USING MULTIPLE UAVs FOR FILMING SPORT EVENTS

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Figure 1: Subaru Imreza WRX STi.

1 Introduction

The purpose of this assignment is to investigate the usefulness and technical feasibility of using multiple unmanned aerial vehicles (UAVs) for cinematic filming of motorsport events. The study examines whether coordinated aerial platforms can provide filming perspectives that are difficult or impossible to achieve with conventional ground-based cameras and single-drone setups, particularly in fast, dynamic environments such as rally racing.
The report is structured into multiple sections. It begins with a general overview of the current state of UAV filming in motorsports and related technological trends. The operational requirements for a multi-UAV filming system are then defined, followed by an the proposed mission concept. The regulatory framework and risk assessment methodology are subsequently analysed, with particular focus on European legislation and practical constraints for field deployment. A technical demonstration scenario is presented to illustrate the capabilities and limitations of the concept under realistic conditions. Finally, the report concludes with a discussion of future developments, including potential improvements in autonomy, safety and other future improvements.

2 Overview

2.1 Historic Background

The motorsport that will be the main focus of this paper is the FIA World Rally Championship (WRC), the most popular rally championship with cars that push the limits of innovation and define the commercial market 1.
In this race, cars consisting of a driver and a co-driver compete in every possible outdoors environment such as snow, gravel, and tarmac, in a series of races that take place all over the world.
This championship has a rich history and impact in the motorsports world because it began in 1973 and ever since then the whole industry has been greatly inspired by the competing cars driving the commercial market forwards. This presentation will focus on the Monte Carlo Rally because of its ideal-for-drone-usage geography.

2.2 Structure of the race

The Monte Carlo Rally 2024 took place in January 25-28. The choice of an already completed race was made with the purpose of having as much data as possible to reach the most logical decisions in organizing and implementing the mission. The headquarters was located in Gap, in the Provence-Alpes-Côte d'Azur region of France and consisted of

- 17 special stages.

- Total competitive (stage) distance was 324.44 km.
- Total distance including transport / liaison sections was 1,649.89 km.
- The surfaces were mixed: mainly tarmac but with snow / ice / variable conditions.
- 14 total mountain passes.

2.3 Purpose and Challenges

That said, it is only natural for the use of UAVs to be used in filming the races. The two main challenges that will be addressed are the usefulness of the filming angles by drones and their feasibility regarding operation time and environmental hazards that need to be overcome.

3 Requirements

3.1 General Equipment

The most necessary, general purpose item that will be used is a power generator for charging drone batteries and provide enough power for ground station gear. Since the operation will take place in the wilderness, but with small towns nearby, the best option will be a high capicity battery, instead of a noisy power generator. That is why a DJI Power 2000 Portable Power Station is ideal.
Moreover some camp equipment would be helpful for setting up the ground station, winter clothes, blankets and a portable radiator.

3.1.1 Transportation

Given the structure of the Monaco Cup the team will arrive on the first stage by driving a van, that will be rented from the UoB. This van will also serve as a ground station for the team members to conduct their filming. The vehicle will carry all necessary equipment, including charging stations, spare batteries, tools, and monitoring devices to ensure uninterrupted operation throughout the event. It will also provide a sheltered workspace for checking footage, planning flight paths, and coordinating with the rest of the team. This setup allows the crew to remain mobile and fully operational across all stages of the competition.

3.2 Drone Requirements

Since the operation will take place in 3 days, with a duration of 12 hours each day, with breaks included, the drones that will be used have to fill certain criteria regarding specifications and performance.
Four of the following custom builds will be examined and deployed, so that we can cover a 3 angle simultaneous filming and have a spare one as a back up:

- Type of drone: Hexacopter. It should provide resilience and stability to strong wind currents that might appear near the alpic region.
- Flight Controller: Pixhawk 4 2. A really solid, general-purpose flight controller that should not limit the operation in any way as well as keep the overall cost manageable.
- Frame Size: 800mm.
- Battery: 6S Li-Ion (9 batteries). Fits the frame, weight, and task of the drone properly. Cycling through the batteries and recharging them will be essential in capturing as much footage as possible. Average estimated flight time 18-23 minutes.
- Propellers: 15” carbon (24 for spares). The material reduces noise pollution in nearby forests and ecosystems.
- Payload: Sony a7S III (3 Cameras). It will provide 4K 120 fps footage, which will not limit the filming by any means. The camera weights at 699 g.

4 Team Requirements

In this section, the roles of the team members are addressed, in view of team members having multiple roles to save time and space. Their training and task assignment can take place during the development of the algorithms.

Figure 2: Pixhawk 4 Flight Controller.

4.1 Management and Coordination

- **Operations Manager:** In charge of supervising the mission, ensuring regulatory compliance, and coordinating other roles to successfully carry out the mission. Additionally, keeps track of time and schedules.
- **Safety Manager:** Responsible for risk assessment (SORA), safety procedures before every flight, and crisis management.
- **Flight Authorization Officer:** Responsible for approving and filing flight plans with the appropriate aviation service.

4.2 Flight Operations

- **Remote Pilot in Command:** In charge of flight safety, mission execution, and the emergency, non-autonomous part of the operation.
- **Payload Operator:** Supervises the data collection from the camera and ensures the filming part of the operation is executed flawlessly.
- **Visual Observer:** Essential to ensure the operation follows local regulations. Assists the pilot by maintaining VLOS at all times and helps with BVLOS tasks.
- **Drone Technician:** Handles pre-flight checks, calibration, and possible repairs.

4.3 Support and Logistics

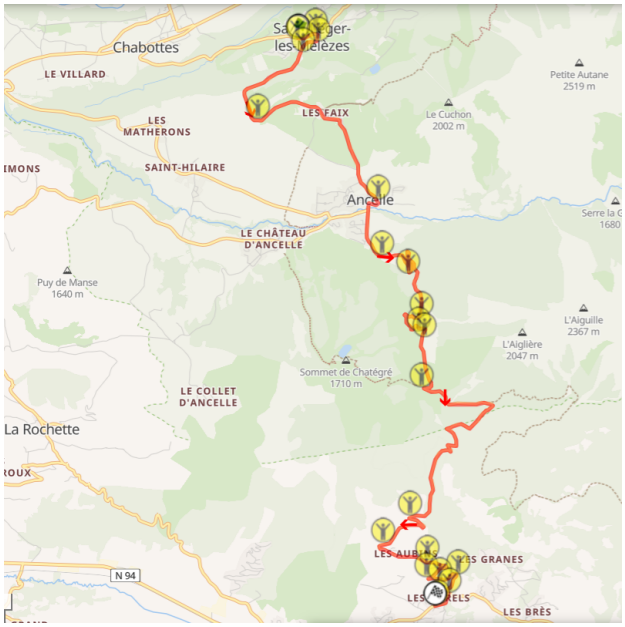
- **Ground Control Operator:** Supervises monitoring tasks and flight data.
- **Data Analyst:** Responsible for image processing and data analysis pre- and post-flight.
- **Driver:** In charge of the van, transportation of the crew and equipment, as well as storage and setup.
- **Medic:** Oversees crew's health, acts as emergency contact and provides care to everyone in need. Additionally, keeps track of nearby hospitals in case of a serious accident.
- **Security Officer:** Secures the perimeter of the ground station / take-off platform from bystanders and natural hazards.
- **Driver:** Responsible for transportation logistics, the condition of the van, and handling possible repairs.

5 Operation Overview

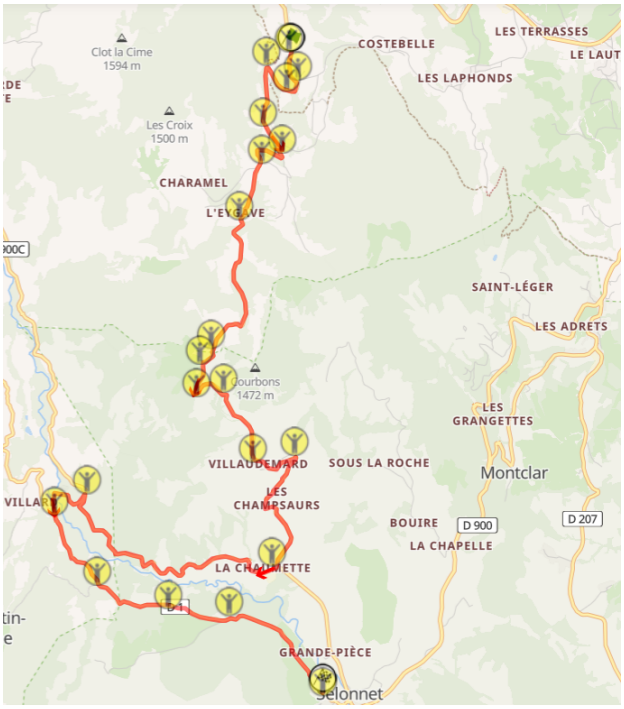
The most efficient way to execute the operation is priotitize capturing as much quality footage in as little time as possible. The table at the bottom 1 shows the race timetable, so by following it and adjusting to the needs of the mission, a useful route for the crew can be created with different locations as the ground station setting up points.
Since DAY 2 stages are going to take place after nightfall, the operation will officially begin on DAY 3, giving the team members enough time to prepare for filming, set up their equipment and rest, as the filming will take place throughout multiple days. The human factor can always affect negatively the mission, even if it is autonomous.
After carefully considering the location of the stages, the best route (for managing realistic time expectations and having the possibility of as much footage as possible), the team could come up with is as follows:

- **Day 3: 2 stages:** First one in St-L´eger-les-M´el'ezes – La Bˆatie-Neuve 1 at 08:51 and second one in St-L´eger-les-M´el'ezes – La Bˆatie-Neuve 2 at 14:56.

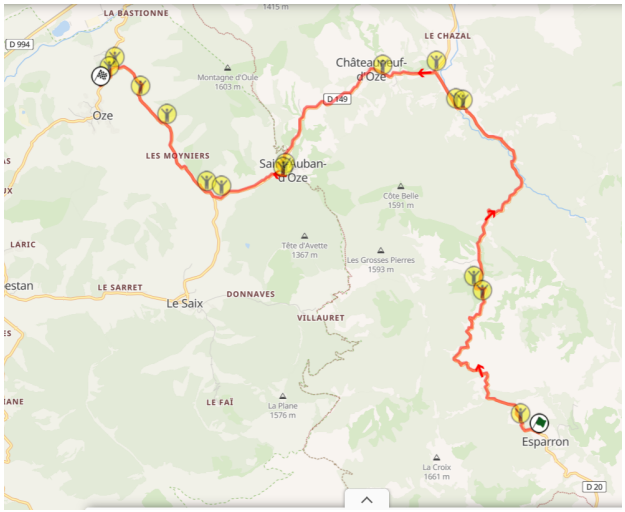
- **Day 4: 2 stages:** First one in Esparron – Oze 1 at 08:05 and second one in Esparron – Oze 2 at 14:05.
- **Day 5: 2 stages:** First one in La Br´eole – Selonnet 3 at 07:04 and second one in La Boll‘ene-V´esubie – Col de Turini at 12:15.



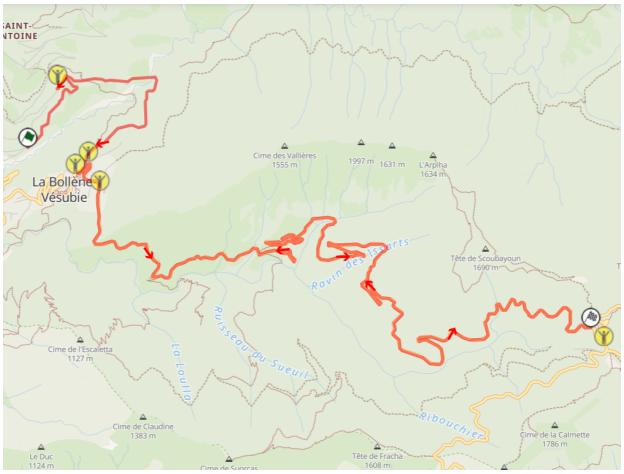
First Stage of Day 3



First Stage of Day 4



Second Stage of Day 3

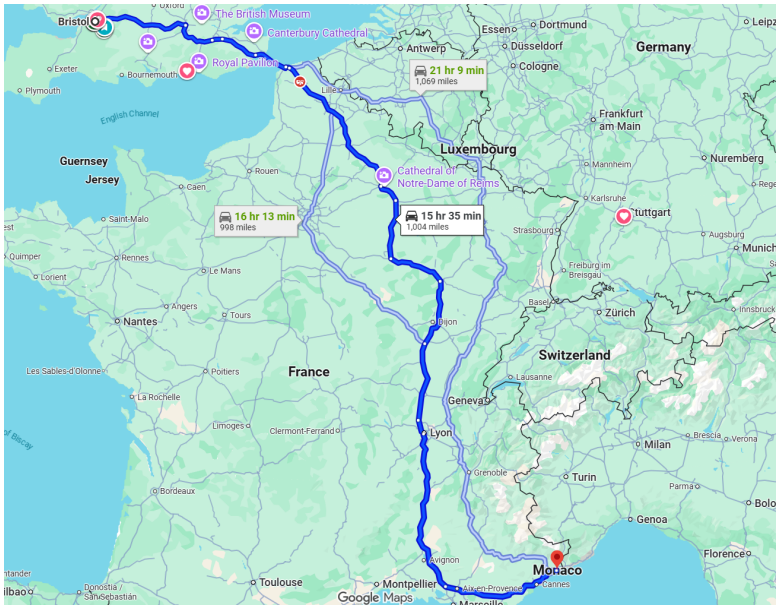


Second Stage of Day 4

Figure 3: Stages of the rally cup

The time is displayed in local time and the team should arrive one an hour before the start of the race at every filming location. That way, it is ensured that the team will have enough time to setup ground stations and move from one filming point to the next one.
Before the start of the operation though, the team has to rent a van to use both as a transportation vehicle and as a ground station. Renting one from the starting point, UoB, and loading it with the essential equipment is the best way to ensure safety with reduced cost.
The time spent on road will be significant: 16 hour drive from Bristol to Monaco 4 and more around the stages. Regular stops and enough consumable supplies will help the crew to be well rested, as well as resting the first 2 days of the rally cup.

Route for DAY 5 transportation



Bristol to Monaco Route

Figure 4: Routes

6 Required Regulatory Compliance

The planned filming operations will take place across both French and Monegasque territories. As such, the mission must comply with both national and European Union regulations governing the use of Unmanned Aircraft Systems (UAS).

6.1 Relevant Authorities

The main authorities which are involved in such matters are:

- **ACM (Automobile Club de Monaco):** Organizer of the Monte Carlo Rally; responsible for granting media and on-site filming access.
- **DGAC / AlphaTango (France):** The French Civil Aviation Authority overseeing UAS registration, licensing, and operational authorizations.
- **Local Préfecture / Gendarmerie:** Regional security and administrative bodies responsible for flight permissions and airspace safety.
- **Event Safety Officer / Media Manager (ACM):** Coordinates ground and air access for filming teams during the event.

Table 1: 2024 Monte Carlo Rally Stages Overview

Day & Date	SS	Stage Name	Dist. (km)	Time (CET)
24 Jan (Day 1)	Shake	Shakedown – Gap	3.28	16:31
25 Jan (Day 2)	1	Thoard – Saint-Geniez	21.01	20:35
	2	Bayons – Bréziers	25.19	21:58
26 Jan (Day 3)	3	St-Léger-les-Mélèzes – La Bâtie-Neuve 1	16.68	08:51
	4	Champcella – Saint-Clément 1	17.87	10:24
	5	La Bréole – Selonnet 1	18.31	11:57
	6	St-Léger-les-Mélèzes – La Bâtie-Neuve 2	16.68	14:56
	7	Champcella – Saint-Clément 2	17.87	16:29
	8	La Bréole – Selonnet 2	18.31	18:02
27 Jan (Day 4)	9	Esparron – Oze 1	18.79	08:05
	10	Les Nonières – Chichilianne 1	20.04	09:53
	11	Pellafol – Agnières-en-Dévoluy 1	21.37	11:06
	12	Esparron – Oze 2	18.79	14:05
	13	Les Nonières – Chichilianne 2	20.04	15:53
	14	Pellafol – Agnières-en-Dévoluy 2	21.37	17:06
28 Jan (Day 5)	15	La Bréole – Selonnet 3	18.31	07:04
	16	Digne-les-Bains – Chaudon-Norante	19.01	08:35
	17	La Bollène-Vésubie – Col de Turini	14.80	12:15

6.2 Applicable Frameworks

Since the operation involves professional aerial filming in European territory, the **EASA (European Union Aviation Safety Agency)** regulations apply. Specifically:

- **EU Regulation 2019/947** – Rules and procedures for UAS operations.
- **EU Regulation 2019/945** – Requirements for UAS and third-country operators [6].

6.3 Operational Category

Based on the project's profile (multi-drone, professional filming, planned autonomous flights near people and vehicles), the operation is classified under the **Specific Category (Article 5 of EU 2019/947)** [5]. A risk assessment according to the **SORA (Specific Operations Risk Assessment)** methodology must be conducted and submitted to DGAC prior to operation [8].

6.4 Drone Registration and Pilot Certification

- All used drones that weigh more than 0,25 kg must be registered on **AlphaTango** and carry identification markings [4].
- Pilots must hold the **EU Remote Pilot Certificate for the Open A2 Category** at minimum, or an authorization for Specific Category flights if autonomy and complex operations are involved.
- There is a minimum pilot age of **16 years**, which will not be of importance since none of the crew members will be underaged.

6.5 Safety and Operational Restrictions

- **Minimum separation distances:** A lateral safety distance ≥ 50 **meters** must be maintained from spectators (something they rarely do), rally vehicles, and non-involved personnel, as recommended under DGAC's [4] *Scénarios*

Nationaux (S-3 operations). Vertical distance from people shall not be less than **30 meters**, unless specific authorization is granted.

- **Visual line-of-sight (VLOS):** At least one remote pilot or observer must maintain uninterrupted visual contact with each drone throughout the mission. For coordinated multi-drone operations, **Extended Visual Line of Sight (EVLOS)** may be used, provided each drone remains within the visual range of a designated observer and continuous telemetry is available.
- **Safety systems:** Automatic **Return-to-Home (RTH)** and **geo-fencing** functions must be active during all missions.
- **Weather and terrain constraints:** Operations shall only be conducted under suitable meteorological conditions—maximum wind speed below **8–10 m/s**, no precipitation, and adequate visibility (minimum 1.5 km). Terrain elevation profiles and stage altitude differences must be pre-loaded into the mission planner to ensure safe altitude margins.
- **Operational timing:** Flights must be scheduled outside active rally passage times to avoid interference with competitors and safety crews. Coordination with local authorities or race organizers is required to confirm safe operational windows.

6.6 Data Protection:

A filming operation is not possible to take place without the necessary Data Protection protocols. More specifically, in the EU countries the General Data Protection Regulation (GDPR) is applied, thus there are certain conditions that the captured footage should meet:

- The footage is used for journalistic, artistic or educational purposes and not for commercial use, unless consent is obtained from the event participants, through the organizer [1].
- The footage is not focusing on any specific identifiable individual unless they actively participate in the race.
- Lastly, the crew is should be granted event filming permission through ACM and DGAC. The process requires submitting list of filming locations and altitudes, UAV type and Data handling procedures.

If the drones do record identifiable footage the University of Bristol's ethics and data protection office can serve as a Data Controller, responsible for keeping the data encrypted and safe and retain it only as long as necessary.

6.7 Regulatory Summary

The figure 5 summarizes the European drone classification system and pilot qualification requirements according to the European Union Aviation Safety Agency (EASA).
As such, the proposed drone falls into the A2 category, due to it's weight and filming application on the field.

7 Risk Assessment

The deployment of autonomous aerial filming operations within a large-scale international motorsport event introduces a series of risks that must be identified, evaluated, and mitigated in advance. The goal of this section is to ensure that the majority if not all operational, health and safety, and environmental hazards are systematically assessed before the field deployment, enabling the crew to make decisions under realistic constraints. To maintain a structured and transparent methodology, the Failure Mode and Effects Analysis (FMEA) framework is applied across all risk domains, allowing for relatively measurable evaluation through severity, occurrence, and resulting Risk Priority Number (RPN).

7.1 Programmatic Risk

Programmatic risks are meant to describe factors that can influence the successful execution of the mission plan and the overall autonomy of the system. These risks directly affect not only the quality of footage collection, but he the level of manual intervention required as well. While the autonomous system is designed to handle unpredictable conditions, the operational environment of the Rally Monte-Carlo includes factors such as mountainous terrain, large crowds, restricted airspace, and rapid changes in weather, which can degrade the performance of perception and control pipelines, no matter how much the environment is hard coded. The table below summarizes the key programmatic risks, their impacts on the mission, and proposed mitigation strategies.

In practice, the programmatic risks are largely controlled through planning ahead of the event, route/ weather forecasting, and on-site decision rules. Since the filming strategy relies partially on autonomous waypoint navigation and

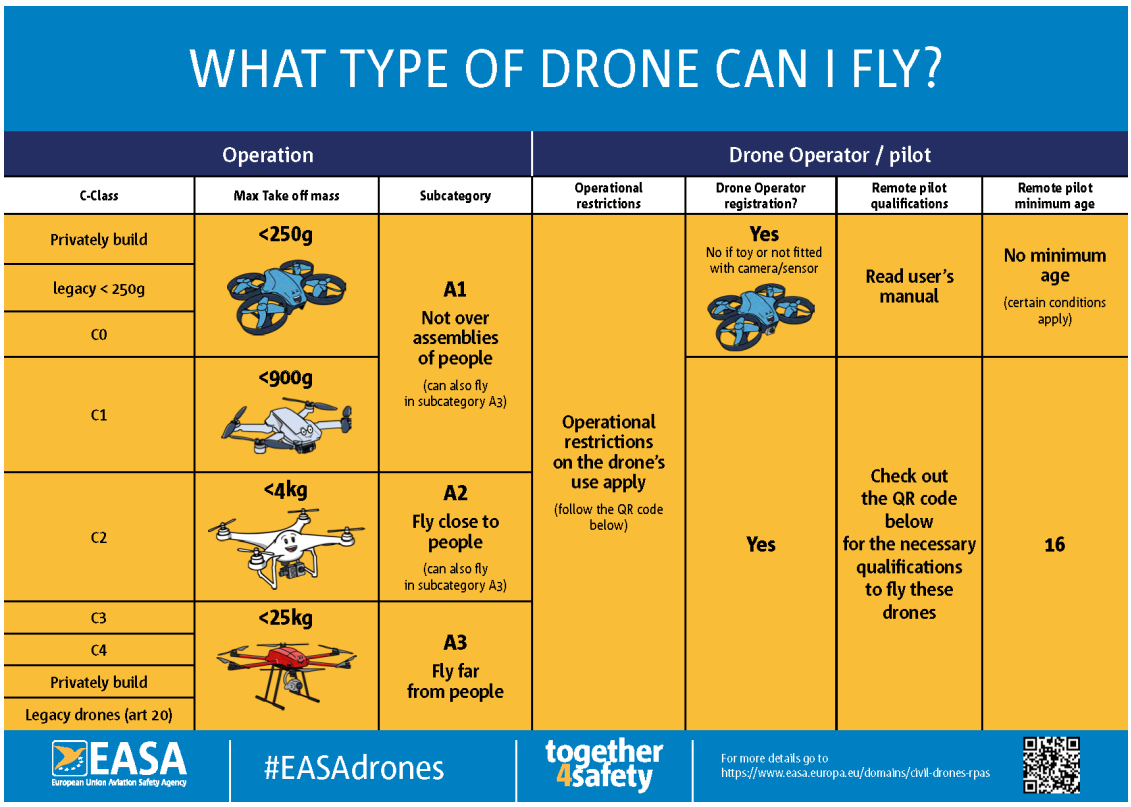


Figure 5: EASA classification of drone categories and pilot requirements.

Table 2: Operational Risk Assessment (FMEA Framework)

Risk	Consequence	S	O	RPN	Mitigation Actions
Adverse Weather	Reduced visibility, unstable flight	8	4	32	Monitor weather forecasts and avoid flights during high wind or rain. Schedule flights in stable daylight conditions.
Transportation Difficulties	Delays in setting up flights, decrease in footage quantity	6	3	18	Check traffic, schedule routes, start early.
Communication Degradation	Reduced autonomy and precision, use of manual flights	7	2	14	Find appropriate locations with strong satellite signal.
UAV Hardware or Payload Failure	Time consuming repair / replacement	4	3	12	Follow necessary safety procedures.
Airspace Intrusion by Unauthorized UAV	Potential disruption or safety hazard due to hobbyist or unauthorized flight	3	2	6	Notify event airspace coordinator and local authorities; temporarily suspend flights until area is secured.

perception-based tracking (car tracking), unexpected disturbances, particularly those affecting localization (GPS degradation) or perception degrading conditions (snow, fog), can reduce autonomy and require manual flight control. This is why the manual pilots role is crucial, as the early arrival, redundant weather checks and test flights are scheduled into the project timeline. These actions reduce the randomness factor and help ensure the highest consistency in data collection across the multiple stages of the rally.

Beyond mission completion, it is essential to keep the health and safety of the flight crew and the public intact during all phases of operation, including long-distance travel, setup and live flight. The presence of fast/unpredictable vehicles, remote mountain segments, and unpredictable spectator behavior creates a complex safety environment in which the drone team must operate responsibly. The FMEA approach is again applied to quantify potential hazards and define concrete mitigation procedures that can be followed in real time.

7.2 Health and Safety Risk

Table 3: Health & Safety Risk Assessment (FMEA)

Risk	Consequence	S	O	RPN	Mitigation Actions
Transportation Safety	Vehicle crash, breakdown, leading leading to crew injury	5	1	5	Driver pre-checks, purchase highest insurance for the van, route slack, spare tire.
Crew Fatigue & Health	Reduced performance, higher error rate, increased accident risk	2	4	8	Enforce shift limits, mandated rest breaks, invest in supplies / hydration, rotate roles, emergency contact / nearest hospital list.
Public / Bystander Behaviour Hazards	Spectators interfering with takeoff/landing, unpredictable actions causing safety incidents	4	4	16	Install signaling protective barriers (tape), Safety Marshall, contact ACM for announcements / audible warnings.
Interference with Competitors	Distraction or physical interference with rally vehicles leading to safety incidents	6	1	6	Thoroughly flight checks and simulations in preparation phase, coordinate with Event Safety Officer, geofences, minimum lateral offsets (e.g., $\geq$50 m), immediate suspend procedure.

While many of the identified risks are unlikely, they carry potentially severe consequences. The presence of large crowds means bystander behavior is one of the most unpredictable elements of the operation, and therefore receives the highest RPN. Preventive communication with event organizers and physical safety barriers are used to minimize this uncertainty. In addition, the long road transport required to reach Monaco poses logistical and fatigue risks that are independent of the flight activity but still affect overall operational readiness. By promoting structured rest cycles, pre-flight medical checks, and clear emergency plans, the team ensures a professional and safe deployment environment.

7.3 Environmental Risk Assessment

7.3.1 Weather Modeling

Mountain weather introduces rapid transitions in wind, precipitation, and visibility that can influence drone stability and perception systems. This makes local micro-climate modeling a critical part of the environmental analysis. Old weather data collections, altitude-dependent temperature gradients and wind pattern simulations are used to determine safe time windows for autonomous flight. In combination with live sensor inputs, this helps the system adjust to dynamic atmospheric conditions.

7.3.2 GPS Reliability in the mountains

Reliable localization is a core requirement for autonomous tracking of fast-moving targets. Mountainous terrain and forested areas can reduce satellite visibility 6, causing intermittent GNSS dropouts or multipath effects. This deviation affects both global waypoint navigation and onboard state estimation. The risk is mitigated through fused navigation systems combining GNSS, IMU data, visual odometry, and real-time map alignment to improve robustness under partial signal loss.

7.3.3 Sound Pollution

Being part of the EU results in taking action against wildlife disturbance and noise pollution. Consequently, conducting an electroacoustic test is necessary before any further progression.
After thorough investigation, the conclusion is that comparing the noise produced by both the competing cars and the deployed drones is vital in finding out the environmental effects. Specifically, rally cars of WRC/Rally 1 category, usually produce sound waves of pressure levels of up to 110-120 dB(A) when measured from a close distance [7], whereas the hexacopters are around 70-95 db(A), which is a lot less given the logarithmic measuring scale [10]. The only worrying thing is that of being exposed to high frequency sounds produced by drones, which can result in migraine and minor health

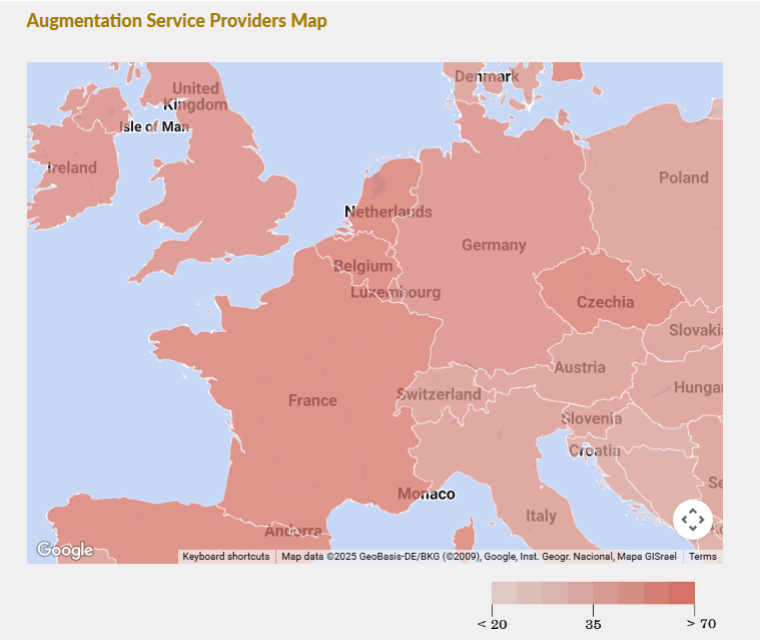


Figure 6: Augmentation Service Providers Map.

issues, which also is something subjective and not of great importance since the operation will not last for long periods of time.

8 Cost Analysis

The total cost of the mission includes all expenses related to preparation, deployment, and support throughout the Monaco Cup.

- **Transportation Costs:** Covers rental of the UoB van, fuel, tolls, and parking fees. The van also serves as the mobile ground station during operations.
- **Drone and Equipment Costs:** Includes the primary UAVs, backup components, batteries, chargers, sensors, safety gear and any required repairs or replacements.
- **Software and Algorithm Development:** Covers computational resources, software licenses, simulation tools, and time allocated to algorithm development, testing, and optimisation.
- **Personnel Costs:** Includes travel, accommodation, daily allowances, and preparation work performed by all team members.
- **Administrative Costs**Covers insurance, registration fees, communication costs, and logistical materials.

The total budget is estimated as:

$$\text{Total Mission Cost} = C_{\text{transportation}} + C_{\text{equipment}} + C_{\text{software}} + C_{\text{personnel}} + C_{\text{misc}}.$$

Which by rough estimations would come close to 80.000£.

9 Supportive Path Planning Algorithms

9.1 Algorithm Presentation

This section is devoted to present an overview of an ideal algorithm that is probably too ambitious to become real, but for the sake of this assignment it will be presented as an actual feasible algorithm.
The one thing that is certain however, is the limitations under which the drone has to operate. Limitations that derive from the legislation protocols of all combined authorities, which have been addressed in previous sections.
As such, the demonstration is constrained by the technical requirements defined for C2-class unmanned aircraft operating in the A2 subcategory under Regulation (EU) 2019/947. The drone has a calculated mass of under 4 kg, including the

gimbal, camera payload, and battery.
According to A2 regulations, the aircraft must maintain a minimum horizontal safety distance of 30 m from uninvolved people during normal operation (tracking mode), reduced to 5 m only in low-speed operation (stand-by mode), with a speed of less than 3 m/s, with active mitigation systems such as geofencing and obstacle sensing.
The maximum permitted altitude for the mission is 120 m AGL, and during the demonstration flights the drone will follow a path between 35–50 m AGL, ensuring safe separation from spectators and avoiding ground effect turbulence at very low altitude.
The nominal cruise speed during the tracking phase is limited between 10 to 15 m/s (36–54 km/h) to remain within the sensor-stabilization envelope of the gimbal and to maintain GPS accuracy while following the moving vehicle.
The aircraft endurance is 18–22 min per battery pack, depending on wind conditions (usually ¡8 m/s headwind) and tracking acceleration, with an average current draw of 12–15 A at 22.2 V nominal battery voltage (6S Li-ion) 10.
The payload mass is limited to ¡600 g, including a camera drawing 6–8 W and recording data at 4K/1200fps, to avoid exceeding the thrust-to-weight ratio required for rapid climb maneuvers (¿2:1).
Positioning and geofencing rely on multi-constellation GNSS (GPS/GLONASS/Galileo), with a nominal horizontal RMS error of ±1.2 m and vertical error of ±1.5 m, requiring a minimum satellite visibility of more than 11 satellites for stable tracking, something that is provided at the specific locations 6.
These technical limitations define the safe operating envelope of the demonstration and require careful planning of the flight trajectory, timing and battery management to maintain compliance throughout all stages of the mission. The table below **??** and the flow chart 7 summarizes everything.

Table 4: Operational Constraints and Technical Parameters of the Demonstration

Parameter	**Value / Requirement**
Regulatory Class	C2 UAS, A2 subcategory (EU 2019/947)
Maximum Take-Off Mass	< 4 kg (including payload and battery)
Safety Distance (Normal Operation)	≥ 30 m from uninvolved people
Safety Distance (Low-Speed Mode)	≥ 5 m at $v \leq 3$ m/s
Operational Altitude Limit	≤ 120 m AGL
Flight Altitude During Demo	35–50 m AGL
Cruise Velocity (Tracking Phase)	10–15 m/s (36–54 km/h)
Battery Endurance	18–22 min per battery
Nominal Battery Voltage	22.2 V (6S Li-ion)
Average Current Draw	12–15 A
Payload Mass Limit	< 600 g (camera + gimbal)
Camera Power Consumption	6–8 W
Recording Specifications	4K / 1200 fps
Required Thrust-to-Weight Ratio	> 2:1 for rapid climb
Minimum Satellite Visibility	≥ 11 satellites
Wind Conditions (Expected)	< 8 m/s headwind

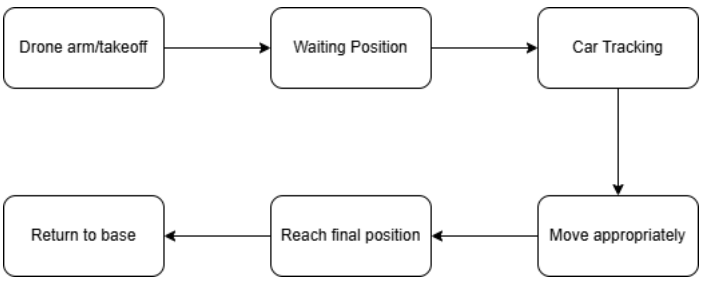


Figure 7: Basic Flow Chart of the Algorithm.

As discussed above, there will be no significant changes details about the vision or the control system, only the logistics of their development.

9.2 Desired Angles

This is the part where things will become slightly more subjective[9], due to the nature of cinematography. After carefully researching the field and considering the limitations[3], three simple filming angles were chosen.

- **Front Angle:** A drone is placed in front of the car's path, waiting for the car to appear from the horizon. Acts as the coordinator by notifying the rest of the drones to be prepared to move/capture footage, since it has the best spotting position, as shown from the second image in the figure 9.
- **Side Angle:** The drone is placed at the outside of the turn to have a clear path, with no risk of ground collision, capturing a more of a dramatic angle as shown in the bottom left image of the figure 9.
- **Back Angle:** The drone is placed at the back of the car's path, to follow it from behind capturing footage that shows the high speed moving car as in bottom right of figure 9.

9.3 Developing and Testing

The development and validation of the autonomous tracking system are planned over a period of approximately 9–12 months, progressing through simulation, laboratory testing in the universities flight lab, controlled flight trials in University authorized space in the UK and final demonstration phases.
The initial simulation and algorithm design phase requires around 6–8 weeks, during which the perception, planning, and control modules are developed and tested on virtual data and recorded flight logs. This is followed by Flight Lab integration and bench testing for approximately 4–6 weeks, where the navigation software, gimbal tracking logic, and safety failsafes are validated under hardware-in-the-loop (HIL) conditions. The next phase, consisting of controlled field experiments in the UK, spans 6–8 weeks and includes step-by-step validation, starting from waypoint navigation, followed by vehicle tracking at low speed, and finally full autonomous pursuit under the supervision of the remote pilot.
Once the autonomous performance meets the minimum expected reliability thresholds, the system undergoes a 2–3 week preparation and certification process for the demonstration in Monaco, including local GNSS mapping, flight plan adjustments, and regulatory documentation.
By the end of the development the team members will have enough time to build coordination, trust and familiarize with one another. From initial simulation to real-world demonstration, the development pathway is expected to take approximately 9–12 months, with each phase providing incremental safety validation before the system is deployed in a live rally environment.

10 Demonstration

10.1 Unity Simulation

To show an early stage of the behaviour of multi-UAV filming and experiment with different viewpoints, a custom simulation environment was developed in Unity. The basic flow of the simulation is shown in Figure 8, where the car motion, drone behaviour, and camera positioning logic are executed in real time.

It illustrates the main interaction between the virtual car, the UAV navigation model, and the camera system. The car follows a predefined trajectory, while the drone continuously adjusts its position and orientation to match the motion of the target. The simulation gives the user the opportunity to switch camera angles through all three of the drones and a static camera by pressing the "C" key.

To analyse the quality of the captured footage, multiple camera angles were implemented inside Unity, including static, front-facing, side-following, and rear-tracking perspectives. The results are shown in Figure 9, where each sub-image represents the output from a different virtual camera setup. By observing these viewpoints, a comparison of coverage, stability, and visual quality can be performed without deploying a physical UAV.

A video of the active tracking part of the mission is demonstrated in Unity Game Engine simulation, which can be found here: https://youtu.be/iq9$_Ogw9SmI$.

Due to Copyright reasons, the appearance of the simulation was minimalistic, with a few textures of the objects like the car missing. Another reason was that the assignment insisted on having a simplistic demonstration part as well.

10.2 Battery Performance

The following plots show a simplified simulation of battery discharge in two operational modes: Waiting Mode (stand-by, ¡3 m/s, minimal thrust demand) and Tracking Mode (active tracking, 10–15 m/s cruise, active gimbal stabilization) [11]. The simulation uses the measured power draw of a 6S Li-ion battery configuration (22.2 V nominal) under representative current consumption profiles obtained from typical UAV motor efficiency curves [2], payload consumption (6–8 W camera), and gimbal stabilization energy. The graphs were generated by simulating a model that by applying a piecewise discharge model, integrates current draw over time, making a lot of assumptions regarding constant environmental conditions and no regenerative braking effects during deceleration.

In the battery over time consumptions figure 10 on the top left plot demonstrates the discharge profile in Waiting Mode, where the aircraft remains airborne in a low-thrust state, holding position using GNSS positioning and obstacle-avoidance

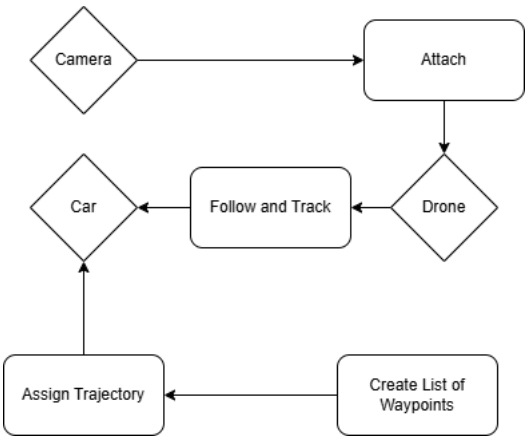
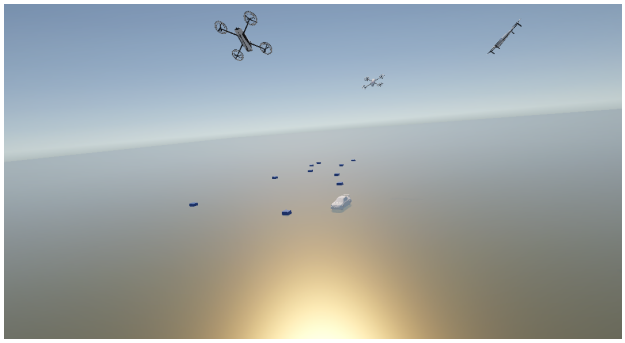
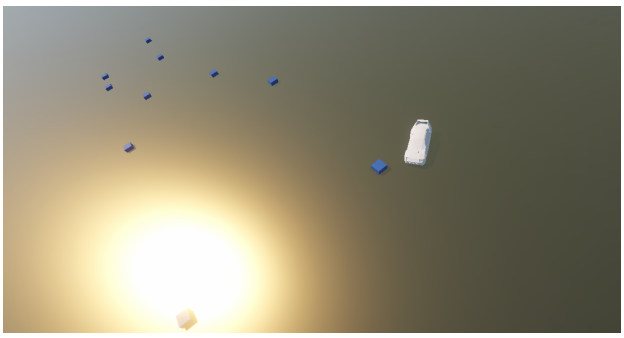


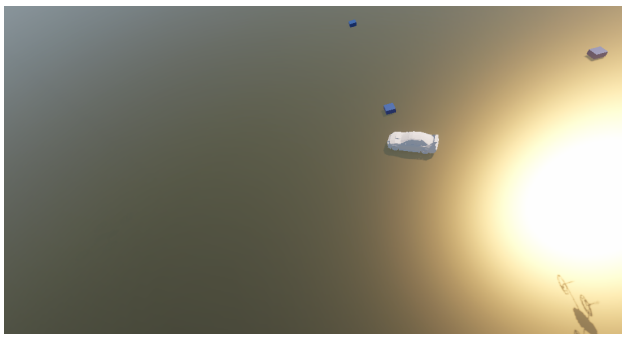
Figure 8: Basic Flow Chart of Simulation.



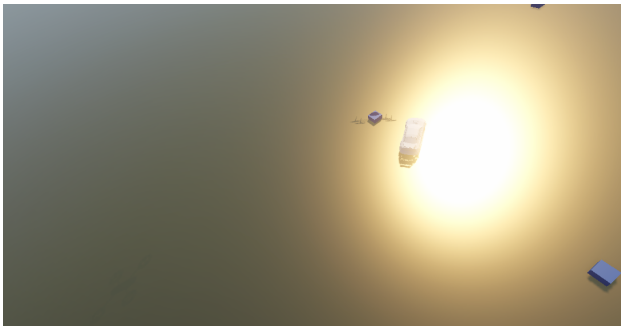
Static Camera Angle



Front Camera Angle



Side Camera Angle



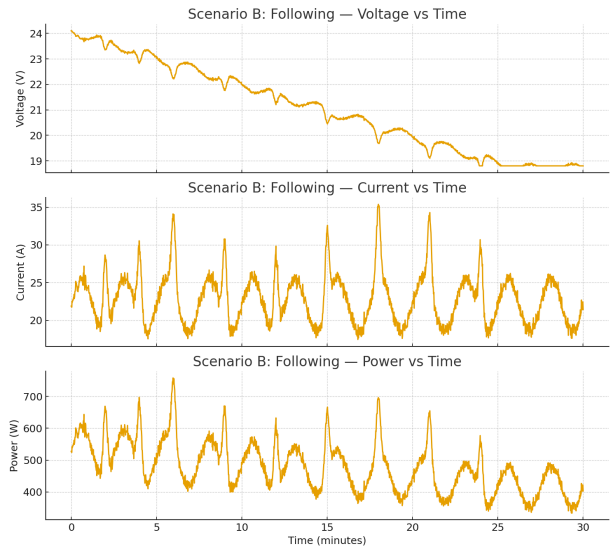
Back Camera Angle

Figure 9: Different Angles of Simulation

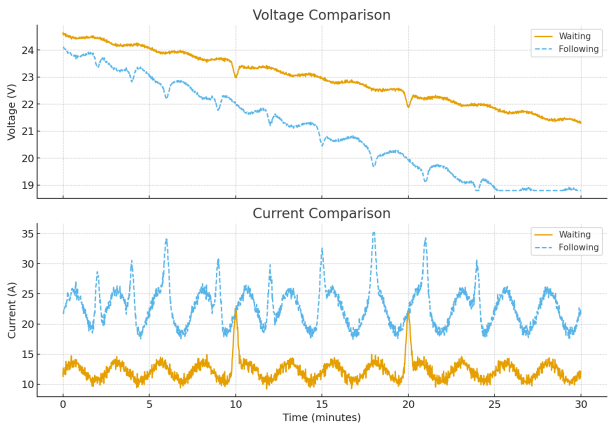
sensors. The consumption rate is low and almost linear due to stable hover with minimal accelerations. The top right plot represents the Following Mode, where thrust spikes and dynamic attitude corrections result in a significantly steeper discharge curve. Lastly, the bottom plot directly compares both modes, clearly showing the difference in endurance and highlighting the sensitivity of battery life to acceleration and velocity changes.

In the context of a WRC filming scenario, the operational profile of each drone consists of short bursts of activity: approximately 5–10 seconds of active filming, followed by landing and battery-saving stand-by while waiting for the next competitor. Given that rally cars pass at intervals of around 3 minutes, the drone is not required to remain airborne continuously. A proposed solution to that problem instead, would be that a pulse-style operation is used, as shown in 7: Starting with take-off, reach waiting position, then track, reach final position, then return to base and wait for manual command. This makes battery endurance far less critical than in continuous-flight missions and ensures that a single battery pack can support multiple vehicle passes, providing enough time airborne to capture footage. By skipping a car, the crew can have enough time to even replace a battery.

Waiting Mode



Following Mode



Comparisson of two modes

Figure 10: Battery over time consumption

11 Future Developments

The state of this system is at an early prototype stage, at best. So in this section some future developments or possible Improvements will be addressed. Because the system currently relies on manual oversight, the starting point would be to integrate a fully autonomous perception–planning–control pipeline capable of selecting optimal camera angles in real time. Path planning would greatly improve after this change.
Next, advancing in battery simulation is of great importance and will help define the feasibility of the operation, as well as be able to plan more accurately the behaviour of the drones.
Most importantly however, the focus should greatly shift to the development of the computer vision algorithms. Due to their complexity, none were mentioned in this report. This is not realistic because the drone depends on them for tracking the object and moving accordingly to maintain the filming angle.
Lastly, after proving that the system is reliable, the next step of expansion should be, in collaboration with the authorities, to provide more autonomy to the system and have the drones follow the cars for more than one turn.

References

[1] (2016). Regulation (eu) 2016/679 of the european parliament and of the council on the protection of natural persons with regard to the processing of personal data and on the free movement of such data (general data protection regulation). `https://eur-lex.europa.eu/eli/reg/2016/679/oj`. Accessed: 2025-02-18.

[2] Beigi, P., Rajabi, M. S., and Aghakhani, S. (2022). An overview of drone energy consumption factors and models. In *Handbook of Smart Energy Systems*. Springer, Cham.

[3] Bonatti, R. et al. (2020). Towards a robust aerial cinematography platform: Localizing and tracking moving targets in unstructured environments. In *2020 IEEE International Conference on Robotics and Automation (ICRA)*, pages 1–8.

[4] Direction Générale de l'Aviation Civile (DGAC) (2024). Opérations spécifiques et scénarios standards pour drones professionnels. Official French Civil Aviation Authority (Alphatango) guidance on UAS operations.

[5] European Union Aviation Safety Agency (EASA) (2019). Commission implementing regulation (eu) 2019/947 of 24 may 2019 on the rules and procedures for the operation of unmanned aircraft. Official Journal of the European Union, L 152, 11 June 2019, pp. 45–71.

[6] European Union Aviation Safety Agency (EASA) (2023). *Acceptable Means of Compliance (AMC) and Guidance Material (GM) to Regulation (EU) 2019/947*. Updated AMC/GM for UAS operations.

[7] Fédération Internationale de l'Automobile (FIA) (2025). Fia rally safety guidelines 2025. 7th Edition, March 2025.

[8] Joint Authorities for Rulemaking on Unmanned Systems (JARUS) (2021). Jarus guidelines on specific operations risk assessment (sora), edition 2.0. Technical report, JARUS. Edition 2.0, published March 2021.

[9] Mademlis, I. et al. (2019). High-level multiple-uav cinematography tools for covering outdoor events. *IEEE Transactions on Broadcasting*, 65(3):627–641.

[10] Schäffer, B., Pieren, R., Heutschi, K., Wunderli, J. M., and Becker, S. (2021). Drone noise emission characteristics and noise effects on humans—a systematic review. *International Journal of Environmental Research and Public Health*, 18(11):5940.

[11] Zhang, C. and Kovacs, J. (2018). The impact of wind on uav flight duration and energy consumption. *Drones*, 2(4):1–18.