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Biologically inspired trajectory generation for swarming UAVs using topological distances

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ABSTRACT

This paper presents a trajectory generation logic for a swarm of unmanned aerial vehicles which uses topological distances instead of metric values. Biologically inspired, this method evades exploiting distance measurements in the absence of such capabilities, as it happens in swarming birds. This newly developed trajectory generation logic provides a stable swarming logic which resembles a large aggregation of birds. The hypothesis of this work is that without depth perception, swarming birds rely primarily on their perception of other birds to estimate proximity and adjust repulsive and attractive forces in real-time. From previous biological behavior studies, it is known that a homogeneous and orderly aggregation is exhibited by swarming birds locating themselves side by side rather than in front or behind each other. This behavior, which is based on the relative spatial proximity perception to their nearest neighbors in the flock, allows birds to converge into a highly cohesive and coordinated formation without explicit control of inter-agent distances. Inspired by this biological pattern, a trajectory generation logic is designed and tested in controlling a multi-agent unmanned aerial systems without the use of inter-distances. A six degrees of freedom nonlinear dynamic model for an unmanned aircraft is used for simulation purposes. Each vehicle is provided with a decentralized agent-based robust nonlinear model predictive controller and a set of nonlinear guidance laws for trajectory tracking. The formulation of the proposed trajectory generation, as well as the selected aircraft control, constitute a truly decentralized technique, that allows for an unlimited number of agents within the swarm, as no centralized computations are made.

1. Introduction

Biological groups, such as flocks of birds, are remarkably effective at maintaining optimized group structure, detecting and avoiding obstacles and predators, and performing other complex tasks. The paper is inspired by the interactions found in large swarms of birds, where remarkable patterns known as emergent behaviors are achieved by the following of simple rules. Such impressive inter-agent coordination is accomplished despite their natural physiological constraints. Although individual agents have limited sensing capability and cannot see the whole formation, they can form a flock with no apparent leader, which implies the lack of a centralized command. This highly coordinated collective behavior emerges from localized interactions among individuals within a flock or swarm of birds.

The work done in [1] is the first 3D measurement of the internal structure of flocking birds. This work found a formation pattern between the closest birds in terms of angular distribution. In [2], an accurate 3D swarm of a few thousand birds was reconstructed to confirm that their local interaction does not depend on metric distances, but rather on "topological distance." It was concluded that *topological distance* is based on the relative spatial locations of the closest birds, and not on exact knowledge of inter-distances. This showed that each bird interacts on average with a fixed number of nearest neighbors (statistically between six and seven). Birds beyond the nearest neighbors were isotropically distributed and their relative location had no statistical significance. Based on this, a direct conclusion was that the formation is cohesive, even in the case of time variant density.

Models intended to replicate swarm dynamics and geometry have mainly been constructed around the premise of a metric distance measurement capability. Article [3] developed a local navigation logic using three simple rules: (i) birds move in the same direction as their closest neighbors; (ii) birds remain close to their neighbors; and (iii) birds avoid collisions using inter-agent dis-

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tances. Several models have been developed utilizing the same concepts trying to close the gap between the simulated models and actual behaviors.

Commonly, swarms of birds are modeled through the definition of adjacent zones of each bird, where the rules between pairs of individuals (as defined in [3]) are activated. The work in [4] proposes a fuzzy logic approach to determine each artificial animal (animat) dynamics. Within a concentric circular zone, a set of fuzzy rules translates the information of distance, angular offset, and relative differences in direction of flight speed into individual corrections. In [5] a probabilistic scenario is defined where the rules are executed based on an exponential distribution as a function of the inter-individual distances. Randomly pairs of birds are selected to be updated. Their results were able to replicate original field measurements in [2], supporting the idea of anisotropy within the nearest neighbors. The work in [6] proposes adaptive and time-varying zones to allow birds to interact with a fixed number of nearest neighbors. Their results resembled qualitatively the empirical data collected in [2]. The work in [7] proposes a different approach in the selection of the nearest neighbors. Voronoi cells are used to isolate the adjacent birds, and a Delaunay triangulation is then used to define the topological interactions pairs between adjacent cells. The birds' actions are computed based on concentric zones, mainly based on inter-individual distances. A different approach, where no model is assumed a priori, is done in [8]. A minimally structured (maximum entropy) model obtains comparable results with respect to cited measurements, despite the fact that no causal-effect logic is incorporated.

Most birds do not have a wide depth perception. Depth is perceived through each eye providing a slightly different view of the same scene when there is an overlap in the field of vision. This is known as binocular vision. Although some birds have both eyes facing forward (such as owls), their binocular vision is not believed to be associated with the perception of distance, also called stereopsis [9]. Based on these conditions it seems unfeasible that birds in swarms adjust their positions based on distance values.

Our work proposes to base the individual corrective actions on a closeness and remoteness comparison logic between opposed surrounding birds with no distance measurement. It is based on a topological or qualitative distance comparison (as opposed to metric or quantitative, using the terminology of [2], and related references), reacting to keep themselves at the center of the surrounding birds. A feeling of "closer to" or "further away from" is used to correct the speed of advance of the swarm and to indirectly reduce the distance difference between spatially opposed birds. A homogeneous swarm speed and direction of motion, together with orderly aggregation, emerge as a consequence of this local and approximate spatial reasoning approach, without explicit control of these quantities.

With work in [2] as an empirical reference, biologically inspired and novel 3D guidance logic has been proposed, developed, and tested, with promising results in stability and robustness. Unmanned aerial systems (UASs) were chosen to test the logic, emulating the agents within the swarm, contributing with their nonlinear dynamics to allow a more realistic scenario. The aircraft are controlled in a decentralized way by a robust nonlinear model predictive controller (NMPC), taken from [10,11].

2. Swarming model based on topological distance

2.1. Biologically inspired trajectory generation concept

Biologically inspired, the main premise of the proposed swarming model is the absence of inter-agent distance measurement, which is referred as metric distance (terminology used in [2]). The main hypothesis is that agents within a swarm, especially the interior ones, have no other alternative other than to keep themselves as much equidistant as possible from surrounding closest agents. This seems natural, particularly for swarms with large number of members where interior agents have their vision or other sensors in general hindered and could not take a different role (for example, as a temporary leader). As biological agents lack the ability to measure distances, it is reasonable to postulate that they have the ability to discern the relative closeness or remoteness to their neighbors and use this comparison to keep themselves in a centered position. The simplest version of this comparative approach would assume that all agents are from the same species and share similar properties, mainly size. This similarity would allow a sense of relative closeness by comparing their relative perceived size, but this capability by itself is not enough to keep the cohesion. A biologically preferred distance between agents and a preferred speed are assumed to be predefined and common for all members of the swarm.

The space surrounding each agent is divided into solid angles (defined by a range of azimuth and elevation angles) and a radius. These ranges are referred to the agent's position and the direction of the speed vector $\vec{V}$, and horizontally leveled with respect to the inertial coordinate system $\boldsymbol{I}$. As shown in Fig. 1, the space is divided into six lateral azimuth ranges, $\{\xi_1, \xi_2\}$, $\{\xi_2, \xi_3\}$, $\{\xi_3, \xi_4\}$, $\{\xi_4 - \pi, \xi_3 - \pi\}$, $\{\xi_3 - \pi, \xi_2 - \pi\}$, and $\{\xi_2 - \pi, \xi_1 - \pi\}$, a forward looking sector $\{\xi_4 - \pi, \xi_1\}$, and two vertical elevation angles, ν and $-\nu$, generating twelve lateral sectors and two forward sectors. Each of these spherical sectors is bounded by the radius d_p. Motivated by bird's physiology, a blind sector is considered to point backwards. Relative closeness is evaluated between opposed sectors (for example, between sector $\{\xi_2, \xi_3\}, \nu, d_p$ and sector $\{\xi_3 - \pi, \xi_2 - \pi\}, -\nu, d_p$). The number of sectors and their width have been selected arbitrarily but based on a natural biological constraint, assuming that birds cannot concurrently manage a large number of narrower sectors.

The hypothesis in this project, which is tested with unmanned vehicles, is that no cohesion, separation keeping, or alignment happens deliberately, but only an individual autocentering process. Based on the relative closeness perception, locally around each agent, a cohesive swarm congregation emerges globally. Possibly as a consequence, a fixed number of closest neighbors (6–7 agents as reported in [2]) distributed mainly to the sides, arises as a local pattern, and globally the density appears to become constant, independent of the swarm size. The majority of the models based on or derived from the three rules presented in [3], that allow for a cohesive aggregation of birds, are based on distances. The presented logic reproduces the same patterns achieved by those models without resorting to distance measurements, but to relative closeness perception.

In the present work, and as opposed to previous studies and modeling, no distance is used at the guidance level; although some works slightly depart from this restriction. For example, in [6] an adaptive interacting range is adapted online to interact with a predefined number of birds (based on averaged positions and speeds of the closest birds, with a simplified aerodynamic model), and its self-perception relative to the imaginary reference to the nearest neighbors. The research in [4] makes a step towards a more realistic approach by doubting that birds are able to perform sophisticated or time-intensive mathematical calculations. It shows that there must be simple logics to follow in the swarm generation, by questioning that birds are able to perceive the precise information on which most existing mathematical models are based. The research presented in this paper goes a step further than [4] by judging perceptions of distances and angular locations through a simple comparison of relative closeness/remoteness with surrounding birds. This is what probably a human being would do