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

Dedication and acknowledgements

Firstly, I would like to dedicate this thesis to my family, who have always supported me and are making a big effort to provide me with the best education.

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Chapter 1

Introduction

This 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" [5, 11]:

- 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. [8]

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 [9], 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 [19], distributed in the sectors shown in Figure 1.1.

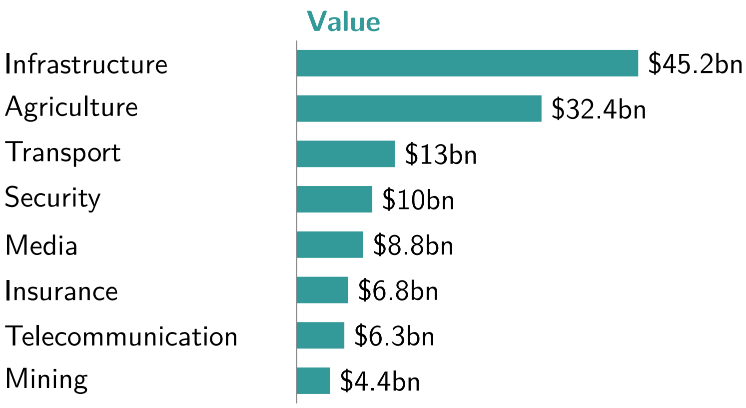

Figure 1.1: Distribution of potential UAV markets [19]

[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 [18]

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 [13]. 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 [7] 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 [12] 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

[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 [2], as well as accommodating unmanned aircraft within the Airspace System [3]. 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 [10]. 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 UAV

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 [14]. That approach will be adapted to the project, and some useful tools and concepts will be used [6], 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 [16]. 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" [1], of at least 17,038.62 € per year, with a maximum of 1800 working hours. Thus, the 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 €.

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

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. . .)

CHAPTER 2

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 [15] in the sector actively support the Dronecode Project, of which Ardupilot is part, such as Intel, Qualcomm, Parrot, 3DR, Yuneec, AUAV, Walkera... [4]

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

[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 [17]). 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

[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 5^{th} 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.

STABILIZE

ALTITUDE HOLD

LOITER

RLT

AUTO

GUIDED

CHAPTER 3

STATE OF THE ART

APPENDIX A

Begins an appendix

Bibliography

[1] *Disposición 16097 de boe núm. 274 de 2011*, 10 2011.

[2] *Civilian unmanned aerial vehicles ready for takeoff*, tech. report, 04 2012.

[3] *Unmanned aircraft systems: Perceptions and potentials*, tech. report, Arlington, 05 2013.

[4] *Dronecode*, 04 2016.

[5] U. AERIAL VEHICLE SYSTEMS ASSOCIATION APPLICATIONS, *Uas applications*, 2016.

[6] N. AERONAUTICS AND S. ADMINISTRATION, *NASA systems engineering handbook*, US National Aeronautics and Space Admin, Washington, 1 ed., 12 2007.

[7] AESA, *Ley 18/2014, de 15 de octubre, de aprobacion de medidas urgentes para el crecimiento, la competitividad y la eficiencia*, 10 2014.

[8] G. AGUADO, Á. MELGOSA, A. DE MIGUEL, Á. ORDAX, J. PERALES, J. L. SÁEZ, AND L. C. SÁNCHEZ, *Uav application in search & rescue at sea*, UC3M, 05 2016.

[9] AIRBUS, *Airbus demonstrates aircraft inspection by drone at farnborough*, 07 2016.

[10] P. BERGQVIST, *Drone jobs: What it takes to fly a uav*, 06 2014.

[11] J. DAILY, *Dull, dirty, dangerous - it's robot work*, 02 2015.

[12] EASA, *Regulation (ec) no 216/2008*, 02 2008.

[13] ICAO, *Manual on remotely piloted aircraft systems (rpas)*, 2015.

[14] INCOSE, *What is systems engineering?*

[15] D. I. INSIGHTS, *Top20 drone company ranking q2 2016*, tech. report, Hamburg, Germany, 06 2016.

[16] Á. MELGOSA, *Internship memoir: Centum solutions*, tech. report, UC3M, 05 2016.

[17] K. OGATA, *Modern Control Engineering*, Prentice Hall, 5 ed., 2010.

[18] K. P. VALAVANIS AND G. J. VACHTSEVANOS, *Handbook of Unmanned Aerial Vehicles*, Springer Reference, New York, 2015.

[19] A. WISNIEWSKI AND M. MAZUR, *Clarity from above pwc global report on the commercial applications of drone technology*, tech. report, 05 2016.