Semester Report 4

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Title of the dissertation: Design and Realization of an Autonomous Soaring Robot Using Real-Time Information from Wild Birds and Realistic, Data-Driven Model of Atmospheric Convective Updrafts

1 Introduction

Thermal soaring is a form of flight where objects gain altitude using thermals (localised convective updrafts) reducing the need for powered flight (e.g. wing flapping). This type of flight is a challenging due to the complexity of the physics of thermals, but several wild bird species master this challenge. To be successful birds have to adjust their flight to remain close to the center where the updraft is the strongest. They often face this challenge by flying as a flock: the presence of other birds in the same thermal could inform each individual what's happening in other points in space. This social information induces complex group dynamics in multiple spatiotemporal scales.

The main goal of this doctoral project is two-fold: to unravel the rules of collective thermalling of birds and to understand the properties of the thermal they fly in. Using available datasets of bird trajectories I am determining detailed air velocity fields. This in turn allows me to study the physics of thermals and to uncouple the birds' tracks from the air velocity leading to a "pure" study on collective motion.

2 Summary of research work carried out in the previous three semesters

The past semesters were dedicated to the first planned task on this doctoral project: data-driven modelling of thermals using the high-resolution GPS tracks from soaring birds. I am modelling the GPS velocity (velocity relative to the ground) as the sum of two components: the velocity of the air relative to the ground and the velocity of the bird relative to the air. The first step in this task is to decompose the GPS velocities. However, each individual component is unknown making it impossible to determine the validity of the decomposition. To address this issue, I have resorted to synthetic data where each component is known.

In order to be relevant, this synthetic dataset must partially replicate the complexity found in the collected data. To achieve this, the simulated birds' motion must be generated with flight dynamics of an unpowered aircraft under realistic constraints. Moreover, the air velocity field has to include a variety of components that may change in time and in space. Finally, in this complex atmosphere the synthetic birds' must behave appropriately in a way that mimics the stereotypical yet irregular circling in a dynamic and localised updraft.

2.1 Synthetic Dataset

The synthetic dataset is composed of two parts: the air velocity field and the birds' motion. The synthetic air velocity field has been developed to allow a wide variety of complex velocity fields similar to those found by birds when using thermals. It may currently include four components: the (horizontal) wind, thermal's vertical velocity profile and thermal's horizontal rotation, as well as turbulence. All these components may be functions of space and time.

First the thermal core is determined by integrating the air velocity where the thermal is strongest. It establishes, for a given altitude Z and time t, the X and Y coordinates around which the thermal profile and rotation are calculated. At each time step, given a bird's position, all these components are evaluated and summed.

To simulate birds' motion, each bird is assumed to be in steady flight at all times. In this quasi-stationary framing, there are three forces acting on the bird (lift, drag and weight) whose sum vanishes when the bird

is not turning. When turning, the bird produces an horizontal, inwards component of the lift, which is balanced by the centrifugal force, and hence the total force remains zero.
The bird turns by means of the roll motion (defined by its bank angle) which determines its turning radius as well as its velocity. The bird's motion relative to the air is determined by physical parameters - lift coefficient, drag coefficient, mass and wing area - that can be different for each bird. To remain inside the thermal, the bird adjusts its bank angle to keep the bird in the vicinity of an estimated thermal core.
It's important to note that synthetic birds are generated one by one and, therefore, there is no social influence or interaction between them. This will be part of later stages in this doctoral project.

2.2 Decomposition Algorithm

At present, the decomposition algorithm assumes the GPS velocity (velocity relative to the ground) as the sum of the air velocity and the bird velocity, that each bird is in steady flight at all times and that the air velocity does not change over time. Each iteration includes three steps with increasing level of detail:

1. Thermal Core and Wind Estimation

2. Air Velocity Local Averages

3. Apply Steady Fight Rules

On the first step, the thermal core and the (horizontal) wind velocity are estimated by means of a weighted average of the position and the velocity. With this it is possible to separate the wind component from the air velocity and perform a change of variables where the thermal is vertical. On the new frame of reference, since points that are close to each other experience the thermal in a similar way, the air velocity of these points are assigned the corresponding local average. Lastly, in this comoving frame of reference, steady flight rules are applied, yielding estimates for the three components of the birds' velocities and consequently the air velocity. In order to apply the rules of steady flight, one has to use each bird's physical parameters - lift coefficient, drag coefficient, mass and wing area - which are unknown. Currently the parameters in use are constant and equal to all birds, but, the rules for iterating these parameters will soon be implemented.

3 Description of research work carried out in the current semester

During this semester, we studied the effect of turbulence on the flight of the simulated birds. In order to do so, a large number of simulations would have to take place, to explore a significant portion of the parameter space (such as thermal size, thermal strength or turbulence magnitude). However, the turbulence data we are working with is very large and can't be loaded to memory in its entirety. For this reason, the turbulence data is stored in a HDF5 file and only the necessary data is loaded to memory. This makes the simulations take a long time to run. To address this issue, we are currently studying the possibility of a multilevel hierarchical composition of the data from different spatial and/or temporal scales (so containing less data points per level) and by doing so we make use of the self-affine properties of turbulence to make sure the correlation function of the turbulence velocity field remains the same.

On the side of the decomposition algorithm, studying the output and performance of the previous version, I found several places where the method could be further improve. Derivatives, previously calculated using first differences, are now calculated using the five-point stencil technique, yielding velocities and accelerations significantly closer to the ground-truth data.
The wind calculation was also modified to use the thermal core estimate instead of the GPS velocities. Previously, as described on the previous report, the wind was calculated from the understanding that the angle the thermal inclines by must coincide with that of the birds' trajectories, on average. Along the X direction:

$$\tan\theta_x = \frac{v_{air,z,max}}{v_{wind,x}} = \frac{\langle v_{ground,z}\rangle}{\langle v_{ground,x}\rangle} \implies v_{wind,x} = \frac{\langle v_{ground,x}\rangle}{\langle v_{ground,z}\rangle} v_{air,z,max} \tag{1}$$

And similarly for the Y direction. This angle, however, can be also be calculated from the parametric curve defined by the thermal core estimation.

$$\tan\theta_x = \frac{1}{dX_{TC}/dZ_{TC}} = \frac{v_{air,z,max}}{v_{wind,x}} \implies v_{wind,x} = \frac{dX_{TC}}{dZ_{TC}} v_{air,z,max} \quad (2)$$

which is trivially calculated with the use of a cubic spline. This method was found to be a much more accurate estimation of the wind. This method is also much more robust to the presence of birds in exploratory phase, which will certainly appear in the recorded dataset. Furthermore, if so desired, the extrapolation to altitudes not used in the thermal core estimation is also closer to the ground truth data.

4 Studies in current semester

During the current semester I was enrolled in the "Graphs in the bioinformatics" (FIZ/3/063E) class taught by Prof. Gergely Palla, and "Environmental fluid hydrodynamics II. EA" (FIZ/3/037E) class taught by Dr. Miklós Pál Vincze to strengthen my understanding of modelling techniques and atmospheric phenomena.

5 Publications

The method described above is close to being completed and applicable to GPS data collected from soaring wild birds. My supervisor and I expect this work to result in a strong publication on a high impact factor scientific journal in the near future.

6 Teaching activity

Last semester András Zábó joined our research group as a MSc student. The decomposition algorithm and synthetic data presented above were the basis of his project and, along with Dr. Máté Nagy, I was his thesis supervisor. The time dedicated to assisting and advising Mr. Zábó allowed me to improve my mentorship skills, and to further understand the strength and limitations of the synthetic data generation and the decomposition algorithm.

7 Professional Activities

Over the course of my doctoral studies I had several opportunities to give talks on the research group's meetings about the progress of my project, and gather constructive feedback from colleagues and collaborators.
During the first year of my doctoral studies I became administrator of two servers in the Department of Biological Physics, including the HAL server - a central server in the department for over ten years that has been used by dozens of users and hosted numerous (private and public) webpages of past and ongoing projects. In September 2021, this server stopped working and, along with Prof. Peter Pollner, I was responsible for the critical and long migration of this server to a new machine.
During the migration of HAL, a Gitea server (a git-based version control system) was installed to replace the old SVN server. In order to encourage colleagues in the department to use this system, in collaboration with Dr. Gábor Vásárhelyi, I organized a workshop on this technology.

8 Awards

2021 FCT PhD Studentship by FCT (Science and Technology Foundation, Portugal)
2021 Kooperatív Doktori Program by NKFI