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Chaos-enhanced mobility models for multilevel swarms of UAVs

Martin Rosalie [a,*], Grégoire Danoy [b], Serge Chaumette [c], Pascal Bouvry [d]

[a] SnT, University of Luxembourg, Luxembourg
[b] FSTC/CSC-ILIAS, University of Luxembourg, Luxembourg
[c] University of Bordeaux, LaBRI, UMR5800, Talence, France
[d] FSTC/CSC-ILIAS/SnT, University of Luxembourg, Luxembourg

A R T I C L E I N F O

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A B S T R A C T

The number of civilian and military applications using Unmanned Aerial Vehicles (UAVs) has increased during the last years and the forecasts for upcoming years are exponential. One of the current major challenges consist in considering UAVs as autonomous swarms to address some limitations of single UAV usage such as autonomy, range of operation and resilience. In this article we propose novel mobility models for multi-level swarms of collaborating UAVs used for the coverage of a given area. These mobility models generate unpredictable trajectories using a chaotic solution of a dynamical system. We detail how the chaotic properties are used to structure the exploration of an unknown area and enhance the exploration part of an Ant Colony Optimization method. Empirical evidence of the improvement of the coverage efficiency obtained by our mobility models is provided via simulation. It clearly outperforms state-of-the-art approaches.

1. Introduction

The development and usage of Unmanned Aerial Vehicles (UAVs) has quickly increased in the last decades, mainly for military purposes. Nowadays, this type of technology is also used in non-military contexts, for instance for environment protection, by search and rescue teams, by fire fighters and police officers, or for environmental scientific studies. In order to increase their potential, swarms of UAVs are now envisioned. In this context the payload and sensors are shared between UAVs to address the limitations encountered when using a single UAV, such as autonomy, operation range and resilience. Although the technology for operating a single UAV is now mature, additional efforts are still necessary for efficiently taking advantage of UAVs swarms.

In this paper we address the problem of area coverage with a swarm of UAVs collecting data via sensors. This problem is addressed in the framework of the ASIMUT project funded by the European Defence Agency (EDA). The military aspect implies that an additional constraint has to be considered: the unpredictability of the trajectories eliminating sweeping or patrol algorithms. Although this paper is dedicated to UAVs, the problem remains similar for other unmanned systems like ground, surface or underwater vehicles. To solve this problem two main techniques have been proposed: online and offline path planning. Offline path planning consists in precomputing the flight plan of the UAVs. The main asset of this approach is that the trajectories of the UAVs are easily monitored from the Ground Control Station (GCS). However, this technique is not adaptive to any change of configuration during the flight: the scheduled path can be irrelevant by the time the UAVs execute it. On the other hand, online methods compute the trajectories of the UAVs at runtime. The advantages and drawbacks of online methods are the opposite of those of offline approaches: they are flexible and resilient but it becomes impossible to predict the trajectories of the UAVs. As a consequence, in this paper we will propose a mobility model that combines the assets of both online and offline methods.

The latter method relies on the Ant Colony Optimization method (ACO) introduced by Dorigo [1], and more precisely on the work of Kuiper & Nadjm-Tehrani [2] who adapted the ACO algorithm to the coverage problem for UAVs. Kuiper's mobility model uses repulsive pheromones to guide the UAVs over the area they have to cover. The UAVs share a map of virtual pheromones that indicates recently visited areas when high pheromone concentrations are present. The UAVs then have a higher probability to move to the least recently visited areas.

* Corresponding author.

E-mail addresses: martin.rosalie@uni.lu (M. Rosalie), gregoire.danoy@uni.lu (G. Danoy), serge.chaumette@labri.fr (S. Chaumette), pascal.bouvry@uni.lu (P. Bouvry).

URLs: https://martinrosalie.gforge.uni.lu (M. Rosalie), http://pcog.uni.lu/members.html (G. Danoy), http://www.labri.fr/perso/chaumett/ (S. Chaumette), http://pcog.uni.lu/members.html (P. Bouvry).

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Our contribution proposed in this paper consists in an ACO-based mobility model for UAV swarms that uses a chaotic dynamical system. It addresses part of the questions raised by a survey on algorithm dynamics and complexity [3]. Chaotic dynamics are the solution to a deterministic system with the following properties: the solution is bounded, globally time invariant and sensitive to initial conditions, and consequently, unpredictable on a long-term. Using such solutions in a UAV mobility model would thus permit to obtain deterministic but unpredictable trajectories. Our objective is here to study in detail the impact of different chaotic systems and parameters on the area coverage by the swarm. Recently, Zang *et al.* [4] provide a detailed review of various applications of chaotic dynamics for mobile robots: several discrete and continuous dynamical systems are used to generate chaotic dynamics. We choose to use the Rössler system [5] as a basic system to explore a combination of chaotic behaviours from Ordinary Differential Equations (ODE) with Ant Colony Algorithm. This system is a reference in the literature, as one of the first ODE systems with a simple chaotic mechanism. The Ma system [6] has also been considered to illustrate the transition from the random part of an ACO algorithm to a chaotic one.

This paper is an extension of some of our previous work [7]. More precisely, we additionally provide a complete description of the chaotic dynamics used, as well as a detailed analysis of the methodology applied to build a mobility model from first return maps. We extended our study with two additional chaotic mobility models, detailing the properties of the periodic orbits and their impact on the efficiency of the coverage. We also analyze in detail the influence of the periodic orbits on the exploring patterns they can generate. Finally the performance of the new mobility models is also studied via the metrics and compared to the models from literature.

This article is organized as follows. We first introduce the context and the problem definition. Then we describe the related works regarding the two main topics upon which we elaborate our contribution: Ant Colony Optimization and chaotic dynamics. In the third section, we present our chaotic mobility models based on differential equations systems. The next section contains a description of the integration of our best chaotic mobility model into an Ant Colony Optimization algorithm. In the two last sections, we describe our experimentations including the metrics and the statistics we produced. We finally give a conclusion and describe our future work.

2. Context and problem definition

In this section we first present the context of the work, i.e. the ASIMUT (Aid to SItuation Management based on MUltimodal, MUltiUAVs, MUltilevel acquisition Techniques) project. We then describe the tackled problem of area coverage with a swarm of UAVs.

2.1. ASIMUT project

The purpose of the ASIMUT project, supported by the European Defence Agency (EDA), is to improve the situation awareness of an operator through area coverage and detection of threats based on multi-sensor and multi-source data fusion [8]. [1] Information is delivered by heterogeneous swarms of autonomous UAVs flying at different altitudes. One of the objectives of ASIMUT addressed in this article is the efficient surveillance of an area by means of a swarm of UAVs (these UAVs collect data with their embedded sensors). It should be noted that the operation takes place in a military context where the unpredictability of the trajectories is mandatory to prevent interception. Fig. 1 details all the components of the system including the heterogeneous swarms (High Level Coordination Swarm and Low Level Coordination Swarm) and the mission management entities. A real deployment of this model is planned in our roadmap.

[1] More information on ASIMUT is available on the project's website: https://asimut.gforge.uni.lu.

2.2. Problem definition

This work focuses on the mobility management of a swarm of autonomous UAVs to maximize the coverage of a squared geographical area. In addition to the unpredictability constraint induced by the military context, the trajectories of the UAVs still need to be monitored from the Ground Control Station (GCS) located on the middle of one the area edges. It is indeed mandatory for supervisors and users of this type of system to know and anticipate the positions of their UAVs.

To summarize, the objective is to "*maximize the coverage while ensuring unpredictable trajectories*". Additionally, we intend to provide an adaptive method resilient failures or losses of UAVs. As a consequence, the problem we address here is at the edge of the path planning for UAVs and the autonomous distributed coverage. This is not a path planning problem because of the resilience constraint. We are thus clearly explore an original problem.

Thus, two characteristics have to be considered:

Coverage consideration As the main purpose of the swarm is to cover a given area, the UAVs have to synchronize their exploration by preventing the other UAVs to explore already visited areas. However, we do not consider that revisiting an already visited area is forbidden but it is not profitable to satisfy the coverage objective.

Unpredictability consideration Because of the non predictability constraint, articles giving the optimized solution of a coverage problem [9] have not been considered. Indeed, in such approaches the UAVs coverage pattern is too explicit to be used in a military context.

We propose to formulate the problem as follows. 10 UAVs evolves on a square area with positions given by a couple of real number (x, y). The surface is discretized in a 100×100 grid. The UAVs can move according to three directions: ahead (A), 45° on the left (L), or 45° on the right (R). During the resolution, when a UAV reaches a cell, the latter is considered as visited and this, during the whole simulation. The objective function is to minimize the number of steps required to visit the whole area:

$$\min_{t} \max_{\text{traj}_t(x)} f(\text{traj}_t(x)) \quad (1)$$

where t is the number of steps, $x = [(x_1, y_1), \ldots, (x_{10}, y_{10})]$ the position of the 10 UAVs, $\text{traj}_t(x)$ the trajectories of the UAVs from 0 to t and f the percentage of area covered depending on the trajectories of the UAVs using the 100×100 cells.

3. Related work

In this paper we address the following problem: an area has to be visited regularly by UAVs in order to collect information. One of the constraints is that an observer should not be able to anticipate the reconnaissance pattern of the swarm. A solution proposed by Kuiper and Nadjm-Tehrani [2] was to introduce a random process to prevent the UAVs trajectories from being predicted. In the same article the authors also proposed ACO algorithm and compared it to the random approach. These two approaches are presented in detail hereinafter. Similarly to the random walk, the *chaotic walk* is introduced by Iba & Shimonishi [10]. It only uses the logistic map to determine the next angular direction of a UAV. A map is an iterative application that neither diverge, nor converges to a point. This logistic map ($x_{n+1} = \alpha x_n(1 - x_n)$) converges to a dense set of points, between 0 and 1. This map generates a chaotic dynamic when $\alpha = 4$ and it produces $x_n \in [0 : 1]$ as an output. We already tested this chaotic mobility model for coverage purpose and