UAV Obstacle Collision Avoidance System

Subsystem integration for safer autonomous flights

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ABSTRACT

The large growth that the civil Unmanned Aerial Vehicles (UAVs) market has experienced in the last decade is now triggering the urge of both professionals and enthusiasts to use this technology to perform tasks that would be more difficult to accomplish with their traditional procedures. However, many times these tasks require precision flight and do not allow the slightest physical contact with the UAV. Currently, very qualified pilots are needed since there have not been significant advancements on on-board obstacle detection technologies, and manual control is still a must.

The main goal of this thesis is to develop an affordable Obstacle Alert and Collision Avoidance System (OCAS) that can be easily deployed to a wide range of UAVs. The approach followed is to embark a series of ultrasonic rangefinders to continuously monitor the minimum distance of the vehicle with its surroundings. The data provided by the sensors is then processed on an onboard computer, and control commands are sent to the main controller board in the case that an obstacle is detected and a possible collision identified. The final result is an integrable payload subsystem that would improve the situational awareness capabilities of any UAV that integrates it, reducing the risk of collision with its surroundings.

Keywords: UAV, obstacle detection, collision avoidance, system integration, ultrasonic rangefinder, Ardupilot

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T his chapter will be used to acquaint the reader with the emerging UAV market, and the challenges it is facing on its way towards maturity. Also, the reasons for its rapid evolution will be exposed and finally, focusing on the contents of this thesis, the personal motivation and the methodology will be explained to further expand on the topics of interest in the following chapters.

1.1   Background information

The first remotely radio controlled models appeared in the early twentieth century as small prototypes for potential manned aircraft. Afterwards, and during most of the century, the investigation and development lines were directed towards the military scope, in which the main objective of UAVs, which is still applied today, was to substitute manned aircraft in three types of military operations, commonly known as "the three D's" [4, 5]:

- Dirty: operations performed in a contaminated environment.

- Dangerous: operations entailing some risk for the pilot.

- Dull: long and monotone operations, such as monitoring operations.

In the 70's and the 80's, efforts were directed to improve the technical characteristics of these vehicles. But it was not until the late 80's when a revolution in the industry took place with the introduction of the GPS navigation system, whose accuracy in geolocation opened a whole new spectrum of possibilities.

Regarding the civil sector, the potential applications of UAVs in the non-military field are much more diverse. Nowadays these vehicles are in the process of finding new niche positions

in the civilian market, having been introduced up to now in different industry sectors such as agriculture, forest fire fighting, search and rescue, aerial photography, cartography, or security and surveillance, among others. Despite the latter, the use of UAVs for civil purposes is relatively recent in comparison with the military sector. This late implementation in the civilian field was caused mainly by two limitations which are of minor relevance in the fighting industry: legislation and economy. [6]

1.2 Socioeconomic environment

Apart from "the three D's" mentioned in Section 1.1, another reason for the embracement of UAVs within the industry shall be considered. The final goal of any company is to create profit to their shareholders, which can be done either by increasing the revenues or by decreasing the costs of their activities. UAVs enter in the latter category. The consistent usage of smaller tools as compared with the manned workpower usually means that the equipment costs can be lowered, as well as the man-hours needed to perform the task [7], not to mention that most of the time the number of workers needed can be reduced to as low as one or two, in charge of operating the UAS (Unmanned Aerial System[1]).

This phenomenon is already proving to be very effective for the companies taking advantage of it, but research also shows an even bigger potential that is still waiting to be exploited, claiming that UAVs could have replaced $127 billion worth of human labour in 2015 [1], distributed in the sectors shown in Figure 1.1.

Figure 1.1: Distribution of potential UAV markets [1]

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[1]UAS refers to the bigger system that incorporates one or more UAVs, as well as the Ground Control Station or other related subsystems

1.3 Legal framework

Due to the fast-evolving UAV industry, the aviation authorities have not yet been able to develop a reasonable set of regulations and standards to harmonize the legislation across borders. Aditionally, this regulatory framework should consider the idea that each system has unique capabilities and characteristics and also that development and innovation are very important concept in the field, and should not be dampened by restrictive rules [8]

However, there have already been some efforts from ICAO to outline some general rules to give a global sense of what is expected from the UAV sector [9]. In addition to that, some countries are creating their own legislation to enable the operation of Unmanned Aerial Vehicles within their territory.

For example, the Spanish government issued an urgent provisional regulation on October 2014 [10] that affects to Remotely Piloted Aircraft Systems (RPAS[2]) not exceeding 150 kg of Maximum Take Off Mass (MTOM). Heavier UAVs are subjected to European regulations [11] Focusing on the smaller segments, UAVs are separated according to their MTOM as follows:

MTOM < 2 kg: Flights Beyond Visual Line Of Sight (BVLOS) are allowed, but conditioned to the publication of a NOTAM (NOtice To AirMen). Apart from that, all the other rules in the 2 kg to 25 kg apply.

2 kg ≤ MTOM < 25 kg: Only operable in areas separated from groups of buildings in cities, or groups of people elsewhere. Flight shall always take place in uncontrolled airspace, within Visual Line Of Sight (VLOS) and at a maximum distance of 500 m from the position of the pilot, not exceeding 400 ft of heigt over the terrain.

25 kg < MTOM: Flight is only allowed for firefighting, search and rescue missions. They shall only operate in uncontrolled airspace and according to the limitations stablished in their Airworthiness Certificate, as emited by AESA.

Nevertheless, even if Spain or other countries have their own regulations to control the usage of UAVs in their territories, it is still important to have an international and stable legislation to allow the sector to grow to its full potential.

1.4 Motivation

Traditionally, the most important payload that could be carried in an aircraft was human beings, that would perform their mission while aloft. Nevertheless, the advancements on sensing technology and wireless communications have forced a change on traditional aviation. Apart from commercial aviation, where the final objective is to transport people form one place to

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[2]RPAS are considered as a subset of the UAS group. Fully automatic vehicles do not belong to the RPAS category, since the existance of a remote pilot is required at any time

another, in almost any other mission the role of the human workforce is to pilot the aircraft and/or operate the payload systems. This secondary role of the human operators implies that, given the maturity of the involved technology, they could be substituted by intelligent computer systems or, at least, disembarked form the aircraft into a safer Ground Control Station (GCS). The process of "unmanning" the aircraft also brings the advantages of decreasing the weight of the aircraft and thus improving its endurance and manoeuvrability, avoids putting the pilot in a dangerous situation, and helps alleviate the errors associated with tedious and repetitive tasks, among others.

However, there are also some downsides. In the technical department, there are still some issues regarding the electromagnetic spectrum allocation for the data-link with the vehicle [12], as well as accommodating unmanned aircraft within the Airspace System [13]. In addition, the most accused issues for experienced pilots are those related with the loss of situational awareness that comes as a result of eliminating the physical cues (body inertia, vibrations...) and relying on instrumental readings only [14]. Hence, some enhanced systems need to be integrated into the vehicle to overcome this limitations, providing the pilots with additional information for the safe execution of the mission.

Finally, for this project, the goal is to provide a system that reduces the risk of the widest range of UAVs from crashing with nearby obstacles, so that regular operations are carried with a higher level of safety. Eventually, the authorities could consider the increase in overall safety as a standard, triggering the modification of existing regulations to a more permissive set, and allowing the industry to take advantage of all the benefits that the incorporation of UAVs could bring to their activities.

1.5 Project objectives

According to the motivation as stated in Section 1.4, the final goal of this project is to develop a working prototype for proof of concept of a system able to detect and avoid obstacles that threaten the integrity of the UAV. Towards that end, some more specific objectives can be defined as follows:

- Identify the requirements needed for the Obstacle Collision Avoidance System (OCAS) to correctly fulfill its purpose

- Define the functional architecture of the OCAS

- Define the interfaces (communication channels and protocols) to be used by the OCAS for its correct integration on the UAV.

- Define the interaction channels and procedures between the UAV equiped with OCAS and Ardupilot and the operator.

- Develop a first working prototype as proof of concept of the Obstacle Collision Avoidance System (both hardware and software) and integrate it on a real UAVtroduction.tex

Additionally, the architecture of the solution should be designed with modularity in mind, permitting easy adaptation of the algorithms for later research activities.

1.6 Methodology

As some may have noticed, the objectives defined in Section 1.5 remember of the first steps that are usually taken in the Systems Engineering approach for interdisciplinary design [15]. That approach will be adapted to the project, and some useful tools and concepts will be used [16], such as the requirements capture, the Functional Flow Block Diagram (FFBD), the Functional Architecture definition or the product integration via interfaces definition.

Finally the prototype created from the process will be tested in a series of common situations to prove that the product is capable of completing its task. Also, it will be demonstrated how the OCAS has been designed with flexibility and modularity in mind, explaining the possibilities to expand its features and proposing some ideas for future work.

1.7 Time planning

For any big project with defined deadlines, time management is of utmost importance. The elaboration of the thesis has been carried out during more than 10 months, and the different work phases have been monitored with a project management software tool. The resulting Gantt Diagram can be consulted on Figure 1.2.

It is worth mentioning that in the period from 01/11/2015 to 05/05/2016 I was doing my professional internships at Centum Solutions [17]. Thus, most of my research during that time was guided by the interests of the company. Nevertheless, that stage proved very useful for the summer period, when my work was exclusively focused towards my thesis.

1.8 Budget

This section describes all costs associated to the project and proposes an estimate of the budget needed to replicate it. The final cost results on **6391.86 €**, which is divided as follows.

1.8.1 Personnel expenses

The base annual engineering salary for an Engineering Degree holder in Spain is, according to the Spanish "XVI Convenio colectivo nacional de empresas de ingeniería y oficinas de estudios técnicos" [18], of at least 17,038.62 € per year, with a maximum of 1800 working hours. Thus, the

Figure 1.2: Gantt Diagram of the Project

Component	Unitary Price	Units	Total
F450 kit	399 €	1	399 €
Propeller blades	2 €	4	8 €
Radio transmitter / receiver	51 €	1	51 €
Telemetry radio	48 €	1	48 €
Primary battery	40.85 €	5	204.25 €
Secondary battery	14 €	1	14 €
Raspberry Pi	33.81 €	1	33.81 €
Wireless WiFi adapter	19.95 €	1	19.95 €
Ultrasonic range finder	4.50 €	8	36 €
Resistor	0.05 €	30	1.50 €
Connection wires	0.10 €	50	5 €
Camera	24 €	2	48 €
Optical flow sensor	36 €	1	36 €
TOTAL			**904.51 €**

Table 1.1: Prototype hardware costs

minimum salary can be calculated as 17038.62 €/1800 $h = 9.47$ €/h. With an estimated working time of approximately 550 hours, the calculated personnel expenses are 5216.50 €.

1.8.2 Software cost

Most of the work has been performed on open-source software systems, such as Arduino / Ardupilot and Raspberry Pi / Linux. However, the calibration and initial programming and testing, prior to the payload deployment, was done on a laptop machine running Windows 10 Pro, listed at 279 € per license on the Microsoft Store.

1.8.3 Hardware cost

For the hardware part of the project, the aforementioned laptop will be considered together with all the components needed to build the test platform.

The PC was bought for 500 €. Assuming a linear depreciation period of 4 years, and that the dedication to the project equals the amount of total labour hours, the resultant expense is estimated as 7.85 €.

Unexpectedly, the prototype is composed of numerous individual components acquired to different sources. In Table 1.1, an estimation of their cost is done according to current prices on relevant stores. Notice that the F450 kit already includes most of the components needed for the UAV to fly (motors, controller board, frame. . .)

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A BRIEF INTRODUCTION TO ARDUPILOT

As it was mentioned in Section 1.4, it is intended to bring the technology developed within this project to the widest range of UAVs. However, there exist in the market several families of controller boards (which can be considered to be the brains of the vehicles, in charge of all the basic functions required for an stable flight) that can only be used with specific hardware and/or software, not being compatible with each other since they implement different communication protocols. Furthermore, some manufacturers work with proprietary software, of which little information on the low-level functioning is available to the public.

It is clearly impractical to try to target all the existing standards for this project, so a compromise needs to be made. The thesis will be elaborated for the Ardupilot family of controllers, for being the most widespread open-source[1] alternative. Some of the leading companies [19] in the sector actively support the Dronecode Project, of which Ardupilot is part, such as Intel, Qualcomm, Parrot, 3DR, Yuneec, AUAV, Walkera...[20]

It is important nonetheless to clarify some concepts and features of any Ardupilot-equipped UAV. More information can be found at `www.ardupilot.org`.

2.1 Basic features

The most basic but important feature of the controller is to give control to the pilot over the vehicle. There are several components that make this function possible.

Firstly, the pilot expresses the desired movements of the vehicle through a Radio Control (RC) transmitter, shown in Figure 2.1a. The signal at 2.4 GHz is received by the RC receiver located in the vehicle, depicted in Figure 2.1b. Then the receiver translates the electromagnetic wave into

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[1]The software is being developed at GitHub: `https://github.com/ArduPilot/ardupilot`

several PWM (Pulse Width Modulation) signals, one for each input channel up to a maximum of 8 channels, which are inputted to the controller board. However, for the primary control of the vehicle, only 4 channels are needed: throttle, roll, pitch and yaw. The additional channels are used to control extra features such as the flight mode, the landing gear or the camera controls.
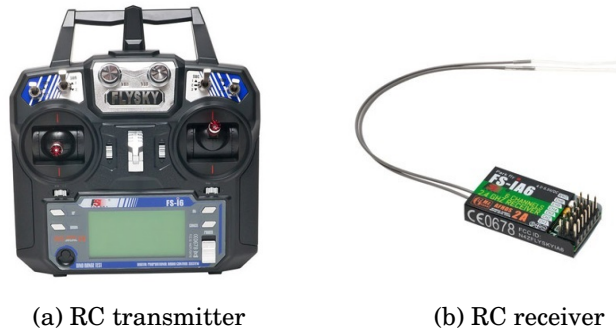

(a) RC transmitter   (b) RC receiver

Figure 2.1: FlySky FS-i6 Remote Control (`www.flyskyrc.com`)

The second step is to translate the commands from the pilot into signals to the control elements of the vehicle. These can vary depending on the type of vehicle (for example the yaw command affects the rudder in the case of a fixed-wing aircraft, the tail rotor collective control for a conventional helicopter or the differential throttle in the diagonals for a multicopter) but the underlying processes are similar.

Every Ardupilot controller board must have at least and Inertial Measurement Unit (IMU) consisting of a 3-axis accelerometer plus a 3-axis gyroscope for the state determination of the vehicle. Additionally, a barometer, a GPS and other sensors can be integrated. Hence, reading the pilot's commands from the RC receiver and the state of the vehicle from the IMU, the output to the control elements can be computed by some regular PID control loops (more information on the topic can be found at [21]). To the output pins of the controller board are connected the control elements, be it some servo-motors for the control surfaces of a fixed-wing aircraft or brushless motors with propellers for the case of a multicopter. These elements are externally powered by the primary battery.

2.2   Ardupilot as part of a UAS

If Ardupilot wants to be used as a professional tool to enhance production or reduce costs, it can not rely on manual control only. For more advanced missions and proper calibration of vehicles with diverse configurations and physical properties, it is necessary to tweak the parameters that the control loops necessitate for their real-time computations. It is in those cases when a Ground Control Station can become useful. By connecting the vehicle to an external computer, the operator is no longer limited to the 8 input channels that the RC transmitter can provide.

Instead, the limit on the amount of information that the Ardupilot board can broadcast or absorb is only bound by the communication protocol that is implemented between the two.

For the Ardupilot ecosystem the protocol used is also open-source and receives the name of MAVlink[2] (MAV stands for Micro Aerial Vehicle). Its open nature allows developers to create a very diverse set of software and applications to communicate with the UAV, from the widespread Mission Planner and APM planner, to versions that run on Android devices for on-the-field operation or developer-oriented libraries that run under Python.

Another feature that is worth mentioning is the lightweight nature of the protocol, which not only permits the connection via USB cable, but also wirelessly through what is usually called a telemetry radio, which effectively is a serial transmission of data over a 433 MHz radio wave carrier.

An experienced operator can take advantage of all the mentioned features to receive real-time information on the state of the vehicle while it is on the air, and also to send high-level commands to the vehicle. Those options will be further discussed in Section 2.3.

Figure 2.2: Screenshot of Mission Planner GCS, implementing the MAVlink protocol

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[2]More information on the protocol can be found on qgroundcontrol.org/mavlink/start. The message definitions and generator code can be found at its GitHub repository github.com/mavlink/mavlink/

2.3 Advanced features

For an Ardupilot UAV to be able to automate some missions and procedures there are some additional requirements. Firstly, the IMU is appropriate for the evaluation of the vehicle's state variables, but the knowledge of its environment can only be acquired through absolute positioning sensors. Those sensors are usually a GPS module for horizontal positioning and a barometer for altitude measurement. Secondly, a wireless data-link provides a much more flexible way of interacting with the UAV during the execution of the mission.

2.3.1 Flight modes

Ardupilot has separated the mentioned advanced features in different flight modes, which can be activated with the 5th channel on the RC transmitter or from the GCS. At the time of writing, there are 15 different flight modes, but just the most relevant ones for the project will be described here. A summary of the most important features can be found in Table 2.1
[From this point onwards the concepts involving Ardupilot will be particularised for the multicopter variant, since it is the type of vehicle that will be used for the prototype. Similar information can be found for fixed-wing aircraft, helicopters and rovers at the support page.]

STABILIZE The default mode for manual control. Uses only the IMU data to control the flight. The pitch and roll channels define the Euler angles (instead of the rotation rate of Acrobatic mode) so that when the controls are released to neutral position, the vehicle will level off automatically. The yaw channel does control the yaw rate of the UAV instead, while the throttle channel Ardupilot will not compensate for wind or other disturbances.

ALTITUDE HOLD Very similar to the Stabilize mode. The only difference is on the throttle channel, which controls the ascension rate instead of raw power transmitted to the motors. When the throttle stick is centered, the vehicle will hold the current altitude using the information measured by the onboard barometer.

LOITER Incorporates the GPS data to the Altitude hold mode, making it possible for the UAV to compensate for wind and IMU drift. The pilot still has control on the vehicle similarly to Altitude hold but when the control sticks are released, the position will be kept within a 1 metre error (provided good quality GPS signal).

AUTO This mode allows to automate missions and procedures. With the help of a GCS application, such as the one shown in Figure 2.2, the operator can click on a map to define waypoints and actions (take of, land, point to a certain direction, etc. are within the options) and save a data file to the vehicle's internal storage. Later, when the mode is activated, the vehicle will follow the predefined route without the need of direct input from the pilot. The throttle, yaw, pitch and roll controls will be disregarded when Auto mode is active, but the pilot can change the active mode at any time from the RC transmitter.

RTL (RETURN TO LAUNCH) RTL mode is commonly used as a failsafe feature, when communication either with the pilot or the GCS is lost. It is a very specific version of the Auto mode that automatically starts the return to Home procedure, landing the vehicle exactly where it took of from. The

Mode	Sensors used	Throttle	Roll/Pitch	Features
Stabilize	IMU	Power	Euler angles	Fully manual
Altitude hold	IMU + Barometer	Ascension rate	Euler angles	Enhanced altitude control
Loiter	IMU + Barometer + GPS	Ascension rate	Euler angles	Disturbance rejection
Auto	IMU + Barometer + GPS	No control	No control	Mission automation
RTL	IMU + Barometer + GPS	No control	No control	Failsafe
Guided	IMU + Barometer + GPS	No control	No control	Real-time control

Table 2.1: Summary of the relevant flight modes

Home location is defined as the point were the motors were initially armed (the arming procedure resembles the engine startup of a conventional aircraft: the motors will not spin unless the vehicle is armed)

GUIDED The solely difference between the Auto and the Guided modes is that whereas in the Auto mode the mission needs to be completely defined and uploaded to the vehicle before it is executer, the Guided mode allows for on-the-fly control of the vehicle from the GCS, taking complete advantage of the MAVlink commands over the telemetry link. This characteristic makes it very flexible for real-time development of applications.

The relatively recent history of "small" (considered as weighting less than 25 kg) commercial UAVs implies that the technologies involved have not reached a high Technology Readiness Level (TRL) [22] until very recently, or are still under development (TRL 6-7). For that reason, most of the work considered in the present chapter is not yet ready for the market and has a great capacity to improve. Universities are actively exploring the autonomous aptitudes of UAVs, but the economical exploitation potential is still small due to the low reliability issues that these systems are encountering in non-controlled environments.

3.1 Environment sensing

Knowing the environment is the initial step towards any interaction of a system with its surroundings. That knowledge could in principle be acquired a-priori and then copied into the system, but when either time-changing or completely unknown scenarios are considered, having a means of sensing the environment is essential.

3.1.1 Radar

Radar stands for RAdio Detection And Ranging. Its usage dates back to 1904, when Hülsmeyer registered the patent for his Telemobiloscope [23], using a primitive variant of the radar for detecting metallic ships.

Nowadays, the radar works by emitting one powerful radio signal impulse against the object that needs to be located. If the signal reaches a solid object on its path, the electromagnetic wave will be distorted and part of it will be reflected back to the emission point, where a second listening antenna can detect it.

The distance of the detected object is calculated by measuring the flight time of the signal since it was emitted until it is detected, applying the signal propagation speed ($3 \cdot 10^{8} \, m/s$ for electromagnetic waves) as correction factor. The azimuth position of the object can be estimated if the initial signal was created by

a highly directional antenna, since the orientation of the transmitting antenna can be measured and the sensed object must be contained in the electromagnetic radiation field.

The fact that radar uses electromagnetic waves implies that the response time can be very high, although some technical issues may arise for the same fact at the time of processing the returned signal. For that reason, radar-based sensor systems focus on temporal processing techniques to improve the results of the measurements [24].
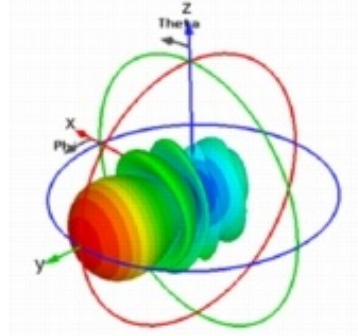

Figure 3.1: Highly directional radiation pattern. Source: `cisco.com`

3.1.2 Sonar

The ultrasonic rangefinder (commonly known as sonar, for SOund Navigation And Ranging) relies, like the radar, on the measurement of the flight time of a signal rebounding against the target. However, instead of being electromagnetic waves, the carriers are sound waves, with a frequency usually beyond the human hearing range upper threshold (hence ultrasonic).

It is important to mention that the calculation of distance from the flight time of the rebounded signal is to some degree dependent on the environment: The speed of propagation of sound depends on the temperature of the medium through which it propagates as $a = \sqrt{\gamma R_g T}$. Thus, the temperature of the air should be monitored to compensate for variations during the flight. Fortunately, the error associated with temperature changes around room temperature is of the same order than the accuracy of the sensor itself, so it is safe to consider ambient temperature at the initial calibration stage only and assume it stays constant thereafter, since it can be proven that for the measurement of distance to an object at approximately 1 metre, the error due to a temperature change of 10 K is of the order of 1 milimetre.

3.1.3 Lidar

LIght Detection and Ranging also works by measuring the time of flight of a signal. In this case, it is a visible light pulse, usually produced by a laser for its high coherence and low dispersion.

This system is convenient for ranging objects that are small or at a long distance from the sensor, but the small measuring point of the laser beam has some limitations when the mapping of a large area is required. In these situations, multiple measurements are usually performed sequentially with a rotation of the laser emitter between pulses, but the procedure significantly increases the latency of the system for obstacle detection, and also the complexity of the sensor system itself.

In summary, lidar is a good alternative for ranging, but not so much for detection.

3.1.4 Computer vision

The usage of regular cameras for physical environment sensing is certainly different than the previously considered, since it is not the flight time of a pulsated signal what encodes the information. Instead, one or more cameras provide a two-dimensional array of data each that can be processed to extract information of distance and location, among others, of any object that is within frame.

It is in that processing where both the advantages and draw backs of computer vision lie. On one hand, many different transformations can be applied to the stream of data from the cameras, and information can be extracted on very diverse aspects such as colour, luminosity, movement, position, texture. . . [2] Additionally, advanced processing techniques and even artificial intelligence can be applied to the image, which is a very flexible source of information. On the other hand though, the aforementioned processing tasks should be computed on a relatively high rate video stream, which implies several transformations on various video streams (for stereoscopic vision) with a few million pixels per image, at several frames per second. Furthermore, if obstacle detection and ranging needs to be performed, more than one viewpoint (and hence more than one camera) are required, and the matching problem of the objects seen by the two and the geometric transformations are also some quite demanding computational problems. Such a workload can only be dealt with by higher-end computer graphics cards nowadays at a reasonable rate for the effective control of a moving vehicle.
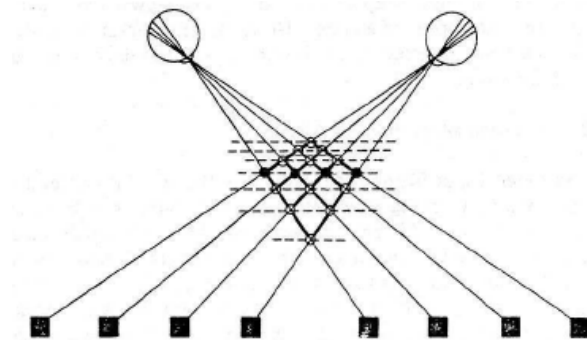

Figure 3.2: The stereo matching problem Source: [2]

3.2 Collision avoidance

The conventional sense and control problem has two very defined parts: the data acquisition stage that has been studied in Section 3.1 and the actuation of the control variables to modify the state of the system. In this section, the application alternatives of the latter in TRL 9 [22] products will be studied.

3.2.1 TCAS on conventional aircraft

The Traffic alert and Collision Avoidance System is the standard system mandated for use by commercial aircraft. It creates a virtual safety volume around the aircraft, which is based on the time to the Closest Point Approach (CPA) [25].

For the system to work, the host aircraft and the threatening aircraft must both equip an ATC transponder. If the external aircraft has only a Mode A transponder, only Traffic Advisories (TA) can be

issued by the TCAS; when it is Mode C or S, also Resolution Advisores (RA) are issued; if the external aircraft is also equipped with a TCAS II, vertical coordination between the two aircraft is additionally provided by means of an ask-answer procedure.

The system relies on two antennas that are usually placed at the top and bottom of the fuselage to provide antenna diversity. The signal carriers are 1030 MHz radio waves for the asking signal and 1090 MHz for the replying ones.

Regarding the actuation component of the system, it is fully manual. When a TA or RA are issued, the pilots are responsible to take the control of the aircraft and perform the recommended manoeuvre. Thus, the system itself cannot be considered to be the one avoiding the collision, but rather helping the higher-level aircraft + crew system accomplish it.

3.2.2 DJI Phantom 4

An Obstacle Collision Avoidance System was not available for commercial UAVs until as recent as March 2016. Chinese manufacturer DJI unveiled their Phantom 4 emphasising its "aerial camera" role for video professionals.

Their reason for including such a system is to facilitate the creative process of filming while the UAV manages the flying aspect of the mission as autonomously as possible. To that end, apart from the primary recording camera, the Phantom 4 also incorporates two smaller front-facing cameras that use stereoscopic vision algorithms to detect potential obstacles in the planned trajectory and modify it on-the-fly. In addition, it also incorporates a lower-level failsafe: when the vehicle is not able to compute a reasonable alternative trajectory before the obstacle enters within a predefined distance to the vehicle as measured by the stereoscopic cameras, the flight controller will command a full stop to stationary flight until the obstacle is manually cleared by the pilot.

Figure 3.3: DJI Phantom 4 with stereo camera OCAS

T he objectives of the project have already been stated in Section 1.5. Following those ideas, the problem that is to be answered in this thesis can be stated with the following question:

> *Is it possible to improve the operational safety of a wide range of UAVs by developing an intermediate functional layer that prevents physical collisions between the UAV and its surroundings?*

The above statement tries to condense the main idea of the thesis in a compact and precise manner. Nonetheless, some concepts within it might need some clarification:

Operational safety: A reliable collision avoidance system reduces the workload of the pilot so that higher-level tasks directly related to the mission can be performed more efficiently and safely.

Wide range of UAVs: As stated in Chapter 2 the project will focus on the widely-spread Ardupilot firmware, which is currently the leading alternative of open-source UAV controller software available.

Intermediate functional layer: The proposed solution shall be easily integrable within existing UAVs; offered as an enhancement to the toolbox of functions of the system. Thus, the solution shall incorporate additional features to the UAS, while the functions provided by Ardupilot should not be modified.

The problems is believed to be worthwhile answering since, as it was proven in the State of the Art chapter (Chap. 3), the technology is not mature and has not been implemented except on very specific products like the DJI Phantom 4.

Furthermore, a fully operable and reliable OCAS would allow for more autonomous operation of the UAV, avoiding the pilot from needing to be focused on the immediate surroundings of the vehicle, thus permitting for an improved situational awareness and leading to a better overall execution of the mission.

Ultimately, a higher safety level of general UAV operations could lead the authorities to reconsider the possibility of them flying for civil purposes with less restrictions, thus enabling companies to save vast amounts of money and manpower on the execution of activities that are currently being accomplished in a less effective way by human workers.

A s mentioned in Section 1.6, the design of the Obstacle Collision Avoidance System will follow the Systems Engineering approach. The main reason is that Systems Engineering provides some methods that prevent the errors with the highest consequences when the system to be designed is complex. As explained by Rolls-Royce Global Chief of Systems Engineering [26]:

> *Systems Engineering collects and organises all the information needed to understand the whole problem, explores it from all angles, and then finds the most appropriate system solution.*

Furthermore, A key study published through INCOSE [3] looked at the phase of detection of errors, and the consequent cost of fixing them. Cost modelling was validated against a cross-industry range of defence and aerospace projects. Figure 5.1 shows the results of the study.

Phase of error detection   **Cost to fix**

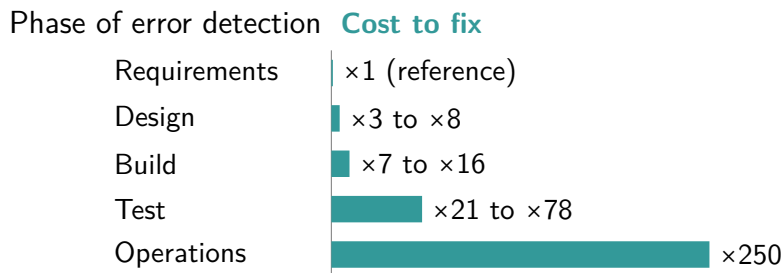| Requirements | ×1 (reference) |
Design	×3 to ×8
Build	×7 to ×16
Test	×21 to ×78
Operations	×250

Figure 5.1: Cost to fix a design error. Source: [3]

Hence, in the present chapter, some of the most relevant Systems Engineering tools from the NASA Systems Engineering Handbook [16] will be applied

5.1 Requirements capture

The design process for a system is requirement driven, since the requirements are what will define the cost, design, schedule. . . A requirement is a statement about or a characteristic of something that is needed.

Requirements can be derived from a variety of sources, like customer needs, stakeholders, regulations, procedures, constrains, etc. However, for this project, customers and stakeholders will be disregarded (since none exist) and the motivation as stated in Section 1.4 will be used instead.

In the present section some requirements will be posed, but only those that directly apply to the OCAS subsystem or its interfaces, since the platform is considered to be completely functional prior to the introduction of the solution (following the modularity concept).

Req. ID	Requirement	Traceability (sourced from)	Traceability (allocated to)
Certification			
1.1	The UAV shall meet European regulations	EC No 218/2008	
1.2	The UAV shall meet Spanish regulations	Ley 18/2014	
Architecture			
2.1	The OCAS shall work independently of the UAV	Motivation	
2.2	The OCAS shall be self-contained within the UAV	Integration	
Functionality			
3.1	The OCAS shall detect obstacles surrounding the UAV	Motivation	
3.2	The OCAS shall avoid collisions with the detected obstacles	Motivation	
3.3	The OCAS shall take control of the UAV in case of danger	Req. 3.2	
3.4	The OCAS shall not interfere with existing Ardupilot functions	Motivation	
3.5	The UAV shall maintain a communications data-link with the GCS at all time	Safety / FFBD	
Performance			
4.1	The OCAS shall detect obstacles closer than 4 m to the UAV	Technical constraint	
4.2	The OCAS shall detect obstacles of at least 0.5 m across	Technical constraint	
4.3	The OCAS shall be powered along the full mission	Safety / FFBD	
Interfaces			
5.1	The OCAS shall know the state of the UAV	FFBD	
5.2	The OCAS shall send commands to the UAV	FFBD	
5.3	The OCAS shall be accessible from the GCS	Human factors	
5.4	The OCAS shall be activated and deactivated by the pilot	Safety / Human factors	
Safety			
6.1	The OCAS shall improve the operational safety of the UAV	Motivation	
6.2	The operation of the OCAS shall not be disrupting to the workflow of the pilot	Motivation	
Reliability			

7.1	The OCAS shall avoid any physical collision	Motivation	
7.2	The OCAS shall be operative regardless of the state of the controller board	Safety	
Ergonomics and human factors			
8.1	The OCAS shall be operable after a short training by any pilot	Motivation	
8.2	The OCAS should be engaged and disengaged at discretion of the pilot	Safety / FFBD	
Loads			
9.1	The OCAS shall stand the same loads as the UAV	Integration	
Weight			
10.1	The UAV + OCAS shall not weight more than the limit of the UAV segment	Regulations	
Environment			
11.1	The OCAS shall withstand the effect of open-air flight	Integration	

Table 5.1: OCAS System-level Requirements

Notice that Table 5.1 is not static, and should be updated during the design process, since some of the tools of Systems Engineering are designed to expose missing requirements. Thus, some requirements have been written at later design stages, as the "Traceability (sourced from)" column shows. Also, the fourth column is to be completed in the subsystem design stage, when the system requirements will be allocated to one or more specific subsystems or components.

5.2   Functional Analysis

The Functional Analysis is an intermediate step between the Requirements Capture and the Design phases. Its purpose is to understand the manner in which the requirements affect the way that the system functions, for the requirements loop; and to identify a feasible solution that functions in a way that meets the requirements, for the design loop.

5.2.1   Functional Architecture

The logical decomposition performed during the functional analysis decomposes the top level requirements and allocates them down to the lowest desired levels. The main outcome of the process is the Functional Architecture (Figure 5.2), which helps establish relationships between requirements, and ultimately build a System Architecture.

The main purpose is to create an association between the requirements and the functions that the system needs to be able to perform to meet them. In the process, any discrepancy or missing items can (and should) be identified and corrected in an iterative manner.
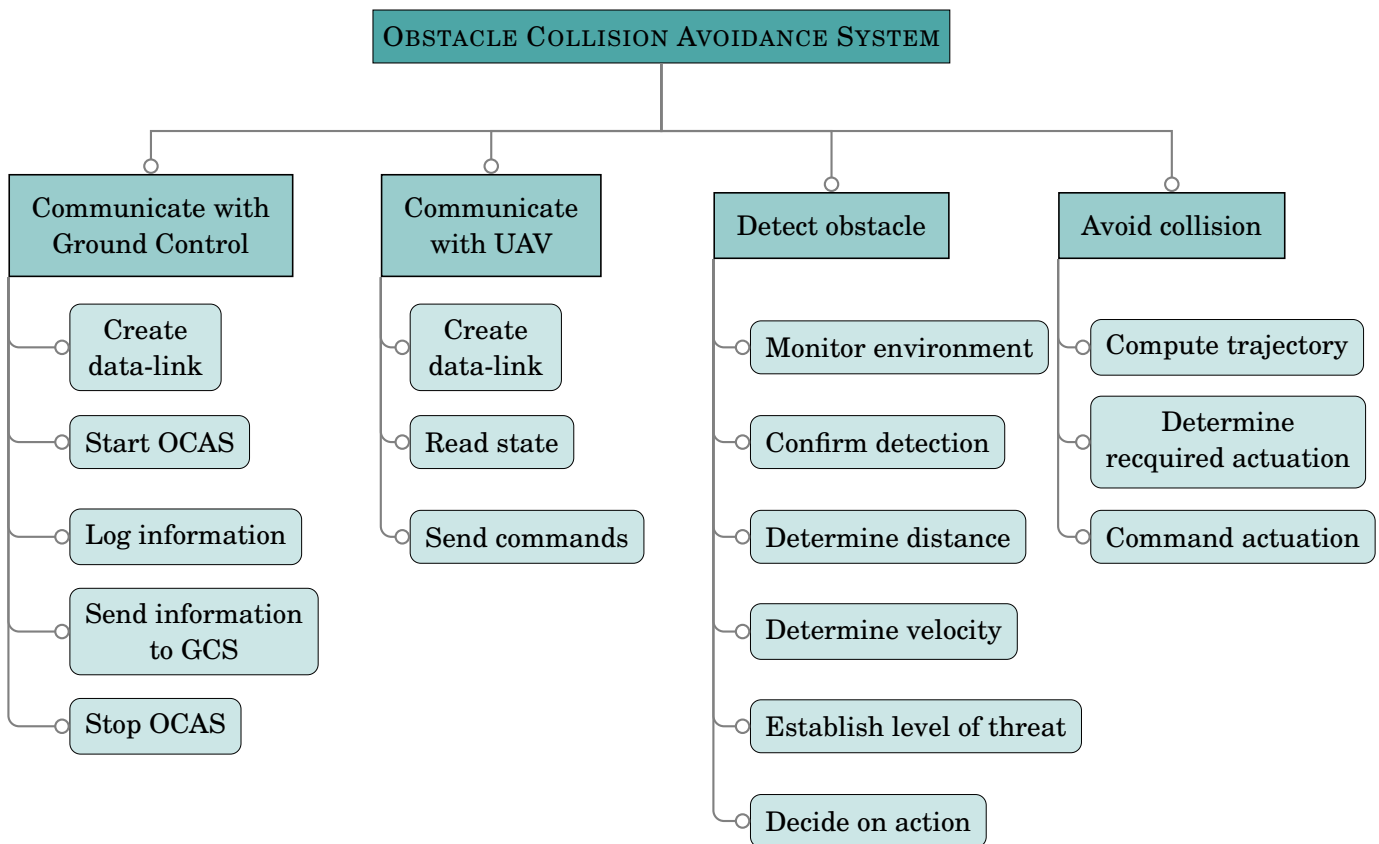
Figure 5.2: OCAS Functional Architecture

5.2.2 Functional Flow Block Diagram (FFBD)

Once the functions of the system are defined, it is useful to dispose them so that the sequential use of each of them during the mission is shown. To that end, the Functional Flow Block Diagram is used.

In the FFBD each function is represented by a block, and it is described in terms of inputs, outputs and interfaces. In the case that a function is composed of several sub-functions, those will be represented hierarchically, so that the general flow is maintained.

The FFBD shows *what* must happen, and provides an end-to-end path considering all the functionality of the system and the predefined use-case scenarios. Parallel or alternate paths might be considered.
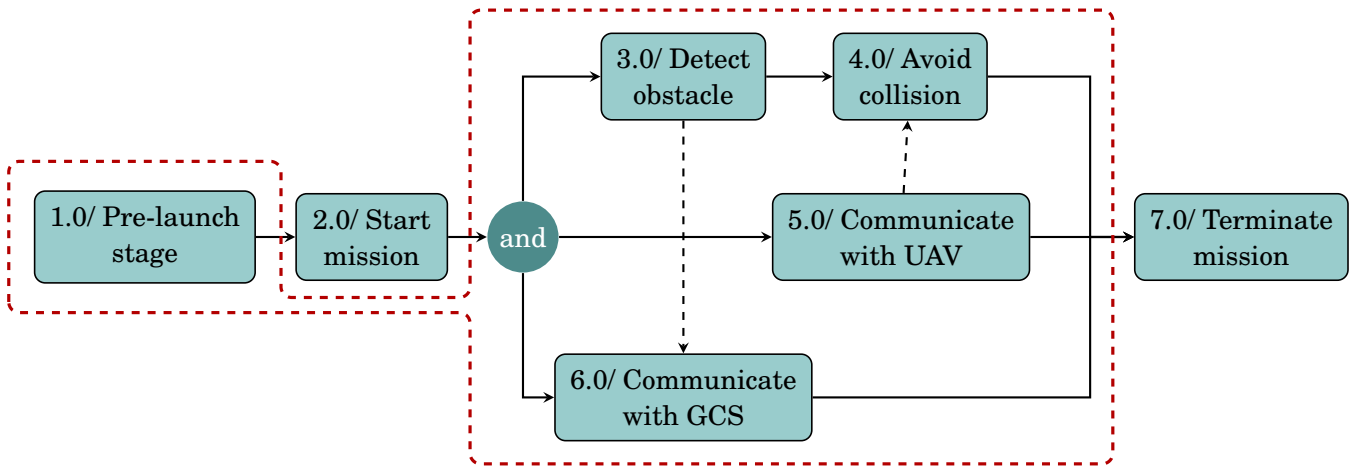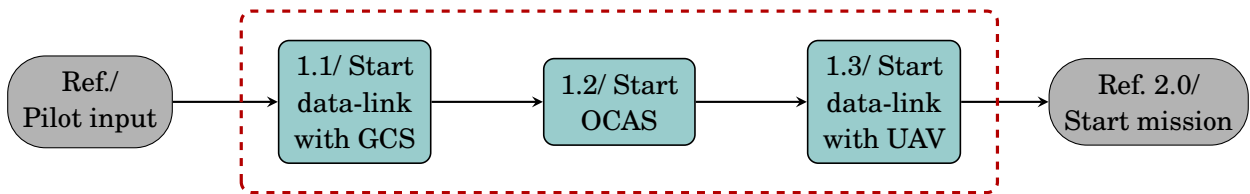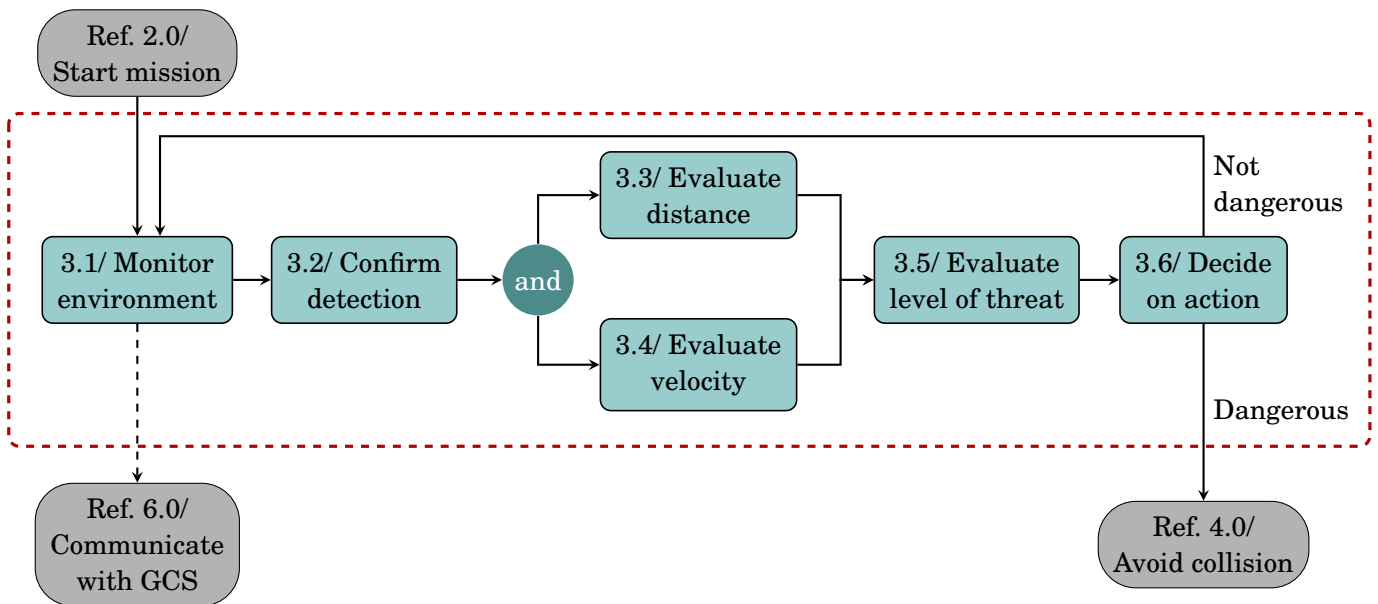
Figure 5.3: OCAS Functional Flow Block Diagram. TOP LEVEL

Figure 5.4: OCAS Functional Flow Block Diagram. 1$^{\text{st}}$ STAGE

Figure 5.5: OCAS Functional Flow Block Diagram. 3$^{\text{rd}}$ STAGE

A

APPENDIX A

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