CHALLENGES IN AUTONOMOUS UAV CINEMATOGRAPHY: AN OVERVIEW

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ABSTRACT

Autonomous UAV cinematography is an active research field with exciting potential for the media industry. It bears the promise of greatly facilitating UAV shooting for various applications, while significantly reducing the costs compared to manual shooting. However, the general problem has not been clearly defined and the challenges arising from current legislation and technology restrictions have not been fully charted. A complete overview of issues related to autonomous UAV cinematography is needed, pertaining to the current situation in the field, so as to guide immediate-future research. The purpose of this paper is to lay exactly this groundwork, with the expectation of providing a global perspective to multiple domain-specific research communities. The outlined issues are partitioned into challenges deriving from ethical/legal/safety considerations and from operational/production requirements. A brief survey of current technological solutions, including their limitations, is also provided for each issue.

***Index Terms*—** UAV cinematography, autonomous drones, UAV perception, UAV regulations

1. INTRODUCTION

Camera-equipped Vertical Take-off and Landing Unmanned Aerial Vehicles (VTOL UAVs, or drones) have severely affected visual media production during the last decade. They provide enhanced flexibility in aerial shot setup, access to hard-to-reach spaces, the possibility of novel visual effects and shot types, as well as easy target tracking and active following, at a small fraction of the costs associated with helicopters, cranes and spidercams.

Although current professional shooting drones are operated by human crews (e.g., pilots, drone camera operators while additional people coordinating the flight and the shooting might also be involved) in an entirely manual manner, they do possess rudimentary navigational autonomy enabled by Global Positioning System (GPS) receivers [1] and on-board autopilot controllers [2]. Increased functional autonomy is expected to significantly streamline the process of UAV shooting. Although state-of-the-art commercial drones already provide a limited level of autonomy, autonomous UAV cinematography is still in its infancy. Moreover, although shooting with an autonomous swarm of multiple, co-operating UAVs bears many advantages [3], it remains a relatively unexplored area.

In an ideal scenario, the director would give general, concise event coverage instructions in near-natural language before the event. Subsequently, a fully autonomous UAV swarm would acquire the desired footage, while automatically complying with any relevant legal restrictions, constantly adapting to the ever-changing situations arising within the event area, and optimally dealing with energy-autonomy, intra-swarm coordination and flight safety issues. All the above would only require the minimal oversight of a single flight supervisor.

Far from attempting to make the above scenario a reality, currently emerging research focuses on solving simple sub-problems, e.g., outputting feasible single-UAV trajectories that allow the camera to capture desired footage conforming to basic cinematographic principles [4] [5] [6]. Additionally, a few relevant commercial applications have been released recently [7] [8] where the desired visual content is typically pre-specified by the director using example key-frames. Little effort has been expended towards researching multiple-UAV/swarm shooting [9], despite the obvious advantages.

A factor heavily contributing to this situation is that the general problem has not been clearly defined and the challenges obstructing the way towards the above-described ideal scenario have not been fully charted. A complete overview of issues related to autonomous UAV cinematography is needed, pertaining to current situation in the field, so as to guide immediate-future research.

This paper attempts to survey the current ethical/legal/safety and operational/production challenges present in the field, to present the corresponding state-of-the-art technological solutions and to showcase their limitations. The expectation is to provide a common understanding of the domain to many different research communities, in order to facilitate further progress in the area.

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2. ETHICAL, LEGAL, SAFETY AND SECURITY CHALLENGES IN MEDIA PRODUCTION

Legal, ethical, safety and security issues arise upon scheduling professional UAV flight sessions, implicitly imposing challenging constraints on the shooting mission. Restrictions deriving from flight regulations, from data privacy rules and, finally, from safety and security considerations are described below, accompanied by corresponding technical solutions.

2.1. Flight Regulations

Different flight regulations apply depending on employed UAV types and their application. The regulations in many countries impose restrictions to the employed UAV weight and permitted flight radius, while also defining special prerequisite conditions (e.g., licensed pilot requirements and insurance policies). An important issue is that flight restrictions vary over different countries, while professional pilot licenses and insurance policies may not be internationally valid.

UAVs are typically classified into different categories, depending on their weight. Adjusting/replacing components, may impact the category classification. For instance, UAVs exceeding 2kg of weight may be required to carry emergency parachutes in some countries [10]. Flying UAVs exceeding 15kg of weight might require special license or even be prohibited [11]. Maximum drone flight altitude is typically restricted to 400ft or 500ft (120m or 150m) within several European countries [10] [11] [12] [13] [14]. Visual Line-of-Sight (LOS) should be maintained by the licensed pilot of the UAV[1], either physically, or using visual aids (e.g., VR-goggles), while the horizontal distance between the drone and the pilot may be limited to specific meters (e.g., 500m).

In addition, due to safety considerations, outdoor UAV flight in most countries is restricted above congested areas, crowds of people and airports, leading to permissible flight zones delineated by law (geofencing). Inherently complying with such a complex and varying web of regulations is a challenge for all autonomous UAV applications.

Thankfully, current aerial path planning algorithms are able to deal with complex dynamic and kinematic constraints in real-time, resulting in nearly-optimal collision-free paths being computed on-line [15]. Thus, the challenge mainly lies in properly estimating the geofences according to current legislation.

2.2. Data Privacy

Although UAV shooting in controlled and/or indoor settings (e.g., TV/film content) does not entail privacy considerations, privacy is an important issue in generic outdoor filming (e.g., sports or entertainment event coverage, newsgathering, etc.).

[1]In future autonomous UAV swarms, the pilot could simply be replaced by a single swarm supervisor, but the LOS restriction is expected to remain in place.

For instance, although it is intended to depict the athletes in a race, footage clearly showing the faces of nearby spectators is a prime candidate for raising privacy concerns. Capturing such footage is nearly unavoidable with UAVs, due to the wide scene portion captured by UAV-mounted cameras, as well as to their enhanced on-the-fly and in-the-field deployability.

Legal restrictions in various countries limit, or entirely prohibit, the redistribution/broadcast of footage which violates privacy guidelines. Such guidelines are already part of the current legal framework in many parts of the world.

A comprehensive example is the European Union, where the General Data Protection Regulation (Regulation (EU) 2016/679) [16], updating and superseding the Data Protection Directive from 1995 [17], explicitly states: The principles of, and rules on the protection of natural persons with regard to the processing of their personal data should, whatever their nationality or residence, respect their fundamental rights and freedoms, in particular their right to the protection of personal data. Such regulatory frameworks typically treat facial images as potentially identifying biometric data, thus restricting their and making their protection a necessity.

Therefore, compliance with data privacy legislation is an issue that must be taken into account in autonomous UAV shooting scenarios. Privacy protection methods for face de-identification [18] [19], face detection obfuscation algorithms [20], or even soft/non biometric identifiers (e.g., tattoos, skin marks etc.) protection methods [21], can be employed to ensure privacy legislation compliance.

2.3. Misuse Avoidance and Data Security

To the best of our knowledge, no specific legislation prescribes protective measures against misuse and vulnerability exploitation. However, the consequences of such an event may include severe privacy and legal implications, thus a level of protection should be provided upon system design and deployment.

The main relevant dangers consist in drone hacking and/or capturing during flight by a malevolent third party, with the objective to study it and convert it (for instance, to carry explosives), or drone hacking with the objective to directly crash it on people or infrastructure.

Simple ways for an attacker to achieve such goals are radio communication or GPS signal jamming, GPS spoofing, drone autopilot firmware hacking and/or communication hijacking. There are documented incidents where an attacker can land or pilot a drone indirectly by using GPS spoofing [22]. Additionally, a Man-in-the-Middle attack can allow an unauthorized person to pose as the ground station and take command of the drone. Weak security in communications can also allow obtaining the video captured by the drone, or its intended flight path.

Several measures can be taken to mitigate the above issues. Redundant localization methods (e.g., Active Radio-Frequency IDentification (RFID) positioning systems [23]) and multi-sensor fusion algorithms (e.g., [24]), secure and signed autopilot firmware updates, as well as autopilot input commands filtering, can be employed to this end.

During a shooting session, a subset of the produced data is stored on-board, while another subset is on-the-fly transmitted over the air. Depending on the application, video footage may be both stored and broadcasted, or only stored on-board for offline processing at a later time. In contrast, real-time transmission of telemetry and control data is necessary for ensuring a secure and safe flight, making them vulnerable to potential security threats.

Therefore, video footage must be protected during storage, using authentication mechanisms to restrict its accessibility to the copyright owners. Telemetry and control commands need to be transmitted at highest priority and to be protected against misuse at the same time. Additionally, in UAV shooting for live broadcasting, the drone-to-ground communication specifications must ensure a minimal bitrate, sufficient for acceptable real-time video broadcast quality.

Secure LTE communications is the state-of-the-art approach for overcoming the above issues; however, it is not yet implemented in commercial UAVs, due to the high cost of the required equipment. Lower cost solutions, such as Wi-Fi, are acceptable for indoor cinematography applications, but cannot operate smoothly in outdoor shooting over long distances. This is due to their inability to simultaneously ensure stable, high communication bitrate with guaranteed Quality-of-Service, in the longest possible range, without the signal being blocked / degraded by obstacles. Therefore, live broadcasting in outdoor scenarios is still very expensive at the current level of technology.

Advanced, real-time encryption [25] and video compression algorithms [26] [27] for embedded systems can be employed to partially mitigate the above issues, by ciphering both the stored and the transmitted data, as well as lightening the bitrate requirements for live broadcasting. However, such methods place a significant overhead to the limited on-drone hardware computational hardware. Therefore, achieving the optimal trade-off is an issue that must be considered carefully when designing autonomous shooting UAVs. Balancing computational resource assignment between autonomy or perception algorithms and encryption or compression modules is an application-specific decision affecting all technological aspects of such a system.

3. OPERATIONAL CHALLENGES IN MEDIA PRODUCTION

Technology has to overcome a number of current limitations if fully autonomous professional UAV shooting is to become a reality. Below, several operational challenges arising during production are detailed, that derive from cinematography requirements, from functional and decisional autonomy goals, from perception needs and from scalability/swarming issues. For each category, the state-of-the-art technical solutions are briefly surveyed.

3.1. Cinematography Requirements

The main challenge specific to autonomous UAV cinematography/shooting applications is how to optimally translate high-level director instructions into a low-level sequence of suitable target assignments, shot types, frame compositions and UAV/camera motion trajectories relative to the possibly moving target being filmed. The above constitute a detailed cinematography plan that varies over time and over different drones (assuming a swarm solution). Ideally, the UAVs should automatically detect target motion, important events and target roles (e.g., the scorer in a soccer game highlight), with the overall plan automatically adjusting accordingly and on-the-fly.

Thus, three separate cinematography-related issues actually arise: how to facilitate optimal high-level specification of the desired footage by the director, how to automatically derive the low-level cinematography plan and how to autonomously and on-the-fly adapt the latter to the current situation. As long as these three challenging issues have been satisfactorily dealt with, designing UAV/camera control algorithms that capture the desired shot sequence is relatively straightforward.

As previously described, there are existing commercial and research interfaces allowing the director to define desired video key-frames to be captured, using VR environments or 3D scene maps, and producing corresponding static drone trajectories, for single-UAV or multiple-UAV shooting missions. However, these systems currently do not handle the aforementioned issues, or only handle them in a very restricted way, implicitly oversimplifying the problem.

One reason contributing to this situation is the lack of a complete and standardized taxonomy for UAV shot and motion types. Such a taxonomy would greatly facilitate the development of interfaces for high-level cinematography specification that lead to precise and sufficient cinematography plans. Despite relevant early work [3], further research needs to be conducted in the area.

3.2. Autonomy Issues

Increased decisional and functional autonomy for the employed UAVs is a necessary prerequisite of fully realizing the previously detailed cinematography requirements in an autonomous manner. Below, several aspects of this goal that are challenging with the current level of technology are detailed.

An important issue in all autonomous UAV applications is geofencing, i.e., the existence of restricted flight zones which a UAV is not permitted to enter. Such restrictions may arise due to previously described legal requirements, or considerations regarding the safety of the UAV itself (e.g., danger of colliding with buildings or trees). The cinematography plan should autonomously adapt to geofencing restrictions that possibly vary over time, e.g., arising from moving crowds of spectators. Care should be taken so that this adaptation preserves as much as possible of the initial directorial vision and intended visual content. Therefore, geofencing presents specific challenges with regard to cinematography applications which, in general, have not yet been investigated. Optimal, on-the-fly adjustment of a UAV swarm shooting mission, in response to dynamic flight zone restrictions, is a relatively unexplored area, although partial work that takes into account static geo-fencing, without autonomously modifying the cinematography plan, has been performed [28].

Another important issue related to autonomy is emergency handling. Commonly encountered emergencies include unforeseen battery exhaustion, communications failure, or adverse weather conditions. Currently, in professional shooting, emergencies are mostly manually handled by the pilot; in case communications break down, the UAV either stops performing any action and simply hovers, or an onboard parachute is activated and the drone lands in a non-autonomous manner. Clearly, all of the above are suboptimal solutions in the context of autonomous UAV shooting. Greater standardization of possible emergencies and emergency handling policies is needed, so that this aspect can be integrated into algorithms oriented towards increased UAV functional and decisional autonomy (e.g., safe landing site detection and emergency path planning to such a site). Additionally, emergency handling should be complemented by automatic, relevant, on-the-fly adjustments to the active cinematography plan at the swarm level. No research effort has been expended yet towards this challenging goal.

Finally, energy consumption is an important issue in autonomous UAV cinematography, since typical drone flight time is severely limited (less than 25 minutes). Optimal, automatic planning and on-the-fly adjustment of the shooting mission and the cinematography plan according to energy consumption considerations and battery status, both at the swarm level and at the individual UAV level, is a prerequisite for increased autonomy. In terms of energy consumption, the following UAV operation ordering may be defined, from the least to most battery-intensive: camera operations (gimbal rotations, zoom), flying down, flying horizontally/hovering, flying up. In general, the direction of UAV flight dominates the energy-related behavior, with camera operations being relatively negligible. Current UAV shooting systems do not, in general, take energy consumption into account, despite the obvious significance of battery life limitations.

3.3. Perception Challenges

Enhanced environment perception and accurate self-perception are of utmost importance for UAVs involved in shooting missions, since perception enables the achievement of almost all cinematography and autonomy goals. For instance, emergency path planning towards safe landing sites cannot be performed without on-demand identification of such sites from sensor data (e.g., camera). Capturing the desired footage of moving targets is, in many cases, impossible without accurately positioning the target within its surroundings at all times. Even more importantly, very few things can be performed autonomously if the drone is not in a position to accurately localize itself within the environment.

The combination of state-of-the-art on-drone LIDAR-based Visual SLAM [29] and accurate differential RTK-GPS units [30] on all UAVs and targets (e.g., athletes in a race) involved in a shooting mission can solve most of the perception issues in a satisfactory manner, since it permits the constant update of a consistent, global 3D map upon which all objects of interest are annotated. However, differential GPSs and LIDARs are heavy and expensive sensors. Additionally, it is not always possible or practical to equip all targets with GPS units, while it may not even be permitted or reasonable to do so with other things the UAVs should autonomously localize (e.g., crowds of spectators, safe landing sites, obstacles to avoid). The challenge for current technology lies in achieving a similar level of functionality using advanced algorithms, intelligent sensor data fusion and only minimal equipment, i.e., one on-drone camera (possibly stereoscopic 3D), simple GPS units on the UAVs and no GPS units on the targets. Despite recent advances in camera-based Visual SLAM and fusing its output with odometry measurements from Inertial Measurement Units (e.g., [24] [31]), the results are not yet robust and accurate enough for stable 3D self-localization and mapping. This is an important challenge for near-future autonomous UAV cinematography applications.

On the other hand, 2D target visual detection, recognition and tracking on video inputs is becoming more and more competent, mainly due to the success of deep learning algorithms and dedicated relevant hardware for UAVs (e.g., the NVIDIA Jetson TX2 board). 2D object detection/recognition/tracking on video footage is important in itself, especially for cinematography applications where the target should be framed in a specific manner indicated by the active cinematography plan. Moreover, the output of such algorithms can be fused with/projected on the global 3D map, acting as an additional information modality beyond SLAM and GPS, thus offering increased perception robustness. Deep learning methods have recently demonstrated high performance on 2D visual detection/recognition problems related to autonomous UAV cinematography [32] [33], while state-of-the-art 2D visual trackers have proven suitable for real-time processing of UAV video feeds [34] [35]. The same underlying technologies can also be employed for on-line crowd, obstacle or safe landing site detection from video footage (e.g., [36]).

Therefore, near-future 2D visual processing algorithms are expected to be mature and robust enough for deployment in autonomous UAV shooting applications. The challenge lies in optimizing them for real-time performance at a low energy expenditure envelope, using the relatively limited computational hardware of UAV platforms. This is a significant issue that only recently has begun to be investigated (e.g., [37]).

3.4. Scalability and Swarming

Cinematography applications typically require capturing of a scene that only takes place once, from multiple viewing angles, perhaps for different purposes (e.g., obtaining witness or principal footage). Therefore, multiple-UAV/swarm approaches are, by far, a superior solution for cinematography applications.

By exploiting a number of UAVs, enhanced drone perception can be expected to be achieved, by exploiting collaborative perception algorithms including collaborative SLAM [38] [39], or multi-view detection and tracking [40]. Challenges include not only developing, improving and accelerating such algorithms, but also exploring distributed processing opportunities within the swarm, as well as centralized data fusion in a master computational node (e.g., centralized multi-view processing, as in surveillance applications).

Additionally, the production and on-the-fly adjustment of a cinematography plan from high-level director guidelines becomes more challenging in autonomous UAV swarms. Different tasks have to be assigned to each UAV and be constantly updated, without requiring additional director input. For instance, the members of a UAV fleet should take dissimilar shots (e.g., when a UAV attempts to take a close-up shot of a target, the other drones should be capturing differing overview long shots). Moreover, UAVs should be able to perceive each other and avoid entering each others Field-of-View, so as to preserve the transparency of the shooting process. Such behaviors may be integrated in advanced formation control and swarm path planning algorithms [28], but this is still a field in its infancy.

4. CONCLUSIONS

This paper outlined current challenges in autonomous UAV cinematography, arising either from legal/ethical/safety considerations, or from operational requirements during production. A number of state-of-the-art solutions were also briefly surveyed. The presented issues have to be methodically investigated and taken into account by any research hoping to lead to practical, fully autonomous UAV shooting systems.

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