Trabajo Fin de Máster
Máster en Ingeniería Electrónica, Robótica y Automática

Aerial co-workers: a task planning approach for multi-drone teams supporting inspection operations

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El tribunal nombrado para juzgar el trabajo arriba indicado, compuesto por los siguientes profesores:

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Álvaro Calvo Matos

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Abstract

This master's thesis has addressed problems arising from the recent increase in the applications of cooperative Unmanned Aerial Vehicle (UAV) teams, which are the autonomy to operate over a long period of time with robustness to possible failures, and the difficulty of providing the team with cognitive capabilities to be able to operate in dynamic environments with humans.

Many of these applications are currently being executed by humans, making the activities much more expensive, time-consuming, and in some cases even dangerous. This is why there is currently a great deal of interest and effort being put into developing solutions to the problems posed.

The aim of the work was to develop cognitive planning techniques for coordinating fleets of quadrotors to assist human operators in inspection and maintenance tasks on high-voltage power lines. These techniques should also extend the autonomy of the system, ensure that safety requirements between drones and human workers are met, and ensure the success of the mission.

A software architecture has been proposed based on a central planner and a distributed behaviour manager. To carry out the planning, a cost has been defined, which is calculated for each task. Thus, each one is assigned to the UAV that consumes the least executing it. On the other hand, to control the behaviour of the drones and ensure the safety of the aerial equipment, a behaviour tree has been implemented.

As a result, it has been possible to develop a software architecture capable of dynamically planning missions while ensuring the safety of the equipment involved. This provides a good base that can be easily adapted and from which more complex planners can be developed in the future. Compared to the typical way of implementing behaviour managers, involving complex finite state machines that are difficult to read, reuse and extend, the use of behaviour trees is a great improvement and will allow the creation of increasingly complex behaviours.

Resumen

Este Trabajo de Fin de Máster ha afrontado problemas que surgen del reciente aumento de las aplicaciones de equipos cooperativos de UAV, los cuales son la autonomía para operar de forma prolongada en el tiempo con robustez ante posibles fallos, y la dificultad de aportar al equipo capacidades cognitivas para poder operar en entornos dinámicos con humanos.

Muchas de estas aplicaciones están siendo ejecutadas actualmente por humanos, haciendo las actividaded mucho más costosas, lentas, e incluso en algunos casos, peligrosas. Es por eso que actualmente existe un gran interés y se están destinando muchos esfuerzos para desarrollar soluciones para los problemas planteados.

El objetivo del trabajo era desarrollar técnicas cognitvas de planificación para coordinar flotas de drones que asistan a operarios humanos en tareas de inspección y mantenimiento en líneas eléctricas de alta tensión. Estas técnicas debían además extender la autonomía del sistema, garantizar que se cumplen los requisitos de seguridad entre drones y trabajadores humanos, y asegurar el éxito de la misión.

Se ha propuesto una arquitectura de software basada en un planificador central y un gestor de comportamiento distribuido. Para llevar a cabo la planificación se ha definido un coste, que es calculado para cada tarea. De esta forma, cada una se asigna al UAV al que cueste menos. Por el otro lado, para controlar el comportamiento de los drones y asegurar la seguridad de los equipos aéreos, se ha implementado un árbol de comportamiento.

Como resultado, se ha conseguido desarrollar una arquitectura de software capaz realizar la planificación de las misiones de forma dinámica asegurando mientras tanto la seguridad de los equipos involucrados. Esto constituye una buena base que se puede adaptar fácilmente y a partir de la cual se pueden desarrollar futuros planificadores más complejos. Comparado con la forma típica de implementar gestores de comportamiento, ivolucrando complejas máquinas de estados finitas difíciles de leer, reutilizar y ampliar, el uso de árboles de comportamiento supone una gran mejora y permitirá la creación de comportamientos cada vez más complejos.

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1 Introduction

The use of UAVs has grown considerably in recent years for numerous applications including real-time monitoring, search and rescue, providing wireless coverage, security and surveillance, precision agriculture, package delivery and infrastructure inspection [1]. With the rapidly developing technology in this area, and demonstrations of what UAVs can do, there are increasing efforts to bring this technology to other applications. With the expected increase in applications for this technology, new problems and challenges arise, including autonomy, safety, obstacle avoidance and coordination of multi-UAV teams. Developing the technology to solve these problems will be a major effort, but as UAVs have proven to be critical in situations where humans are at high risk or highly inefficient, and they have proven their capacity to evolve and develop even more potential in the short term, companies are investing in developing all sort of UAV-based solutions.

1.1 Motivation

With the increase in global electricity demand, a challenge has arisen for electricity supply companies to maintain and repair power grids in a way that minimizes the frequency of outages. According to [2], one of the main causes of power outages is damage to transmission lines due to bad weather or inefficient inspection campaigns.

Figure 1.1 Operators getting off the helicopter during a maintenance mission.

The strategy often used by electric companies to reduce power outages is to schedule periodic maintenance operations on active lines. This is the most suitable method if the correct functioning of the system is to be ensured and when replacing a circuit is unacceptable [2]. These maintenance missions are carried out by experienced crews on board helicopters and equipped with safety suits and harnesses among other things that prevent the operators from receiving an electric shock (see figure 1.1). The problem with this solution is that these activities are dangerous for the operators, as they are working at high altitude and on electrified lines, are extremely time-consuming and expensive ($1500 per hour) and are subject to human error [3].

These are the reasons why distribution companies have the need to develop more efficient and safer maintenance methods. Multiple solutions have been proposed to automate this task [4], but the best of them seems to be the use of UAVs because of their flexibility and ability to inspect at different levels [2]. To achieve this, there are still some important barriers to overcome, such as the limited autonomy of these devices, the strong electromagnetic interference to which they would be subjected due to being close to power lines and the ability to detect and avoid obstacles of different nature that can be found in this type of environment [3]. Providing UAVs with the cognitive capability to operate autonomously in such dynamic environments and with the presence of humans, and providing them with a rapid on-line planning method [5], is key to address these complexities and to safely and successfully accomplish the assigned mission with UAV fleets.

A versatile and reliable software architecture will be essential to integrate and interconnect all the heterogeneous components that compose these cognitive multi-UAV systems. In [6], as part of the AERIAL-CORE European project[1], a multi-layer software architecture is presented for carrying out such missions cooperatively between human operators and a fleet of quadrotors. One of the layers of software that compose it is a high-level task planner. Its function is to coordinate the entire fleet of UAVs to generate high-level behaviours in order to efficiently, safely and successfully complete the maintenance or inspection mission. This type of work has the characteristic of being dynamic, since it is not possible to know in advance what the outcome of the inspection as such will be in order to plan offline, but rather, as the mission develops, new tasks will arise that the fleet will have to attend to. Therefore, the task planner should be able to react to unexpected events (new task, failure of a UAV, loss of connection, less autonomy than calculated, etc.) and to replan online. Thus, this layer will be the main cognitive block of the system [6].

1.2 Objectives

The overall objective of this project was to develop a cognitive task planner that would be in charge of governing the behaviour of multi-UAV teams for the inspection and maintenance of power lines in a collaborative way with human operators, being one of the software layers that compose the aforementioned software architecture [6] developed for the AERIAL-CORE European project. The fleet of governed UAVs acts as an aerial co-worker and can perform various tasks such as delivering a tool to an operator, inspecting regions of the power line or monitoring a worker while operating to ensure his safety. The planner receives both high-level input and feedback from the different equipments that make up the fleet, and processes all the information to elaborate a plan to manage the UAV team or modify it in reaction to an unforeseen event. To achieve this, the following objectives were defined:

- Ensure that resources are used and tasks are executed efficiently.
- Comply with all security requirements and ensure the integrity of equipment and mission success.
- Be able to replan online to react to unforeseen events.

[1] AERIAL-CORE European project homepage: *https://aerial-core.eu/*

- Implement the software layer in Robot Operating System (ROS) and manage the necessary communications with the rest of the software layers and modules that make up the architecture.
- Carry out Software In The Loop (SITL) simulations to prove that the algorithm is able to govern the behaviour of the fleet efficiently and safely, and that it is able to react to unforeseen events dynamically, demonstrating cognitive capabilities.

2 Preliminaries

This chapter focuses on the current state of the art of those technologies related to this project, as well as on the tools used for the development of the task planner as a software layer of a multi-layer architecture. In addition, the research work carried out on the state of the art in work related to the technologies and techniques used in this project is presented.

2.1 Current technology

Although in the last decade the use of UAVs has spread to a large number of applications, the origin of this technology dates back to 1898 with the invention of radio control and the appearance of the first unmanned aircraft, baptised with the name of drone. These were not yet unmanned aerial vehicles, and were mainly used for military purposes.

Figure 2.1 General Atomics MQ-1 Predator. A Remotely Piloted Aircraft (RPA). Source: Wikipedia.

Later, with the development of technology, the first computers of sufficient size and computing power to run the software necessary to operate a UAV autonomously and even to control aircraft with more complex and even unstable dynamics (gliders [7, 8], airships [9], quadrotors [10, 11, 12, 13], multirotors [14], flapping wings [15, 16, 17], etc.) appeared. Even though computational capacity was still insufficient for some applications, the development of UAV systems was made possible by performing calculations on the ground. What was done was to run the critical and most important systems for autonomous flight on the on-board computer (controls, data acquisition, obstacle avoidance, etc.), and to run the more demanding calculations that are not necessary in real time on the ground computers [18].

Figure 2.2 GRIFFIN's flapping wing robot [17].

For an aerial vehicle to operate autonomously, it is necessary to acquire data from the environment and process it in real time. A large number of different sensor configurations as well as numerous data acquisition and processing techniques can be found in the current literature [19, 20, 21].

Once UAV technology reached sufficient capacity and autonomy, the first applications for both single [22, 23, 24] and multi-UAV [25, 26, 27] equipment began to appear. There is great interest in the latter, as they can be configured in different ways [28], collect and process data in a distributed way, increasing the computational capacity of the equipment [29, 30], and generate global collective behaviour emerging from interactions between a large number of UAVs that individually are relatively simple, known as swarming [31, 32, 33].

Current applications often require human presence to carry out certain decisions, with the human pilot overseeing that everything runs smoothly and providing the cognitive capacity to analyse the generally dynamic environment and react to unforeseen situations [34, 35, 36]. This is because providing a UAV with sufficient cognitive capacity to operate fully autonomously in dynamic environments is a very complicated task and requires a great deal of processing power. In recent years, UAV technology has evolved rapidly, benefiting from advances in computing and artificial intelligence. As processors are becoming more powerful, efficient and smaller, UAVs are becoming more and more powerful without increasing their weight or compromising their autonomy. With the increase in the number of operations per second that UAVs can perform, this opens up the possibility of using drones for previously unthinkable applications, applications that require a large amount of processing and usually have to be performed in real time [1, 37]. At the same time, advances in artificial intelligence mean that the perception, analysis and sensory fusion capabilities of UAVs are getting better and better. Advances in technology are breaking down one of the barriers preventing UAV technology from achieving this level of autonomy, and with it, more and more research effort is being devoted to breaking down the other barrier, developing software that enables UAVs to have cognitive capabilities.

Mentioning some of the research that is currently being carried out, we can recall the well-known AERIAL-CORE European project[1], in which major European robotics teams are jointly participating with the aim of developing a fully autonomous robotic system with sufficient cognitive capabilities to work together with human operators in inspection and maintenance work on electrical networks [38]. The PILOTING European project[2] aims to develop a complete inspection platform that will

[1] AERIAL-CORE European project homepage: *https://aerial-core.eu/*
[2] PILOTING European project homepage: *https://piloting-project.eu/*

provide its users with the information they need to draw up maintenance plans for structures [39]. HYFLIERS [3] is a completed European project that focused on the inspection of long pipe arrays in hard-to-reach areas. This, unlike the previous two, is not fully autonomous, but needs a pilot to indicate the inspection points along the pipes, and to supervise the aerial robot while it operates [40]. It is also worth mentioning a recent NASA (National Aeronautics and Space Administration) achievement, which is no less than the first flight of an UAV outside the Earth [41, 42]. This is specifically the Martian helicopter called Ingenuity, whose mission was simply to take off, move around and land in the Martian atmosphere with the added difficulty that, due to the distance between the two planets, this had to be done completely autonomously.

2.2 Related work

According to the literature review conducted by Hazim Shakhatreh et al. in 2019 [1], the market value of UAVs for civil infrastructure inspection is expected to be more than $45 billion, representing 45% of the total UAV market. The development of heterogeneous UAV fleets and efficient algorithms for their communication and coordination is important to have multi-UAV teams capable of carrying out a successful inspection and maintenance mission. If the inspection equipment is to be fully autonomous, so that it can be operated by personnel not specialized in the piloting of aerial vehicles, a module capable of reacting to any unforeseen event and modifying the planning in real time if necessary is required. This module, which could be called a task planner, is usually part of a larger software architecture in charge of fleet management and which tries to provide intelligence to the equipment. The task planner developed in this thesis consists of two distinct modules, the task planner itself and the behaviour manager.

2.2.1 Task planning in multi-drone teams

There are numerous proposals for solving the task planning problem, each with its strengths and weaknesses. Given the lack of a rule of when one planner or another is better, Jiang et al. [43] compared the performance of the different planners in the literature. The conclusion they reached was that Planning Domain Description Language (PDDL)-based planners are better on problems requiring long solutions, while Answer Set Programming (ASP)-based planners are less susceptible to domain object augmentation. When complex reasoning is required, ASP-based solutions can be considerably faster than PDDL-based solutions. On the other hand, in [44] they present a standardized integration of probabilistic planners in ROSPlan, which is a framework for task planning in the ROS. By integrating RDDL (Relational Dynamic Influence Diagram Language) into ROSPlan, they allow combining deterministic and probabilistic planning within the same system.

An example of probabilistic planning is presented in [45], where they use an improved multi-objective particle swarm optimization algorithm to solve the task allocation problem for multiple UAVs. The system consists of two phases with which they try to accelerate convergence and avoid the algorithm falling into local minimum. The results shown by this study reveal a good performance in solving this kind of problems. From a completely different approach, [46] proposes an intelligent task planner focused on fuzzy neural networks. This system selects the best action from a set of possible actions. Time-constrained planning is also something that has been researched, e.g. [47] incorporates time constraints into the planning of multi-agent systems. The proposed solution consists of two phases, first all execution times are pre-computed in a decentralized way and then the possible configurations are tested so that the collective execution time is guaranteed. Finally, mention can be made of [48], where the final planning is done by humans, but they have a series of control interfaces and coordination algorithms that assist them in the decision-making process and compute the shortest path for each UAV taking into account the priorities of the tasks and the

[3] HYFLIERS European project homepage: *https://www.oulu.fi/hyfliers/*

type of UAV required in each of them. The human commander can modify the plan or include constraints, such as assigning a task to a particular UAV for example, and will have to review and accept the plan suggested by the algorithm once it is finished.

The task planner proposed in this work tries to group in the same system strong points such as robustness to failures, the capacity to react and replan online in case of any unforeseen event, the incorporation of restrictions and the consideration of factors such as the type of UAV, the priorities of each task or the battery level of each equipment in an automatic way, without the need for human supervision.

2.2.2 Drone behavior management

In this work it has been called drone behaviour manager to what would commonly be controllers and safety modules executed at different times and levels. Once the aerial vehicle has concrete orders of what to do, in this case, once it has an assigned plan, it is time to execute the controls in charge of carrying out that plan. On the one hand, it will be necessary to execute some control in charge of supervising and ensuring the integrity of the airborne equipment. In [49] a Finite State Machine (FSM) is used in which one of the states is in charge of managing emergency situations, to which it transitions when another module detects and communicates the emergency condition. On the other hand, a high-level controller has to be executed in charge of calling the corresponding low-level controllers at any given moment. In this last study, they develop the complete flight control using FSM that transition from one state to another depending on the information provided by the sensors. The use of finite state machines is in fact the most common. In [50] for example, an automatic landing system programmed in this way is presented. Vitor de Araujo et al. [51] present a solution for the control of UAVs in search and rescue tasks based on a Parallel Hierarchical Finite State Machine (PHFSM) with which they claim to achieve many improvements with respect to other typical implementations.

The problem with this approach is that state machines are difficult to scale and reuse. Moreover, there comes a point where it becomes even difficult for a human to interpret. There is therefore a problem with further increasing the capabilities of UAVs using state machines. As discussed in [52], Behaviour Trees (BTs) are an alternative that provide, among other advantages, scalability, modularity and readability, and could be used for UAV mission management. [53] also emphasises the advantages of using this type of system for UAV control.

Although BTs are already widespread in the videogame industry, there are still not many proposals that use them for the management of autonomous systems. The module in charge of controlling the behaviour of each of the UAVs in this project has been developed using BTs.

2.3 Tools

2.3.1 ROS

2.3.2 Gazebo

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Glossary

ASP Answer Set Programming. 7

BT Behaviour Tree. 8

FSM Finite State Machine. 8

NASA National Aeronautics and Space Administration. 7

PDDL Planning Domain Description Language. 7

PHFSM Parallel Hierarchical Finite State Machine. 8

RDDL Relational Dynamic Influence Diagram Language. 7

ROS Robot Operating System. 3, 7

RPA Remotely Piloted Aircraft. 5, 17

SITL Software In The Loop. 3

UAV Unmanned Aerial Vehicle. III, V, 1, 2, 5–8