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► **To cite this version:**

Nicola Roberto Zema, Enrico Natalizio, Evsen Yanmaz. An Unmanned Aerial Vehicle Network for Sport Event Filming with Communication Constraints. First International Balkan Conference on Communications and Networking (Balkancom 2017), May 2017, Tirana, Albania. hal-01731379

HAL Id: hal-01731379

<https://hal.science/hal-01731379>

Submitted on 14 Mar 2018

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An Unmanned Aerial Vehicle Network for Sport Event Filming with Communication Constraints

Nicola Roberto Zema*, Enrico Natalizio*, Evsen Yanmaz †

* Sorbonne Universités, Université de Technologie de Compiègne, CNRS,
Laboratoire Heudiasyc, 57 Avenue de Landshut, CS 60319, 60203 COMPIEGNE Cedex.

e-mail: {enrico.natalizio,nicola.zema}@hds.utc.fr

† Lakeside Labs, Austria. e-mail: yanmaz@lakeside-labs.com

Abstract—In this paper, event coverage, specifically *Sport Event Filming (SEF)* with communication constraints is formulated. A team of UAVs need to position themselves and plan their paths over a limited area to track the movements (e.g., of the ball) in a gaming field and deliver high quality and timely stream of the events (e.g., ball passes, goals) to the event spectators meeting certain satisfaction criteria. Assuming the goal of maximizing the viewer’s satisfaction, a set of distributed schemes to the UAV movement problem are proposed. They are based on Artificial Potential functions and possess no *a-priori* knowledge of the sequence of game actions. Extensive simulations are used to analyze the performance in terms of viewer’s satisfaction, cost, and networking performance and show that the proposed schemes outperform previous schemes.

Index Terms—Sport Event Filming (SEF) problem, Mobile Camera Drones, UAV Routing Problem, VRP with Soft Time Windows

I. INTRODUCTION

Commercial drone technology market, currently around \$2 billion, it is predicted rocket to as much as \$127 billion by 2020 [1]. According to another study [2] that surveyed managers and employees at Unmanned Aircraft Systems (UAS) companies, aerial photography and cinema will dominate the vertical markets in the next years. In this paper, we envision the usage of Unmanned Aerial Vehicles (UAV) for filming a sporting event and streaming images and replays to the spectators within the stadium. The most popular sport events are played by two teams that confront each other over a field of limited size. The game objective is usually to achieve a certain goal via a sequence of actions, where usually one team attacks and the other defends. This objective can be accomplished by carrying, kicking, shooting or dropping a single object (the *ball* in the rest of the text), such as a ball, a football, a disk etc., in a specific area that is defended by the opposite team. The main actors of the game are the two teams, the ball and the referees; i.e., one or more people that look after player safety and enforce the rules of the game.

The *Sport Event Filming* (SEF) problem, recently introduced in [3], consists of finding the best positions for a

fleet of UAVs in order to maximize the satisfaction of the event’s spectators and minimize the UAVs’ traveled distance. The UAVs move timely over the current position of the ball and film the action. In the original formulation of the SEF problem, no attention has been paid to the communication and connectivity constraints required to deliver a High Definition (HD) stream to the spectators. In this paper, we extend the formulation of the SEF problem by including communications and connectivity constraints for a scenario with two UAVs, which are used respectively as filming and supporting nodes. In the rest of this paper, we will refer to this new problem as *Sport Event Filming with Communications and Connectivity Constraints* (SEF-C³). As for the original SEF problem, the objective is to develop strategies to coordinate the movement of a group of mobile robots in the presence of highly varying time-space constraints. A solution to this problem is of interest for several application domains, and would pave the way for the design of mission-oriented devices and the definition of their coordination/cooperation schemes. From a modeling viewpoint, the problem belongs to the Dynamic Vehicle Routing (DVR) family, which aims at routing vehicles between depots and customers that can appear dynamically during the execution time. To the best of our knowledge, no solutions have been proposed for solving the dynamic SEF-C³ problem, static variants of which are NP-Hard. Some solutions with static cameras exist [4], [5] but they cannot provide the same level of accuracy and entertainment given by mobile devices flying over the game field.

In this paper, we present some new movement schemes for the UAVs of a SEF-C³ problem in order to maximize viewer’s satisfaction and to minimize the distance traveled by the drones, while taking into consideration the main communications and connectivity requirements for a HD multimedia data flow.

Specifically, the contribution of this paper is the following:

- we introduce communications and connectivity requirements into the SEF problem formulation;
- we propose three dynamic movement techniques, based on control theory methods, to solve the problem in a distributed way and without any *a priori* knowledge of the sequence of actions, excluded for the general area

This work has been carried out in the framework of the DIVINA Challenge Team, which is funded under the Labex MS2T program. Labex MS2T is supported by the French Government, through the program Investments for the future managed by the National Agency for Research (Reference: ANR-11-IDEX-0004-02)

they happen.

The rest of this paper is organized as follows: Section II presents the background for the empirical modeling of the problem and its solution. In Section IV and in Section V, we propose the system that offers a practical solution to the communications issues of the SEF-C³ problem and the distributed techniques for the movement of the UAVs, respectively. In Section VI, we test and analyze the distributed techniques through simulation and validate them in comparison to the results of the literature's previous solutions. Finally, Section VII concludes this paper.

II. BACKGROUND

The scientific aspects of using UAVs for the Sport Event Filming (SEF) problem are challenging and constantly growing [6]. The trend started with an increasing interest in scientific data collection using flying autonomous elements [7], [8]. The main issues to face for implementers are summarized in a set of requirements, for the communication infrastructure, that include *high throughput* and *delay-intolerance*. After the technology was ready [9], the first systems that used drones for filming sport events appeared [3], [10], [11]. Different than existing works, the work presented in this paper proposes a meta-heuristic approach directly implementable on the UAVs. Our work is inspired by the one in [3]. However, in our contribution the focus is not just on the event coverage as in [3], instead we aim at maximizing network performance in a realistic communications environment, using distributed techniques that are based on Artificial Potentials. In the following we present the state of the art for this topic.

Artificial Potential methods [12] can be summarized in the application of virtual or artificial forces, which are set among mobile devices and obstacles by creating potential fields that can attract or repulse the devices towards each other [13] and towards a goal. Actual movements are executed by following the gradient descent of the potential function. The scientific literature presents a large body of works that leverage the Artificial Potential for networking-related applications [14]. There are indeed works that use the artificial potentials for target tracking [15], most of them, however, are focused on coverage problems [16], [17]. In this work we use the Artificial Potential method for finding a solution to a motion planning problem using an artificial acceleration force field. As this class of methods are used to keep moving vehicles into formation, we devise to use them to maintain the relative distance between robots under certain threshold and in this way tackle range-based communication issues.

III. A MODEL FOR THE SEF-C³ PROBLEM

We assume that the stadium is structured as a set of two concentric rectangles: the internal one has the average soccer field dimensions, $110 \times 80[m]$, and the external one, which contains also the spectators space, is $210 \times 160[m]$, as in Figure 1. Two UAVs move over the field to film the event and relay the video streaming to all the spectators within the stadium. We will refer to the two UAVs as *filming* and *supporting* UAV in

the rest of the paper. With reference to Figure 1 and according to the measurements presented in [18], we define as 1-Hop the shaded area at the center of the field. When the action (and the filming UAV) is in this area, there is no need of a supporting UAV to deliver HD video to the whole stadium. On the contrary, when the action occurs in one of the filled corners of the field, the farthest sectors of the stadium in respect to this corner (filled in the same way) will not be provided with the HD video by using a single UAV. For readability issues, the figure illustrates the behavior for actions on the right-side of the field only.

Viewer satisfaction

By assuming a uniform distribution of spectators in the stadium, it is possible to compute the set U_{HD} of spectators who would be provided with HD video. The set U_{HD} is computed by considering simple geometric relationships.

By using the following notation:

$$C_1 : t_{arr,i}^f < t_{start,i} \quad C_2 : N_i \in \text{1-Hop} \quad (1)$$

where N_i is the position of the i^{th} action, filmed by the f UAV and relayed (if necessary) by the s UAV. The values $t_{start,i}$ and $t_{stop,i}$ represent the start and stop times of an action of interest (i.e. a sprint or a goal). We can define set U_{HD} of spectators who are provided with high definition video, and their satisfaction $VS_{i,HD}^k$:

$$\begin{cases} (1 - (\neg C_1) \cdot \frac{t_{arr,i}^f - t_{start,i}}{t_{stop,i} - t_{start,i}}) \cdot (VS_{maxHD}), & t_{arr,i}^f \leq t_{stop,i} \\ 0, & t_{arr,i}^f > t_{stop,i} \end{cases}$$

where $t_{arr,i}^f$ is the arrival time of the filming UAV at the position of action i , and $t_{arr,p}^s$ is the arrival time of the supporting UAV at the position of relay p . The two UAVs used for establishing and keeping the multimedia transmission can exchange the filming and supporting role, therefore the superscripts f and s must be considered as "variable" that can assume the values 1 or 2. In the following we will use the variable k to indicate a generic UAV and the variables f and s to indicate the filming and supporting UAVs, respectively.

IV. A TLC SYSTEM TO FILM SPORT EVENTS

In the previous sections, we have introduced the SEF-C³. The purpose of this section is to provide some insight into the real system that can take into consideration the set of networking constraints and allow the practical feasibility of the UAVs distributed movement schemes, which will be presented in the next section.

A. Communication Constraints

The objective of this work is to provide a solution for filming a sport event and deliver the video streaming to all the spectators within the stadium, preferably in HD quality. For the rest of this paper, we consider the data to transfer as a standard MPEG-4 Part 14 stream. For the video to be deemed as HD, the stream has to be composed by either a

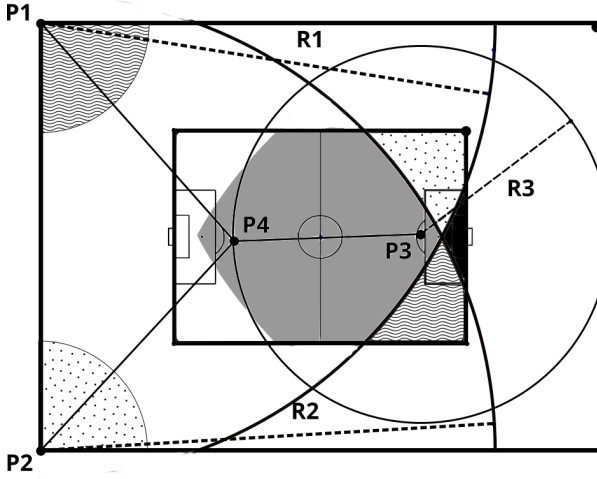


Fig. 1: Model of stadium and game field. In the shaded regions of the field the spectators cannot receive a HD video without using a *supporting* UAV.

H.264 High Profile (HiP, 100) [19] or a MPEG-4 Part 2 with an Advanced Simple Profile (ASP) [20] alone (no audio track). Both these video stream sub-parts are bandwidth-demanding and usually employed only in DVB-HD broadcasting. Their transmission requirements can be upper-bounded by published specifications to 500 ~ 600 Mbps [21]. The *ac* [22] and *ad* [23], [24] standards of IEEE 802.11 are advertised as capable to support an effective bandwidth of more than 600 Mbps even when not used with MIMO configurations. Thus, we devise the filming UAV as continuously broadcasting its video stream using a dedicated IEEE 802.11ac-capable wireless interface.

Broadcasting on a dedicated channel permits data to be correctly decoded by all the devices (spectators and other UAVs), which are close enough to the transmission source to receive the stream with a Bit-Error-Rate below the 802.11ac higher-bandwidth modes threshold. We define as $R_{HD,i}$ the communication range associated with this transmission threshold for the receiving node i . It is also worth considering that using a broadcast strategy there is no medium contention and thus it is feasible to approach the 802.11ac theoretical bandwidth limits.

B. System Design and Roles

According to previous studies [18] and the stadium geometry and dimensions, it is possible to distribute an HD stream to all the stadium spectators using only two UAVs assigned to the two roles. Using this configuration, for the remainder of this paper we consider all the users belonging to the U_{HD} set and, accordingly, we consider the viewer satisfaction composed by $V S_{i,HD}^k$. The UAVs are each dedicated to a side of the playing field and are each responsible for: (i-filming role) capturing the events in their area and diffusing it and (ii-supporting role) relaying the data if no events are detected. Therefore, the filming UAV: (i) always follows the actions (i.e. the ball) and (ii) broadcasts the video stream to both the spectators

in his half-field and the other UAV. The supporting UAV, in turn, has to: (i) re-broadcast the data as received by the filming UAV and (ii) use a movement strategy that keeps it always inside the R_{HD} of all the spectators of its half-field and keep the filming UAV inside its own R_{HD} . The presence of a supporting UAV modifies the ideal broadcasting conditions. The contention can be mitigated by employing either a TDMA or CSMA scheme. However, as we are only considering a few UAVs, we can assume that the communications among the UAVs are perfectly scheduled.

V. MOVEMENT SCHEMES FOR THE SEF-C³ PROBLEM

We propose a system that is capable of continuously satisfying the network constraints presented in Section IV. Specifically, by applying virtual attractive and repulsive forces on the UAVs' control model, the supporting UAV will move away from the filming UAV in order to relay the HD video stream to the farthest spectators within the stadium. The assumptions used to model the geometry of the stadium are the same as those presented in Section III.

The requirements for HD broadcast, described in Section IV, directly translate to a set of distance constraints that the supporting node has to satisfy. The positions of the farthest spectators are identified in Figure 1 with P_1 and P_2 (*corner points* in the rest of the paper), whereas P_3 and P_4 are the positions of the filming UAV and the supporting UAV. Furthermore, R_1 and R_2 are the minimum distances the supporting UAV has to keep from P_1 and P_2 , respectively, to effectively broadcast the HD stream to the farthest spectators. Segment R_3 (not on scale in the figure for display reasons) represents the range the supporting UAV has to stay within the filming UAV to receive an HD video stream.

Considering that the filming UAV tries to follow the actions, in the following, we describe a control system capable of dynamically driving the supporting node. The resulting movements keep the supporting UAV within the three aforementioned distances, while following the filming UAV.

$$\begin{aligned} \dot{x}(t) &= v(t) \\ \dot{v}(t) &= \begin{cases} u(t, x_4, v_4, x_3, v_3) \\ f(t) \end{cases} \end{aligned}$$

where $x(t), v(t) \in \mathbb{R}^2$, $u(t, x_4, v_4, x_3, v_3) : [0, +\infty[\times \mathbb{R}^{2(n+1)} \rightarrow \mathbb{R}^2$ are, respectively, the position, velocity and control input associated with the supporting UAV, and $f(t) : [0, +\infty[\rightarrow \mathbb{R}^2$ is a signal describing the filming UAV velocity. Exploiting the Artificial Potentials, we can set:

$$u = -\nabla V_{x,y} + \gamma(v_i - v_4)$$

where $\gamma(v_i - v_4)$ represents a velocity coupling. This function will be further specified in equation (2) in Section VI.

In order to move into the optimal position for relaying the video stream, the supporting UAV needs the estimation of the euclidean distances from the *corner points* and from the filming UAV and the pre-computed values of the desired maximum ranges (R_1, R_2 and R_3). There are various ways to

obtain this information, ranging from centimeter-accuracy on board GPS systems, to telemetric data relayed on a dedicated wireless interface, to rotating telemeters [25]. In this paper, we assume the presence of such a system for each UAV to be aware of the other UAV's velocity and position.

VI. PERFORMANCE EVALUATION

We use simulations to demonstrate the feasibility of our proposal and the improvements introduced into networking. Specifically, we compare different movement techniques and analyze their performance from two different perspectives. The first perspective concerns with the quality of the events coverage. To this end, we consider the *average viewer satisfaction* to quantify the user experience and the *total traveled distance* by the UAVs to quantify the cost of physical resource consumption. The second perspective relates to networking, where we measure the *cumulative packet loss* of the filming transmissions. Using Network Simulator 3 [26], we have implemented the control model for the movement techniques of Section V and a selected set of techniques from [3]. Specifically, the *Ball-Movement-Interception with Specular Repositioning* (BMI-SR) and the version of *Ball-Movement-Interception with Quasi-Specular Repositioning* (BMI-QSR) with the optimal *detour factor* of 0.6: BMI-QSR_{0.6} are used in our comparison. Note that these techniques have been proposed in [3] only to optimize the event coverage and it is important to investigate their networking performance to illustrate the necessity of incorporating communication constraints into the SEF problem.

A. Simulation Scenario

The simulated UAVs are equipped with a single wireless interface and an Ad-Hoc MAC protocol to simulate a IEEE 802.11ac stack. As the UAVs are always within line of sight of each other, we consider a Ricean fading model, where the signal components coming from secondary paths are disregarded. To model the data to deliver, we use a set of traces coming from actual HD video decomposition into packets, whose MTU is below the maximum allowance for a 802.11ac system [27]. The Artificial Potential method of this proposal is driven by the following set of functions, as described in Section V.

$$\begin{aligned} \text{HPF} &= \frac{1}{R_{HD,i}^2 - \|d_{i,j}\|^2} \\ \text{HCPF} &= \cosh\left(R_{HD,i}^2 - \|d_{i,j}\|^2\right) \\ \text{Binomial HCPF} &= \cosh\left(\left(R_{HD,i} - \|d_{i,j}\|\right)^2\right) \end{aligned}$$

The HPF (Hyperbolic Potential Function) is characterized by a repulsive stimulus when a UAV approaches the R_{HD} boundary and the other two functions (Hyperbolic Cosine Potential Function and Binomial HCPF), instead, try to keep the UAV in the proximity of that value, albeit with different intensities. For all the simulations, we use the parameters in Table I. All the results come from the values upon 20 runs,

statistically averaged over a confidence interval of 95%, not shown for figure readability. For each simulation scenario we created a set of 20 actions whose positions and durations are uniformly and non-overlapping distributed (in space and time). The space is represented by the game field and the time is varied in order to have an action duration between a minimum of 2 [s] and a maximum variable between 6, 8, 10 and 12 [s].

TABLE I: Simulation Parameters

Parameter	Value
Speed of Drones	15 [m/s]
Action Min Duration ($t_{birth} \rightarrow t_{stop}$)	0.2 [s]
Ball Min and Max Speed	{1 ÷ 40} [m/s]
Number of runs for each scenario	20

B. Events coverage

Figure 2 shows the viewer satisfaction over maximum action duration. When the maximum action duration increases, all techniques improve the system performance as, in general, they all have more time to let the UAVs move. For the longest reaction times, the performance of HPF is the best. For the shortest, it is the Binomial HCPF that has the edge. In any case, the proposed solutions represent an improvement over the previous literature as they leverage a more dynamic movement scheme.

C. Networking

In respect to previous approaches, the movements followed by the UAVs, using the proposed approach, are smoother and tend to maintain the same distances between them. This behavior is visible in Figure 3. For this set of measurements, the proposed solutions are designed to maximize the networking performance and thus, keeping the UAVs at the correct distances all the time makes it possible to minimize the packet loss and increase the transmission quality. In the same situation, the results coming from BMI techniques show that they were not designed to consider telecommunications features. For instance, as the BMI-SR approach completely disregards the communications constraints, the performance of the packet loss is the lowest.

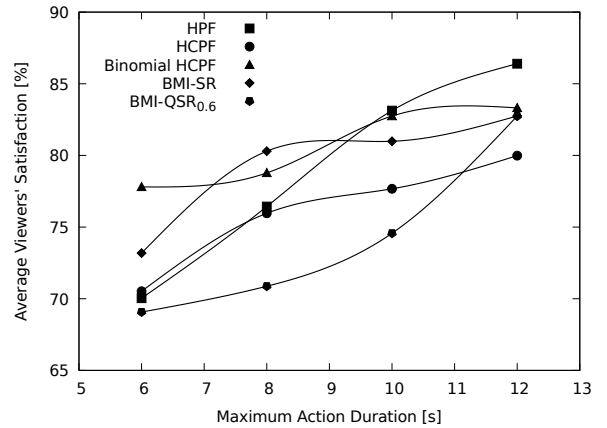


Fig. 2: Average Viewer Satisfaction over varying Maximum Action Duration.

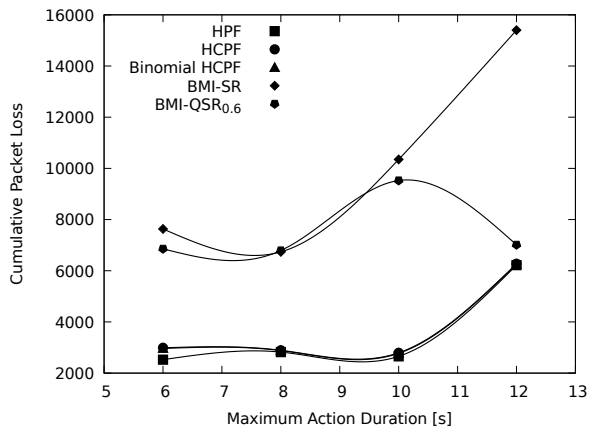


Fig. 3: Cumulative Packet Loss over varying Maximum Action Duration.

VII. CONCLUSION

In the context of coordination schemes for UAV networks, we have introduced the *Sport Event Filming* problem with communication and connectivity constraints (SEF-C³), where the spectators of a sport event within a stadium receive on their personal devices a video stream, taken from two UAVs that fly over the sport field. To coordinate the movements of the two UAVs, we have introduced the set of three distributed techniques proposed in this paper. These schemes have no knowledge of the sequence of actions and use Artificial Potential methods to keep the connectivity of the two UAVs with the farthest spectators within the stadium. Through simulations, we have compared the performance of the the proposed schemes with existing movement techniques in terms of packet loss as well as events coverage. Future works will consider the extension of the proposed schemes to unbounded fields (as for bicycle races). Additionally, we intend to adopt multiband robust optimization [28] to reliably provide the set of positions that maximize the networking performances.

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