downwards always acting on the UAV. If this gravitational force is the only force acting on the accelerometer, the acceleration detected will measure 1g at all instants, and the orientation of the UAV can be computed from the apparent position of the acceleration vector. On the other hand, the z-axis is aligned along the gravitational acceleration vector. If there is no rotation detected on the other two axis (A_x, A_y is zero) then it is impracticable to compute a yaw rotation from the accelerometer – the inverse tangent function of zero divided by A_z is always zero. Figure 4.15 represents the orientation angles from trigonometry equations 4.4-4.6.

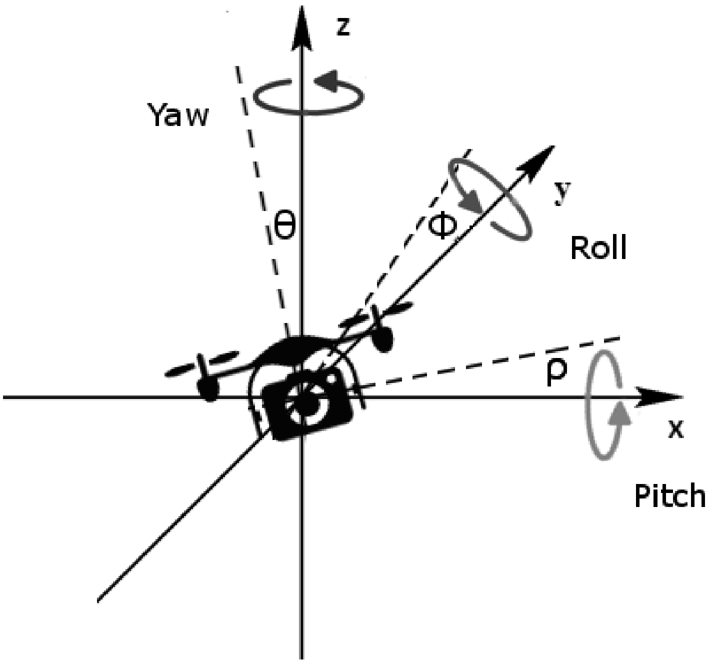


Figure 4.15 - UAV Yaw, Pitch and Roll Angles

$$\rho = \tan^{-1}\frac{Ax}{\sqrt[2]{A_y^2 + A_Z^2}} \tag{4.6}$$

$$\Phi = \tan^{-1}\frac{A_Y}{\sqrt[2]{A_X^2 + A_Z^2}} \tag{4.7}$$

$$\theta = \tan^{-1}\frac{\sqrt[2]{A_X^2 + A_Y^2}}{A_Z} \tag{4.8}$$

Orientation with a Gyroscope

Gyroscope measures angular velocity (ω). For the calculation of the sensors orientation, the sensor position is initialized with an orientation value from the accelerometer. Each measured value is the angular velocity around the axis at small measured intervals (Δt). The product between this interval and the angular velocity measured gives the change in angle (α). The new orientation of the UAV (β) is represented by the initial angle plus this change in angle.

$$\omega * \Delta t = \alpha \tag{4.9}$$

$$\beta = Initial\ Angle + \alpha \tag{4.10}$$

As explained in Section 3.4.4, gyroscope and accelerometer sensors tends to drift over time. The accelerometer results provide precise orientation angles as long as gravity is the only force acting on the sensor. Unfortunately, an UAV moves and rotates in opposite directions in short periods of time, which causes the measurements to fluctuate. In this situations, the accelerometer data tends to be very noisy with brief but significant perturbations. The gyroscope provides accurate data in short term when changing orientation, but also tends to drift over longer time scales.

The solution is to average out this errors in order to accurate results over timescales longer than the perturbations. Fusing the accelerometer and gyroscope data makes the errors cancel out. A standard method of combining these inputs is with Kalman Filter or with a Complementary Filter. In this application it is applied the Complementary Filter (Equation 4.9, 4.10), which combines the accelerometer and gyroscope data.

$$Filtered\ Angle = \alpha * Gyroscope\ Angle + (1 - \alpha) * Accelerometer\ Angle \tag{4.11}$$

$$\alpha = \frac{T}{T + \Delta t} \tag{4.12}$$

Where Δt represents the sampling rate, T represents a time constant greater than timescale of typical accelerometer noise and the gyroscope and accelerometer angle represents the measured orientation value read from the sensor.

Combining both gyroscope and accelerometer data with a Complementary Filter results in precise orientation data. Using the developed application and simulating a yaw, pitch and roll rotation on the UAV, it is tested the filtered combination equation. In figure 4.16, it is simulated a roll rotation of 30º. This represents data from gyroscope (on the left) and the combined data from gyroscope and accelerometer (on the right). Figure 4.17, 4.18 represents the data collected from Gyroscope (which indicates a wrong 51º roll rotation) and accelerometer. The combined solution (Figure 4.16, on the right) gives more realistic representation of the real UAV orientation.

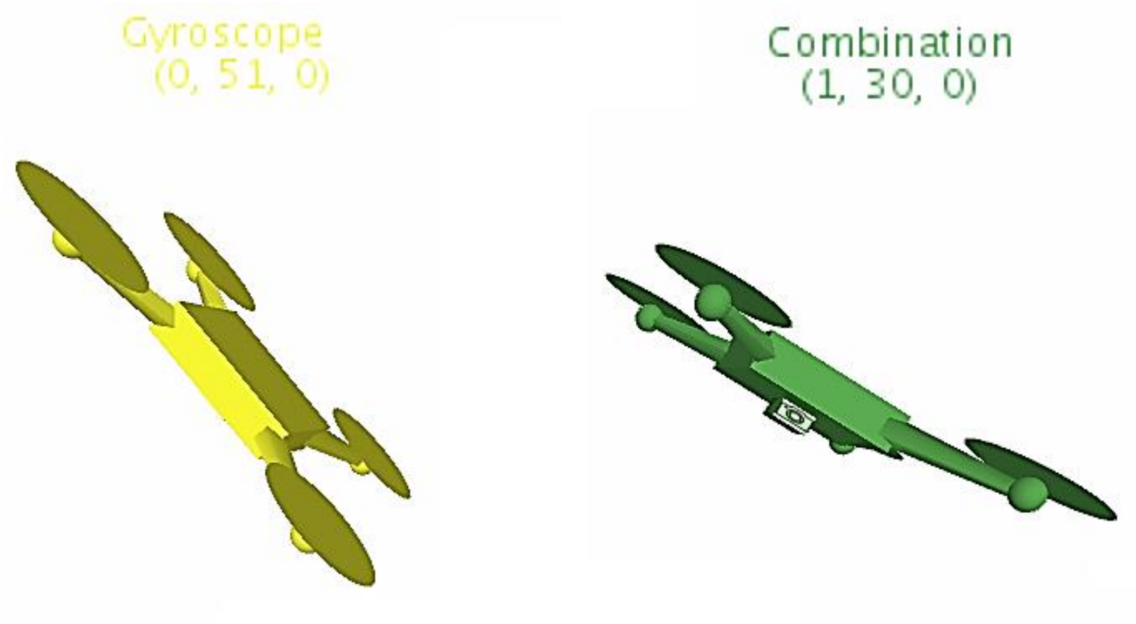


Figure 4.16 - Roll Rotation of 30º with Combined Data

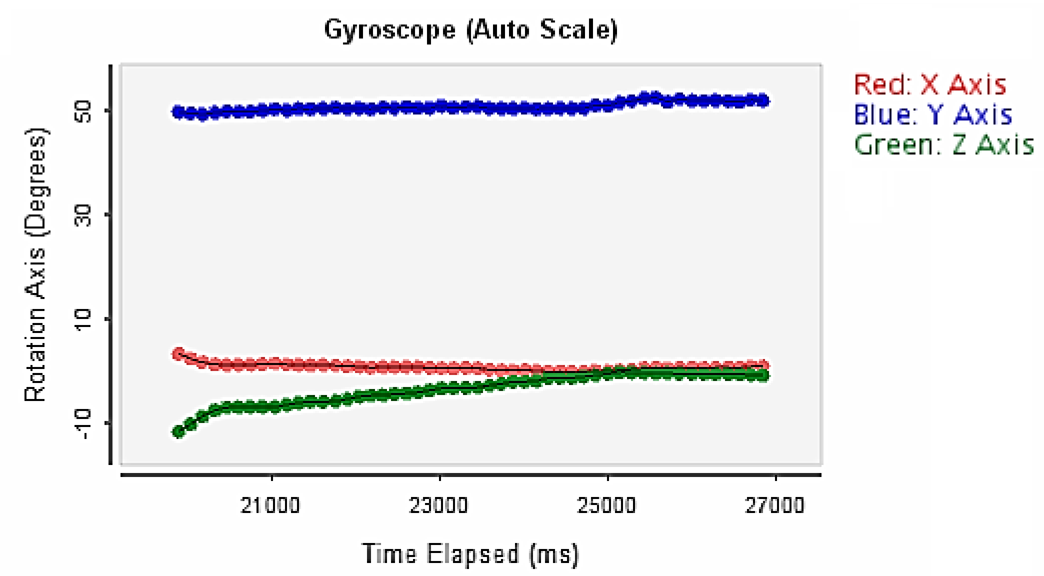


Figure 4.17 - Roll Rotation Data from Gyroscope

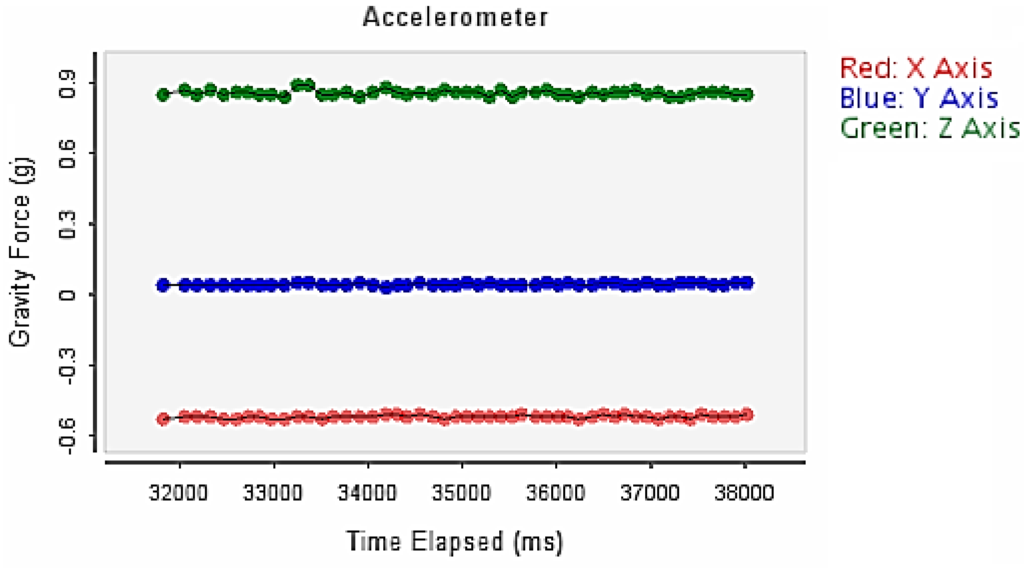


Figure 4.18 - Roll Rotation Data from Accelerometer

4.2.5 Rotational Fall Detection

To achieve better results detecting UAV rotations, some tests were performed to collect and analyzed data with the developed application. The methodology used is the following:

- Simulate a rotation around an axis;
- Collect data from the application developed: accelerometer data and time instants.
- Analyze data collected: define time between a full rotation (360º) and analyze accelerometer data behavior over time.

The obtained results are displayed in Figure 4.20, 4.21 and table 4.10, 4.11.

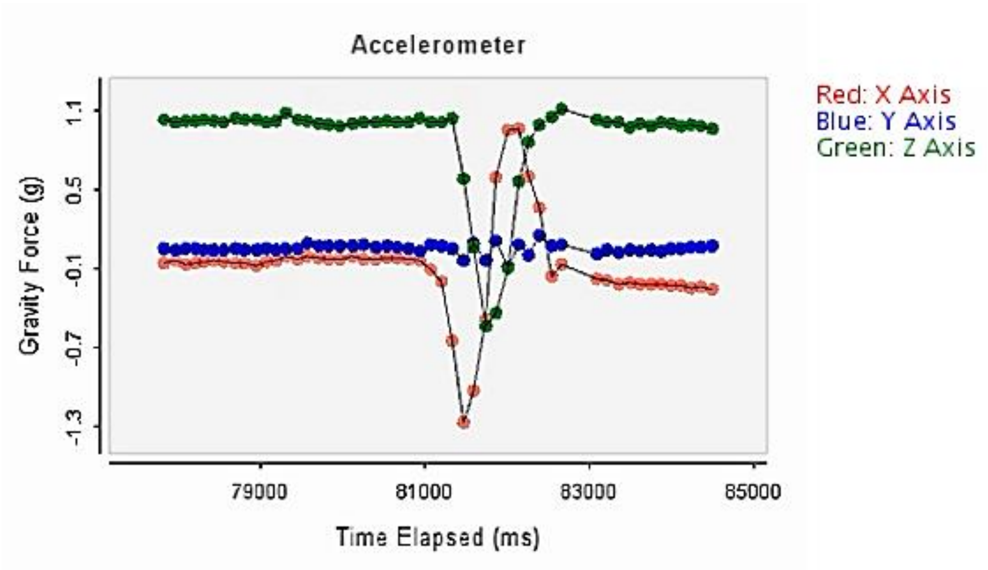


Figure 4.19 - Simulation of a Slower Roll Rotation

X (g)	Y (g)	Z (g)	Time (ms)	Δt (ms)
-0.14	0.08	0.99	79174	1171
-0.28	0.1	0.96	79294	
-0.68	0.09	1.05	79414	
-0.87	0.2	0.65	79534	
-1.1	0.05	0.3	79656	
-0.66	0.02	-0.41	79774	
-0.14	0.03	-0.96	79943	
-0.08	0.04	-1.03	80064	
0.37	-0.07	-0.28	80204	
0.47	0.2	1.36	80344	
-0.15	0.11	1.2	80464	
-0.28	0.01	1.09	80585	

Table 4.10 - Slower Roll Rotation: Acceleration Data and Time Stamps

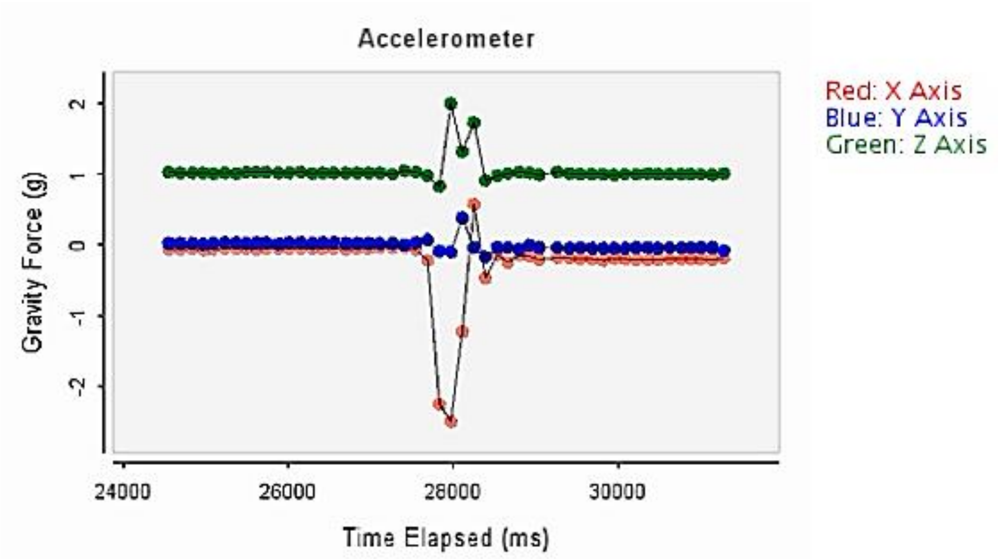


Figure 4.20 - Simulation of a faster Roll Rotation

X (g)	Y (g)	Z (g)	Time (ms)	Δt (ms)
-0.07	0.03	1.03	27550	845
-0.22	0.07	0.98	27690	
-2.26	-0.09	0.83	27834	
-2.5	-0.1	2.0	27970	
-1.23	0.38	1.32	28110	
0.57	-0.04	1.73	28251	
-0.47	-0.17	0.91	28390	
-0.14	-0.04	0.98	28535	
-0.25	-0.04	1.01	28660	

Table 4.11 - Faster Roll Rotation: Acceleration Data and Time Stamps

It was simulated a roll rotation of -360º. The first time stamp corresponds to the start of the rotation and the last time instant corresponds to the stabilization of the UAV after the rotation. As it is shown on Table 4.10 and 4.11, a slower rotation is detected in 1171ms and a faster rotation is detected in 845ms.

From the acceleration values collected three different aspects were observed. Firstly, the y-axis is not affected by the 360º rotation as the rotation orientation does not affect this axis. The z-axis is affected in different ways as it is applied a faster or a slower rotation. In a slower rotation, it goes to an opposite acceleration value of -1g and then stabilizes again to 1g. In a faster rotation, it doubles the acceleration force and then stabilizes again. The axis affected by the rotation, has a similar comportment in a slower or faster rotation. It starts from almost 0g and then experiences a negative force followed by an opposite force.

In the detection of a rotation, data from accelerometer is periodically analyzed over short periods of time. It is defined a timeout of two times a rotation for the detection of a rotational fall. If in this period, two or more rotations are detected the system activates the UAV rescue system. The ROTATION_DURATION is defined as 900ms. It was the experimental value for which this system was able to detect a rotation. The Z_MIN_LIMIT and XY_LIMIT defines the threshold at which a rotation is detected. The following pseudo-code (Figure 4.22) describes the detection code developed:

```
begin rotational_fall
        if TIMER > ROTATION_DURATION * 2
                TIMER RESET;
                EMPTY_ROTATION_LIST;
        end
        else if ROTATION_DETECTED()
                STORE IN ROTATION_LIST;
                if TIMER == 0
                        TIMER_START;
                end
        end
        else if ROTATION_LIST >= 2
                ACTIVATE_RESCUE_SYSTEM;
        end
end

begin boolean ROTATION_DETECTED
        if ACCELEROMETER_Z > (Z_MAX_LIMIT || Z_MIN_LIMIT)
                if absolute value(ACCELEROMETER_Y || ACCELEROMETER_X) > XY_LIMIT
                        return true;
                end
                else
                        return false;
                end
        end
        return false;
end
```

Figure 4.21 - Pseudo Code for Loop Detection

To verify the detection of a rotational fall, it is used the application developed. Figure 4.23, 4.24 represents the detection of two rotations. The rotation counter indicates the number of rotations detected (or flips), which is commonly used by UAV operators. The green led represents a rotational fall detected. In the graphic on top, it is shown the accelerometer values of two rotations detected. The timer defined for a rotational fall detection is two times 800ms, 1600ms. This system takes 1600ms to detect a rotational fall, which consists in at least two rotations in a row.

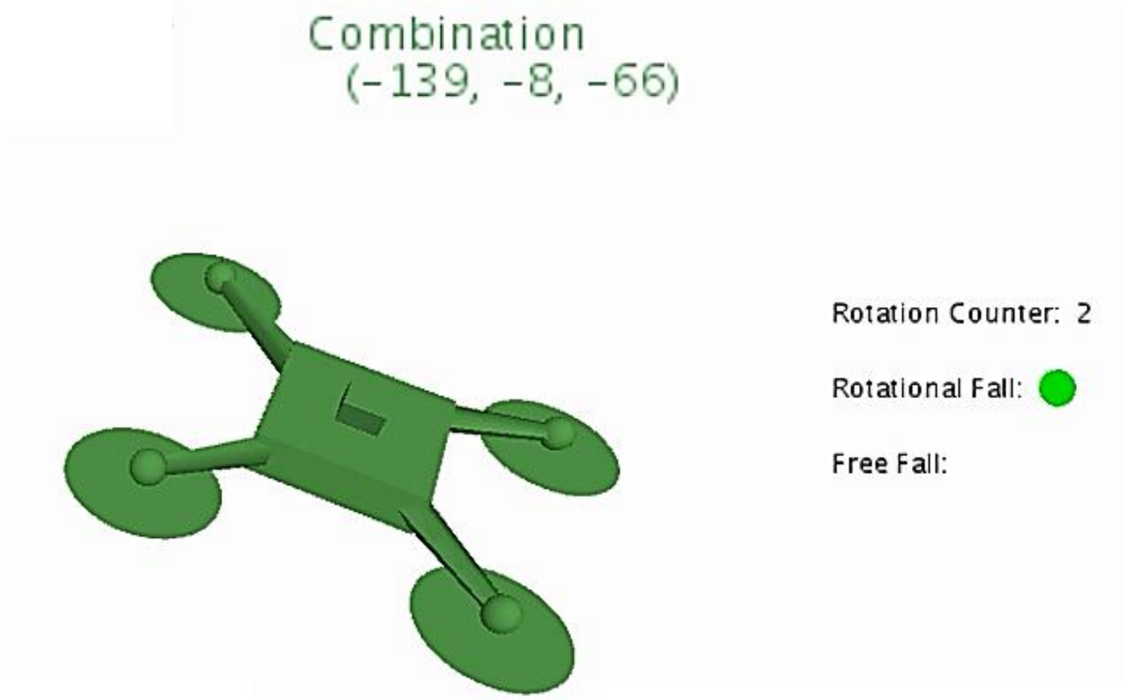


Figure 4.22 - Rotational Fall Detection

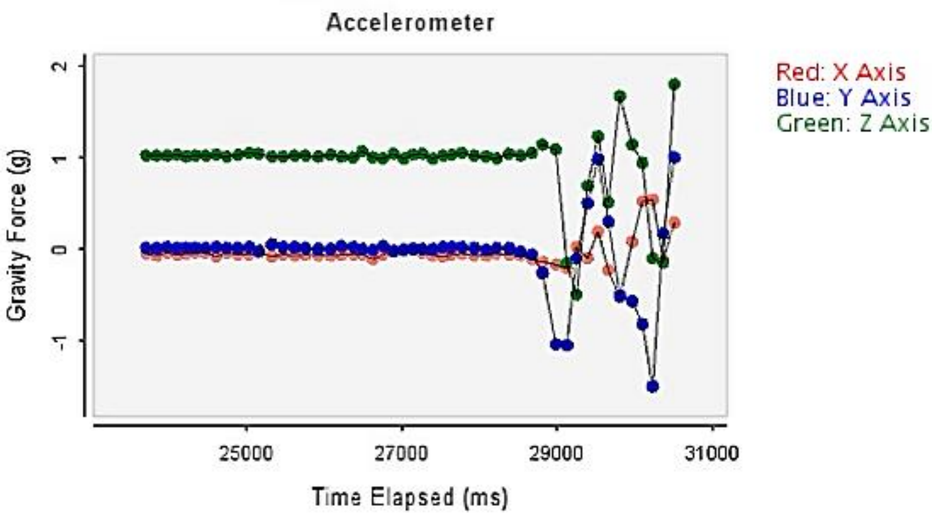


Figure 4.23 - Rotational Fall Detection Graphics Data

4.2.6 Free Fall Detection

To achieve better results detecting an UAV free fall, a data analysis was performed with data collected from the developed application. The methodology used is the following:

- Simulate a free fall along an axis;
- Collect data from the application developed: Accelerometer data from the sensor and time instants.
- Analyze data collected: define time between free fall and understand accelerometer data behavior over time

The obtained results are displayed in Figure 4.25 and table 4.12:

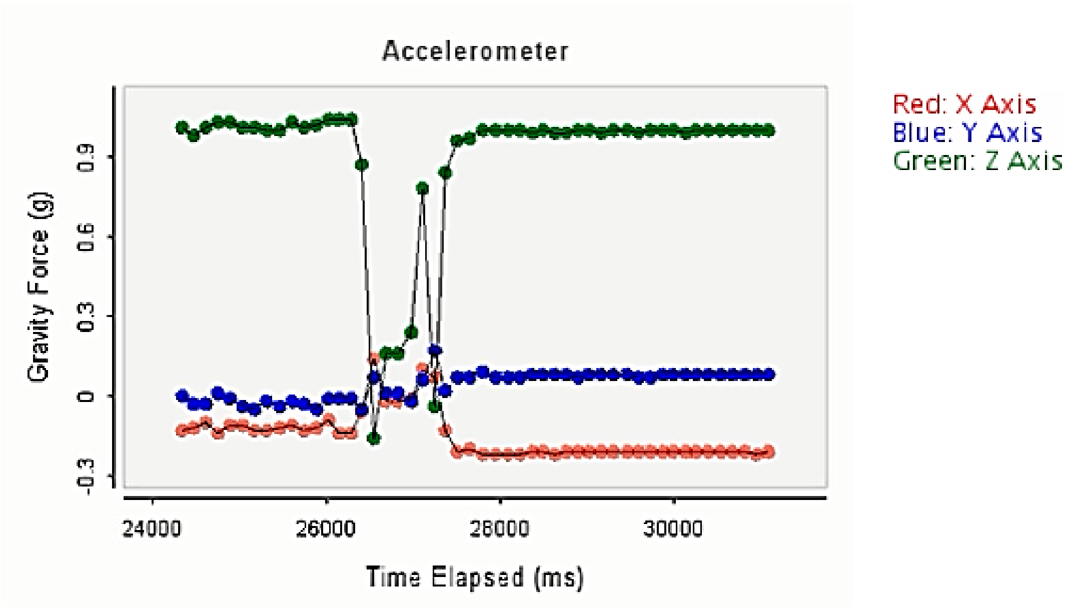


Figure 4.24 - Free Fall Simulation

X (g)	Y (g)	Z (g)	Time (ms)	Δt (ms)
-0.14	-0.01	1.04	26282	261
-0.06	-0.05	0.87	26402	
0.14	0.07	-0.16	26543	

Table 4.12 - Free Fall Simulation Data

It was simulated a free fall aligned with the z -axis from a height of two meters. In figure 4.25, the axis aligned with gravity force (z-axis) starts with a value of 1g. As it starts to fall, acceleration decreases to a value of 0g. When in a state of free fall an object will experience a 0g force on any axis. As it is shown on Table 4.12, a free fall is detected in 261ms. This happens when the x-y-z axes experiences an approximated 0g force. This represents the time needed to make a decision on whether the UAV is on free fall.

A free fall is independent of the orientation of the UAV. As long as the UAV is not subjected to a very fast rotation, this mechanism is still able to detect a free fall. When the UAV is in free fall, the axis will experiment a force of 0g. For the detection of a free fall it is applied the following formula:

$$Sfactor = \sqrt[2]{Xacc^2 + Yacc^2 + Zacc^2} \tag{4.13}$$

When the UAV is held in any orientation and assuming the sensor is in a fixed position in the UAV, at least one of the axes is parallel with the acceleration of gravity (Table 4.13 - a). When the UAV is tilted at an angle, it will always sense some acceleration of gravity on at least two of the axes (Table 4.13 - b). In such cases *Sfactor* (Equation 4.11) will always give a superior value than 0g. During free fall, all of the three axes converge to 0g (Table 4.13 - c). The *Sfactor* will only be zero, or next to zero, when a free fall is detected.

Case	Sfactor	X	Y	Z
a)	1	0	1	0
b)	0.458258	0.4	0.2	0.1
c)	0.022361	0.01	0.02	0

Table 4.13 - *Sfactor* Free Fall Calculations

The following pseudo-code (Figure 4.26) describes the detection code developed for a free fall detection. FALL_DURATION is defined as the experimental value calculated: 261ms. The CALCULATE_SFACTOR indicates the calculation of the formula 4.11. The FALL_LIMIT is defined as 0.05. This value represents approximately 0g with a larger range for quicker detection of the free fall.

```
begin free_fall
        if FREEFALL_DETECTED()
                if TIMER == 0
                        START TIMER;
                end
                else if (CURRENT TIME - FALL_DURATION) > TIMER
                        ACTIVATE_RESCUE_SYSTEM;
                end
        end
        else if TIMER > FALL_DURATION
                RESET TIMER;
        end
end

begin boolean FREEFALL_DETECTED
        CALCULATE_SFACTOR;
        return (SFACTOR < FALL_LIMIT)
end
```

Figure 4.25 - Pseudo Code for Fall Detection

To verify the detection of a free fall, we used the application developed. Figure 4.27 is representative of a free fall detection. The green led represents a free fall detected. In the graphic are shown the accelerometer values. This system takes a minimum of 261ms to detect a free fall.

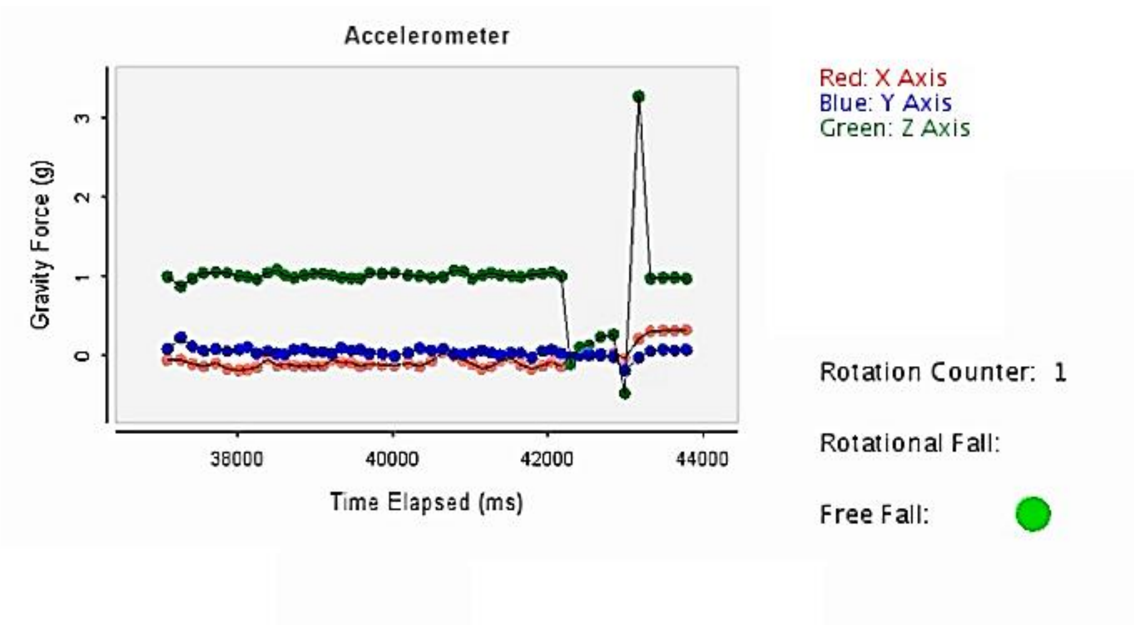


Figure 4.26 - Free Fall Detection

4.2.7 Height and Time Requirements for Fall Detection

Usually, an UAV flies above 10m off the ground. The available time before the UAV hits the ground is crucial for real-time decisions off a successful fall detection. To determine this time we can employ the kinematic equations of motion. The distance is a pre-defined static height, acceleration is the force of gravity and the initial vertical velocity is 0. With some math calculation it is possible to obtain the following free fall time equation:

$$d = v_i * t + \frac{1}{2} * a * t^2 \tag{4.14}$$

$$= 0 + \frac{1}{2} * g * t^2$$

$$t^2 = \sqrt[2]{\frac{2d}{g}}$$

Using Equation 4.12, it is calculated theoretical times of a free fall (Table 4.14).

Height (m)	Time of Fall (s)	Height (m)	Time of Fall (s)	Time of Fall (s)	Height (m)
0.5	0.319	5.5	1.059	1.6	12.5
1	0.452	6	1.107	0.8	3.1
1.5	0.553	6.5	1.152	0.261	0.3
2	0.639	7	1.195		
2.5	0.714	7.5	1.237		
3	0.782	8	1.278		
3.5	0.845	8.5	1.317		
4	0.904	9	1.355		
4.5	0.958	9.5	1.392		
5	1.010	10	1.429		

Table 4.14 - Height and Time Requirements for a Free Fall

The fall detection times registered on the previous simulations, 261ms for a free fall and 1600ms for a rotational fall, were calculated on Table 4.14. The detection time for a free fall would take no more than 0.3m to be detected. For a rotational fall, it would take 12.5m. Considering the pilot does not flip the vehicle, this time is reduced by half (800ms) and the detection of a rotational fall is detected in 3.1m. This is ignoring the fact that a self-rescue mechanism, such as a parachute, would take time to be effective.

4.3 OBSTACLE DETECTION AND AVOIDANCE

4.3.1 System Architecture

Figure 4.25 represents a solution for the detection and avoidance of obstacles. The detection of obstacles is implemented on the Arduino Uno. The collision avoidance module includes a simple communication link between the Arduino and the Pixhawk for alerting the user of an obstacle. The general idea is to immediately stabilize the vehicle with a single communication message.

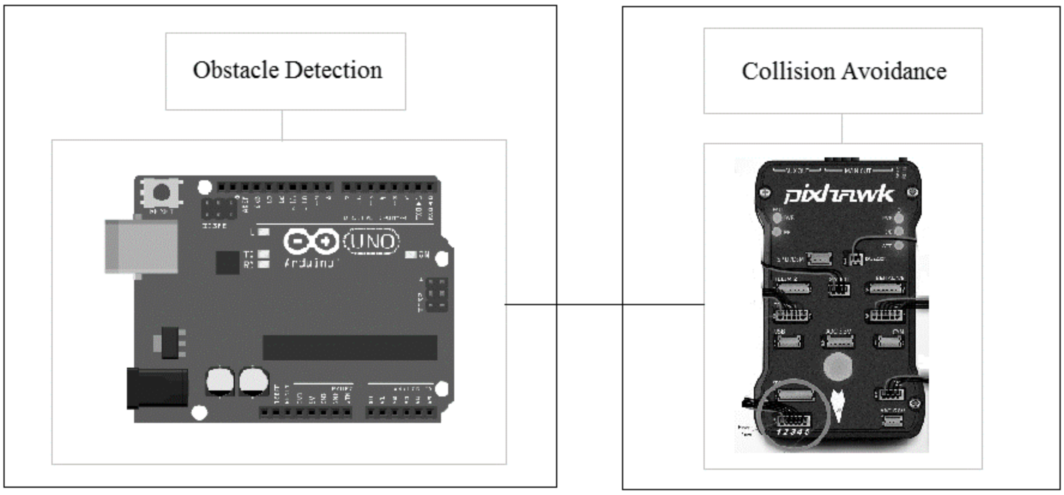


Figure 4.27 - Anti-Collision System Architecture

Therefore, this section can be divided in two parts. The obstacle detection, as the main focus of the implemented system, and the collision avoidance: a simple alert to the FC to take a preventive action.

4.3.2 Obstacle Detection

The first step to implementing a system to detect obstacles is to select a sensor. The sensor adopted was the XL-MaxSonar-EZL0 or MB1260 from MaxBotix. It is an ultrasonic sensor, with a sensitive beam pattern for the detection of people and objects. The sensor range from 25 to 1069 cm. This factor is important when considering fast vehicles (like UAVs), due to its sudden change of direction and ease to reach extreme speeds.

Sensor Dihedral Angle

It is necessary to cover a 360º circle range for the detection of obstacles. The angle of detection of this sensors is denominated the dihedral angle. Literature [4] defines the necessity of using at least 7 sensors to cover all sides with the SRF02 ultrasonic sensor (55º dihedral angle). The XL-MaxSonar-EZL0 has no specifications of the dihedral angle in the datasheet. Thus, several tests are made for the approximate calculation of the dihedral angle sensor. The objective is to introduce several objects in the detection zone to detect the angle θ.

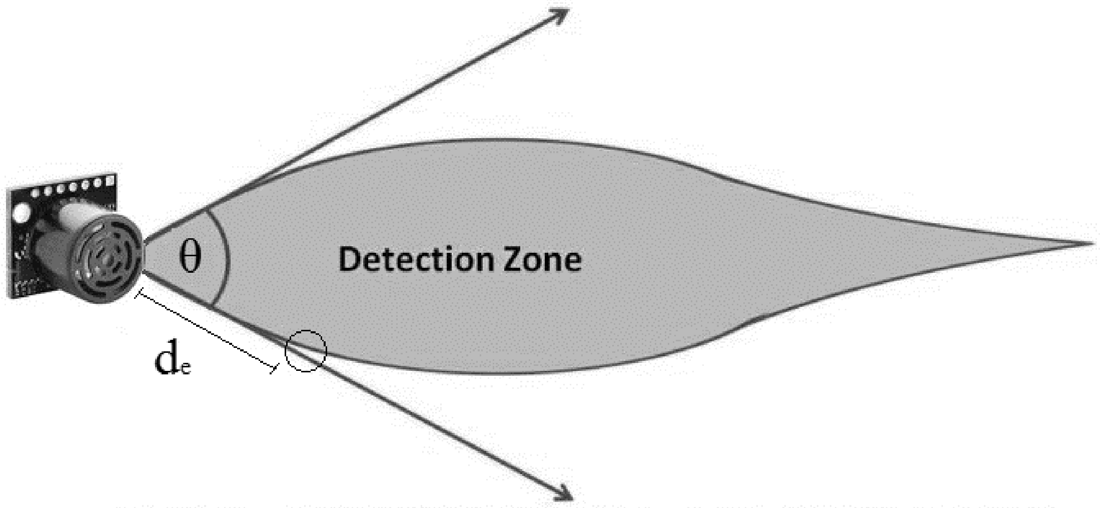


Figure 4.28 - MB1260 Dihedral Angle

Several objects are placed in front of the sensor in the detection zone edges to calculate the approximated angle. Table 4.15 represents the results of the experiment.

d_e (cm)	θ (º)
50	56.72
100	43.13
150	32.52

Table 4.15 - Dihedral Angle Calculation

Dihedral Angle (º)	# Sensors
40	9
45	8
50	8
55	7
60	6

Table 4.16 - Minimum Sensors for 360º Covering

The ultrasonic sensor provides different dihedral angles for different distances from objects. The sensor must quickly react to an alert zone before entering a dangerous zone to avoid damaging the vehicle. Table 4.16 represents the minimum sensors needed to cover a 360º area with different dihedral angles. So on, selecting 7 sensors means some death angles which could possible mislead to a later detection of an obstacle with small dimensions. More sensors means a complex system but adds redundancy to the system. To detect an object at the limit of the alert zone, there must be at least 9 sensors to avoid death angles. Considering the experimental results from literature [9], a constellation of 12 ultrasonic sensors shown a significantly increase of the detection of obstacles. This add some redundancy without putting in risk the sample time of the system for other processes. Figure 4.30 represents the proposed solution with all 12 sensors. This solution is applied so that the sensing angle of the sensors does not generate reflections in the chassis of the UAV. This would cause incorrect measurements in the detection of obstacles. The solution depends on the mechanical structure of each UAV.

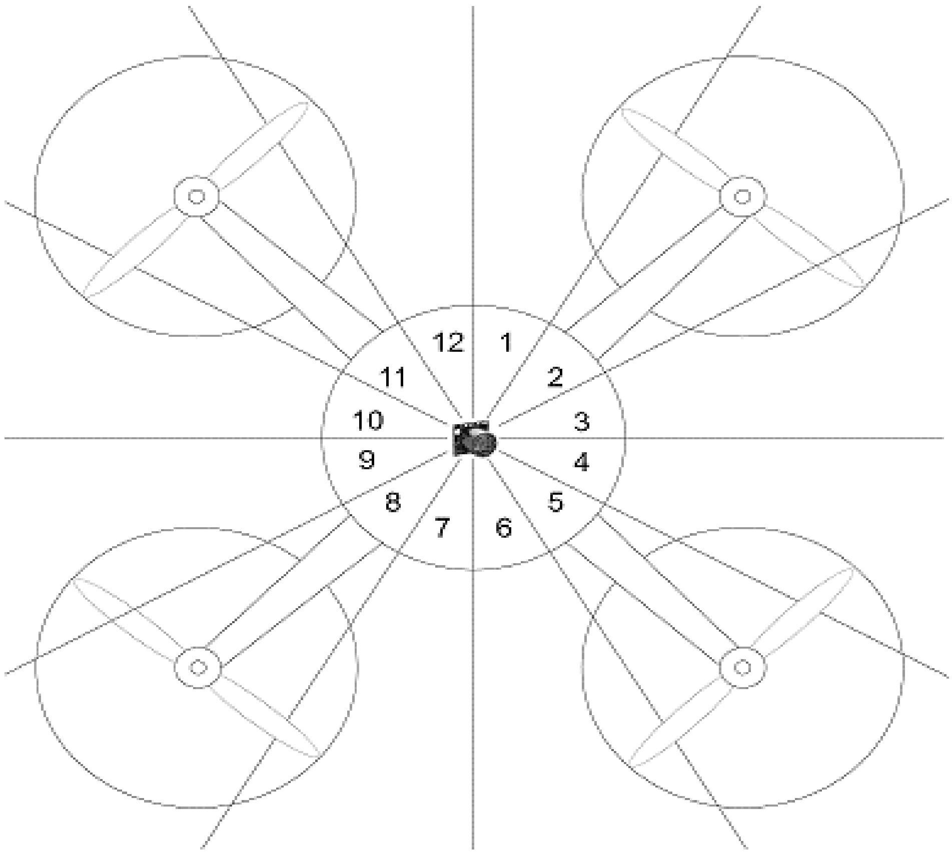


Figure 4.29 - Obstacle Detection Constellation

Smart sensing for obstacle detection

As referenced, there's an interface for the communication between the fall detection and the obstacle detection mechanism. Every time the UAV moves it sends the direction of its movement to the obstacle detection module. This information is processed according to the following guidelines:

- When no direction is detected: all sensors are deactivated.
- When a direction is detected the nearest four sensors are activated for obstacle detection. In Figure 4.27, a simulated movement of the UAV towards the sensor 1, would activate sensors 11, 12, 1, 2 and 4 (the nearest sensors).

In the first mode, the deactivation of the sensors is applied when the UAV is not moving (it is stable in the air or landing). This saves processing time for other vital parts of the safety mechanisms implemented.

The second mode is defined as smart sensing. The sensors are activated considering the direction of the UAV movement, saving processing time (only 4 sensors are activated at once, instead of 12). This solution ensures a minimal dihedral angle of four times the one using only one sensor (> 120º), for detecting obstacles. In Table 4.17, it is shown the results of this experience for an obstacle detection. The sensor readings from the fall detection platform are shown in C_x, C_y, C_z, which corresponds to the combined angle (review Section 4.2.4). The software decides on which sensor the obstacle is, and it activates de nearest sensors.

Cx	Cy	Cz	Sensor
-17.74	13.09,	-3.10	1

Table 4.17 - Obstacle Detection and Sensor Activation

Obstacle Detection Processing Time

The mechanisms developed are processed in an open-source platform, limited to a processing time. The objective is to detect the global processing time of the mechanisms implemented, with particular attention for the time between readings for the obstacle detection. The time between readings are important for the reliability of the system, otherwise an obstacle would be detected too close to the vehicle. The time measured between the sensor readings is represented in Table 4.18. This means a vehicle with this system implemented has a 441.75ms window when it is impossible to detect obstacles.

t_p (ms)
441,75

Table 4.18 - Processing Time for Obstacle Detection

4.3.3 Collision Avoidance

Platforms Serial Communication

This part explains how to connect Arduino Uno to a PX4 flight controller using the MAVLink protocol over a serial connection. This can be used to perform additional tasks such as image recognition and obstacle detection which simply cannot be done by the PX4 due to the memory requirements for storing images or limited port connections to sensors. PX4 uses the TELEM2 port to communicate with Arduino. Figure 4.30 is a representation of the pin connections between the two platforms. The only constraint is to use a voltage divider between the TX1 and RX1 connection to Arduino to adapt the 5V from Arduino to the 3.3V of the PX4. Even so, a voltage level shifter between 3.3V to 5V is able to deal with this constraint.

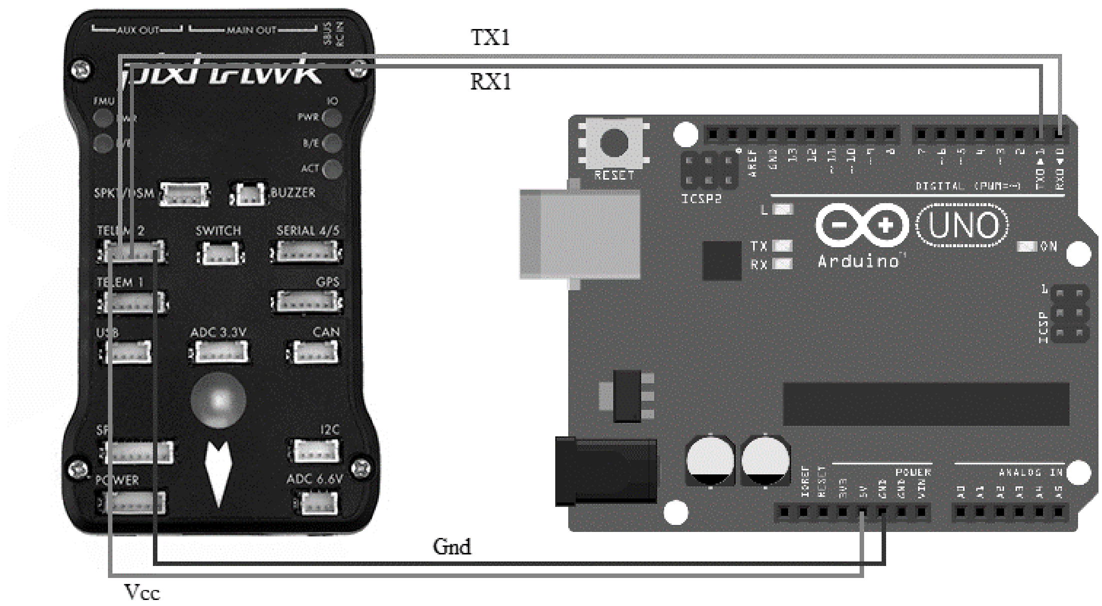


Figure 4.30- Pixhawk and Arduino Serial Communication

Alert Message for Collision Avoidance

Every time the collision detection module detects an obstacle, it transmits an alert to the collision avoidance module. This module is responsible to create a MAVLink message with an instruction to the UAV hold position, which avoids a possible collision. Figure 4.31 represents the MAVLink packet structure sent to the Pixhawk to just hold position and stay stable in the air to avoid a collision.

(Header)

Message Header	Message Length	Sequence Number	System ID	Component ID	Message ID
0xFE	0-255	0-255	1	0	0x4C (76)

Mav Msg COMMAND_LONG (Payload)

T_System	T_Component	Command	Confirmation	Param 1	Param 2	Param 3	Param 4	Param 5	Param 6	Param 7
(1)	(0)	(252)	(0)							

MAV_GOTO_HOLD_AT_CURRENT_POSITION

MAV_GOTO_DO_HOLD

Figure 4.31 - MavLink Message for Hold Position

3D Simulation

The collision avoidance system was tested on a 3D simulated environment. For that purpose, it was used an open-source 3D environment simulator: Gazebo [48]. This simulator is capable of simulating 3D vehicles in simulated environments, outdoor or indoor, and capable of simulating interactions with other rigid objects.

The use of this simulator is intended to simulate the time that a UAV takes to completely reverse its movement to avoid an obstacle and the maximum distance it travels in the course of this braking. In the first case, the UAV needs to abruptly reduce its speed and stop its movement. In the course of this action, the UAV will slide forward slightly after braking abruptly and, consequently, it will tease the opposite effect: sliding back slightly. The measured time (Δt) is measured from the moment the UAV begins to slow down until the moment it immediately slides back. The calculated distance (Δd) corresponds to the distance travelled during these two instants of time.

In this simulation, the methodology involves three different steps:

- Simulate a maximum peak speed.
- Upon reaching that speed, stop the UAV's movement immediately.
- Collect the braking time and the distance traveled.

This simulation is represented in Figure 4.32 and it corresponds to 5 different velocities tested. Table 4.19 represents the numerical data collected with more detail.

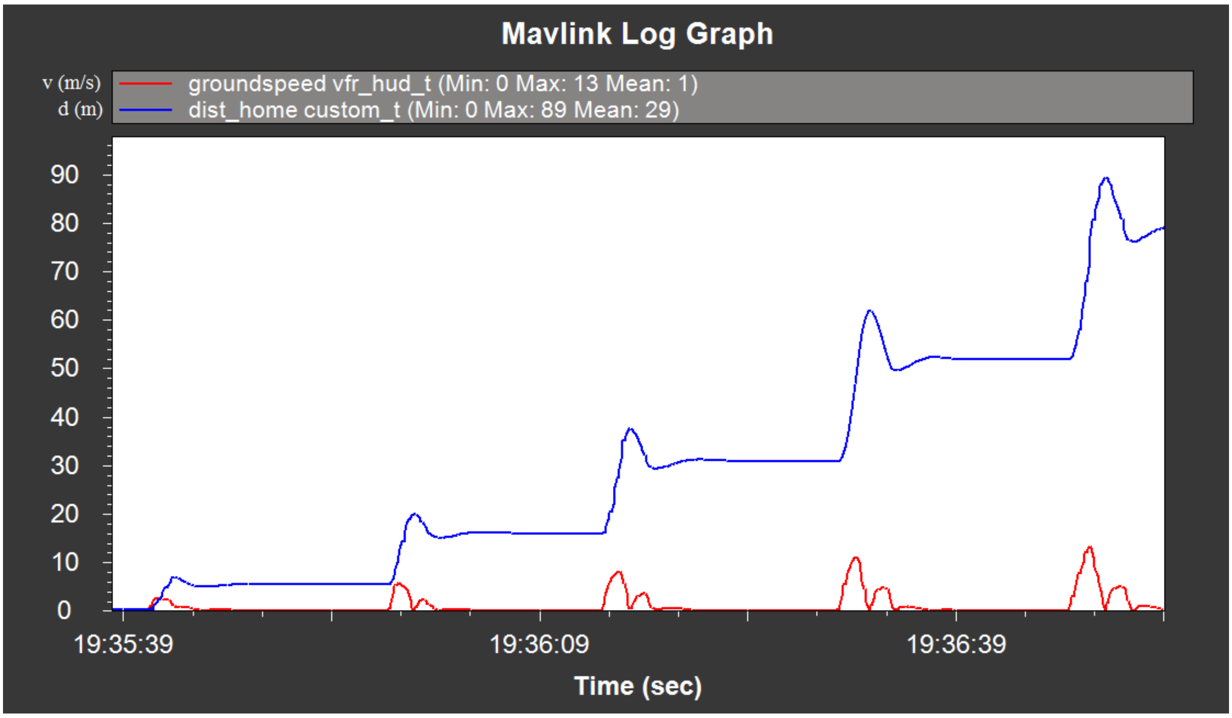


Figure 4.32 - Simulation of UAV Brake Mode

v (m/s)	v (km/s)	t_0 (s)	t_f (s)	Δt (ms)	d_0 (m)	d_f (m)	Δd (m)
2,3	8,3	42,205	42,689	484	5,30	6,95	1,65
5,48	19,7	58,996	59,850	854	14,20	19,60	5,40
8,1099	29,2	14,835	15,735	900	31,52	37,53	6,01
10,84	39,0	31,723	32,767	1044	52,33	61,85	9,52
13,309	47,9	48,672	49,803	1131	78,48	89,27	10,79

Table 4.19 - Data Collected from the Obstacle Avoidance

The proposed test speeds should be between 10 and 50km/h. The velocities tested correspond to the closest value that was able to reach with the simulation tool, spaced at 10km/h intervals. As you can see by increasing the test speed, the distance and the stopping time of the UAV will increase progressively.

Combining the travelled distance (*dp*) during processing time (t_p) from Table 4.18 and the travelled distance (Δd) during the measured time, assuming a constant speed, we have as a result the total time that goes from the moment the UAV processes the reading data of a detected obstacle until it stops its movement. The value obtained in table X.X ($d_p + \Delta d$) corresponds to the minimal safe distance for a certain speed, at which the obstacle can be detected and the collision avoided.

t_p (ms)	v (m/s)	d_p (m)	$d_p + \Delta d$ (m)
441,75	2,3	1,02	2,67
	5,48	2,42	7,82
	8,1099	3,58	9,59
	10,84	4,79	14,31
	13,309	5,88	16,67

Table 4.20 - Minimal Distance for Avoiding Collisions

Chapter 5
CONCLUSIONS AND FUTURE WORK

This chapter contains conclusions, concerning the mechanisms implemented, and suggestions for possible future work.

5.1 Conclusions

In the elaboration of this dissertation different safety mechanisms were created for the reliable operation of 3D vehicles. Several potential failures were identified and analyzed. Then, three different safety mechanisms were developed: a fall detection system, an obstacle detection and anti-collision system and a current monitoring system. According to the different mechanisms developed, the following conclusions were made:

Fall Detection Mechanism:

- The calculation of the orientation of an UAV can be improved through data filtering and with a Complementary Filter.
- The implementation of a free fall detection system, with an IMU sensor, is capable of detecting a fall in 261 ms - traveling a maximum of 0.3m before triggering a self-rescue mechanism;
- A rotational fall can be detected in 1600ms, corresponding to a vertical fall of 12.5m, which can be considered excessive. Considering the pilot does not flip the vehicle, this time can be reduced by half (800ms) and the detection of a rotational fall can be detected in 3.1m. This detection time is more reasonable for a successful detection;
- The system is able to detect single or multi flips of a vehicle.

Obstacle Detection and Avoidance:

- Ultrasonic sensors have different dihedral angles which must be considered for the detection of obstacles;
- Combining ultrasonic sensors reduces dead angles, which could mislead to a later detection of obstacles; this means more redundancy but adds some complexity to the system;
- A smart detection of the vehicle orientation/direction provides a more efficient detection of obstacles and ensures more time for other safety mechanisms implemented;
- In the detection of an obstacle, data collected from sensors must be quickly processed to reduce the distance travelled in the process. The stopping distance greatly increases as the vehicle moves faster, making the obstacle avoidance a combination between the processing time and the stopping time;

- The detection of an obstacle has a minimal safe distance for avoiding objects. This distance depends on the processing time of the data collected by the sensors and the stopping time of the vehicle.

Current Monitoring System:

- With low currents and considering the implemented application, the non-inverting amplifier provides a slightly higher gain in comparison to the differential amplifier;
- The differential amplifier requires more electronic components and more complexity than the non-inverting amplifier;
- In small current applications, low-side or high-side current sensing is suitable and does not interfere with the amplification circuit;
- Resistive Current Sensing provides the means to monitor small currents in electronic applications such as vehicle controllers;
- The detection of small currents with a magnetic sensor, such as a Hall Sensor, requires some amplification of the flowing current;
- The accuracy of the measurement applying Magnetic Current Sensing is highly dependent on the sensor-to-conductor separation to detect and monitor small currents.

5.2 Future Work

As a follow up to this dissertation work, some improvements can be made:

Fall Detection Mechanism:

- The combination between accelerometer, gyroscope and magnetometer may provide better results, with the combination between two 6-DOF sensors or a 9-DOF sensor;
- Rotational Fall Algorithm can be improved by using data collected from gyroscope to provide a faster decision.

Obstacle Detection and Avoidance:

- The communication between the Flight Controller and the monitoring board for sending alert messages; experimental tests for providing more realistic results in the processing time after detecting obstacles;
- Avoidance algorithms to calculate a new direction of movement, diverging from the obstacle.

Current Sense Monitoring:

- Explore other current sense techniques;

Individually monitor the current for all the vehicle critical components, such as the motors.