Semester Report
Third Semester

Pedro Lacerda (pedrolacerda@student.elte.hu)
Statistical Physics, Biological Physics and Physics of Quantum Systems Doctoral School
Supervisor: Dr. Nagy Máté
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 updrafts) reducing the need for powered flight (e.g. wing flapping). Some soaring birds solve this challenge efficiently by flying as a flock. The main goal of this project is two-fold: to understand the properties of the thermals these birds fly in and to unravel the rules of collective thermalling they fly by. Over the course of past semesters, I have tackled the first of these objectives: data-driven modelling of thermals using the high-resolution GPS tracks from soaring birds. These GPS velocities (velocity relative to the ground) are assumed to be 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 goal of this task is, therefore, to make this decomposition and extract the air velocity. However, we don't have a ground-truth dataset to assess the validity of the decomposition. So I have resorted to synthetic data where each component is known and summed onto synthetic GPS data.

Over the course of this semester, the issues pointed out on the previous report. On the side of synthetic data generation, a turbulence model was introduced to the air velocity field. In this model, the generated turbulence can vary in time and in space and include velocity correlation observed in fluids with fully developed turbulence. Regarding the artificial birds, they can now return to the thermal in the case they find themselves out of the updraft. This important step leads to the possibility of more complex trajectories and air velocity fields. On the decomposition side, a new wind calculation was introduced yielding better agreement with the synthetic wind data.

2 Synthetic Dataset

The synthetic data are being generated from the ground up: determine the bird velocity and air velocity separately, sum them and integrate. I shall detail these two components separately below.

2.1 Air Velocity

The synthetic air velocity field may now include turbulence which can vary in time and in space. The turbulence model (conceived by Prof. Tamás Vicsek and implemented in collaboration with Dr. Liang Li, Max Planck Institute of Animal Behavior) is inspired by well established models from statistical physics. It takes the model on Buldyrev et al. and extends it to three spatial and one temporal dimensions. In this model, a rough surface is grown in a 3-dimensional spatial grid. At each time step, a rod, whose length l is drawn from a power law distribution, is "dropped" on each grid cell. The height of each grid cell, h, is then updated by assigning the maximum height of its first neighbours. Finally, the velocities are calculated with:

$$v(x, y, z, t) = h(x, y, z, t) - \overline{h(t)} \tag{1}$$

where the $\overline{h(t)}$ denotes the average in space. This method is ran three times independently to generate the components X, Y and Z of the turbulence velocity field.

2.2 Bird Velocity

As mentioned on the previous semester report, the birds in our synthesized datasets could not fly back to a region of rising air in case they find themselves out of the updraft. This would result either in synthetic birds spiralling down until they reach the ground or in synthetic birds successfully gaining altitude but with exceedingly regular trajectories. This is an important aspect because not only is it a behaviour that is observed in the real data but it lets us generate synthetic data with a broader range of air velocity fields such as narrower or weaker updrafts. It will also allow use to model the downdraft that is known to surround the updraft.
In order to address this issue, the following was implemented: at each instant, the synthetic bird checks if it had

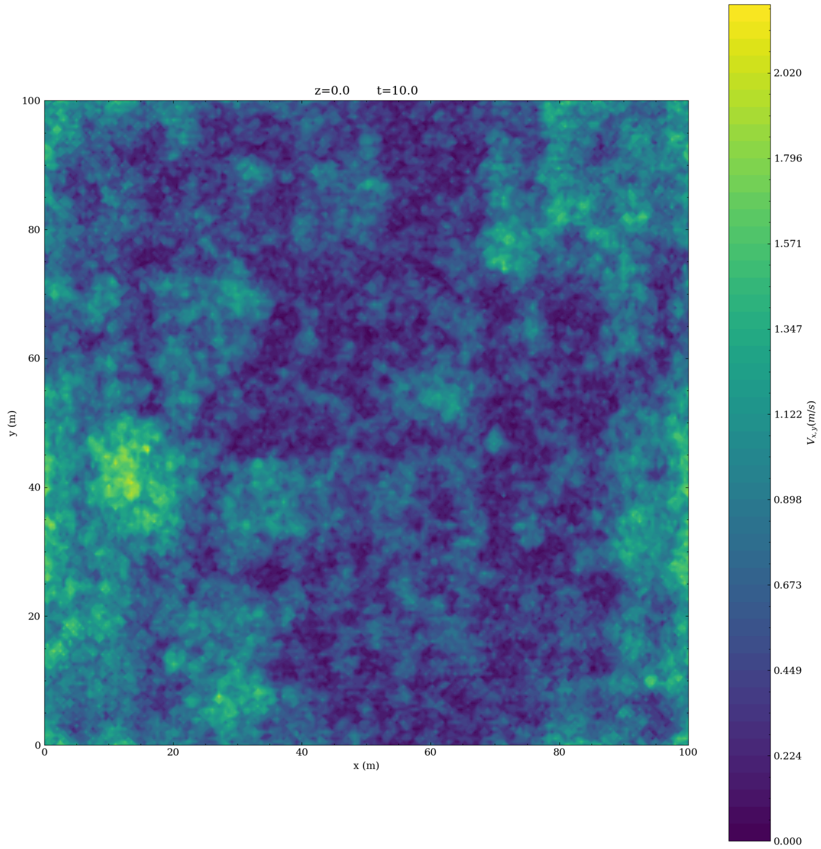

Figure 1: Example of turbulent velocity field - Contour plot of a cross section at $Z = 0.0m$ at the time step $t = 10.0s$ where the color encodes the magnitude of the (v_x, v_y). This turbulent velocity field was generated with 200x200x200 grid cells in X, Y and Z and recorded after 10000 iterations of the algorithm described in the text.

negative vertical velocity in the last N time steps. If so, the synthetic bird stops the thermalling behaviour and will fly towards the position of thermal core estimated at the altitude that is closest to the its altitude at that moment. Once the positive vertical velocity is detected, the thermalling behaviour is adopted.

3 Decomposition Algorithm

One of the first steps of this algorithm is to determine the wind (horizontal) velocity at each altitude. The estimation of wind is illustrated in Fig. 3. As the wind air collides with the updraft, it will incline the thermal and the angle θ (Fig. 3 B) will change:

$$\tan\theta = \frac{v_{air,z,max}}{v_{wind,x}} \tag{2}$$

where $v_{air,z,max}$ and $v_{wind,x}$ denote the maximum of the vertical air velocity and the wind velocity in the X direction, respectively.

While thermalling, soaring birds stay inside the region of updraft (Fig. 3 C). However, assuming their net horizontal movement was only due to the wind, they would lose the thermal since their vertical velocity relative to the air is negative and, consequently, their vertical velocity relative to the ground is less than vertical air velocity relative to the ground (Fig. 3 D). They are, therefore, required to compensate this by flying upwind. Thus,

$$\tan\theta = \frac{\langle v_{air,z} - v_{sink}\rangle}{\langle v_{wind,x} - v_{compensation}\rangle} = \frac{\langle v_{ground,z}\rangle}{\langle v_{ground,x}\rangle} \tag{3}$$

where the $\langle \bullet \rangle$ denote a moving average over the Z coordinate. From Eq. 2 and Eq. 4, we have

$$v_{wind,x} = \frac{\langle v_{ground,x}\rangle}{\langle v_{ground,z}\rangle} \langle v_{air,z,max}\rangle \tag{4}$$

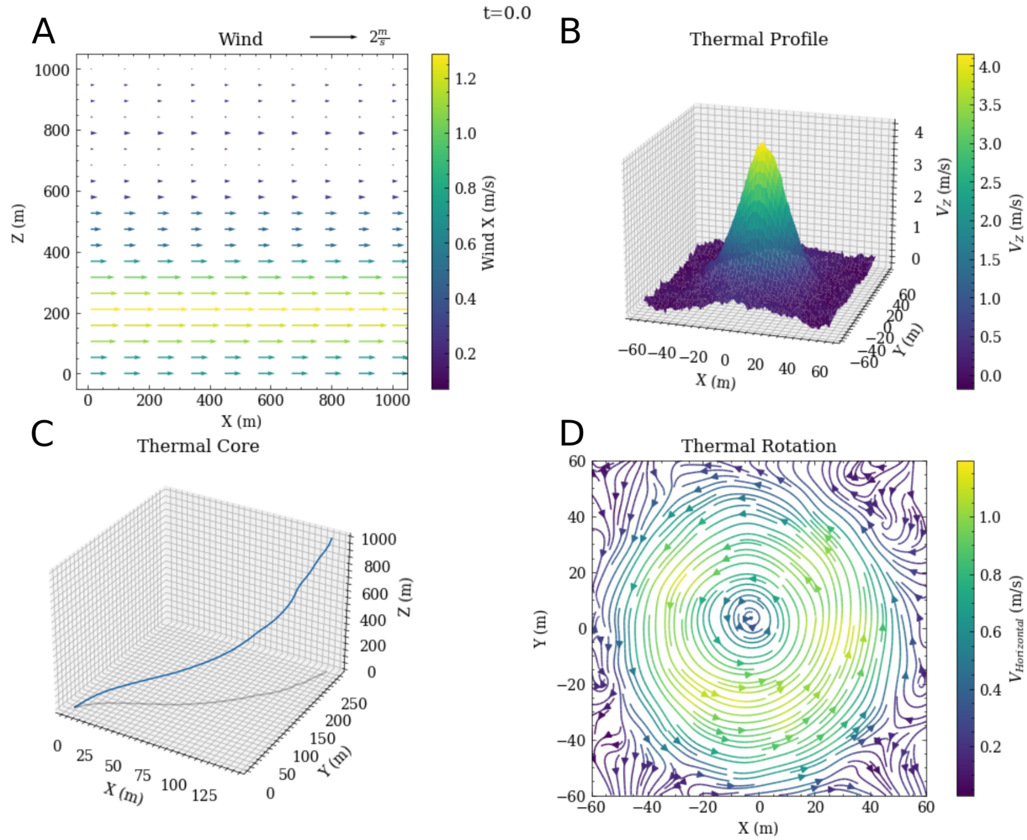

Figure 2: Synthetic air velocity field at the time step $t = 0s$ including turbulent velocity field - (A) data-driven wind along the X direction on earth-fixed coordinate system. (B) Thermal profile on the thermal coordinate system defined as a Gaussian distribution $A = 4m/s$ and $\sigma = 30m$. (C) Resulting thermal core on earth-fixed coordinate system. (D) Thermal rotation on the thermal coordinate system defined as $V_\theta = A\rho(R - \rho)$ where ρ is the distance to the thermal core and R is a parameter $R = 60m$ with maximum value of $2m/s$ at $\rho = R/2$.

In order to complete the calculation for the wind we need the value of $v_{air,z,max}$. Assuming that the thermal vertical velocity profile is maximal in the thermal core, $v_{air,z}$ is well approximated by a quadratic function in a neighbourhood of the thermal core. Thus, on a running window, using points close to the estimated thermal core, a quadratic fit was performed using the values $v_{air,z}$ from the previous iteration. Using the resulting parameter the $v_{air,z,max}$ can be estimated.

4 Future Directions

During the next semester I will further analyse the effect of turbulence on both the decomposition algorithm and on the synthetic data. On a first phase I will run the decomposition algorithm on real high-resolution data of wild soaring birds. This will clarify some of questions we have, such as: should the turbulence be added to the air velocity field as simple summation (Taylor's hypothesis) or should it be weighed with the (local) gradient of the large scale air velocity (source of viscous stress)? What is the order of magnitude of the turbulence experienced by these birds? On a later stage we will attempt to decompose turbulence and find ways to characterize it.

5 Studies in current semester

During this semester I was enrolled in the "Statistical Physics of Biological Systems" (FIZ/3/003E) class taught by Drs. Anna Zafeiris, Liang Li and Máté Nagy, and in the "Evolutionary Game Theory" (FIZ/3/059E) taught by Prof. István Scheuring.

6 Professional Activities

At the very beginning of the semester, HAL - a central server in the Department of Biological Physics - stopped working. Over its life span of more than 10 years, this server has been used by dozens of users and hosted numerous (private and public) webpages of past and ongoing projects. This situation created a number of major problems such

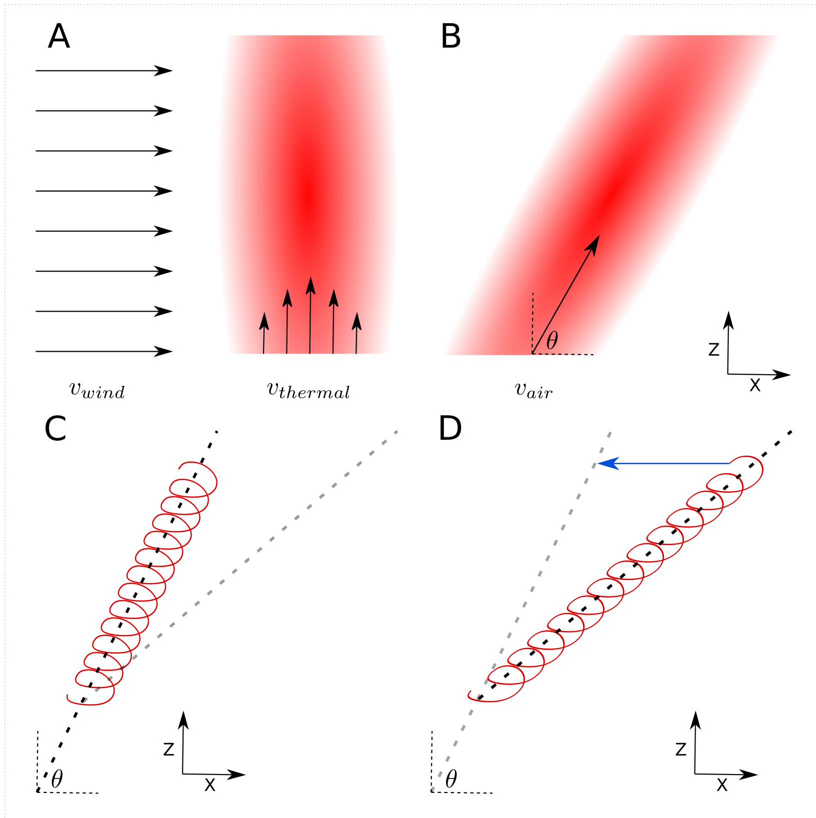

Figure 3: Illustration of a Thermal and Thermalling behaviour in the presence of wind - For sake of clarity, only the X-component of the wind is considered. Likewise, several circle are drawn before any compensation made by the bird: this compensation must happen continuously during circling. (A) Separate wind (horizontal black arrows) and thermal updraft (red) before collision. (B) Thermal column geometry after the collision with wind. Here θ denotes the angle of inclination of the thermal which in the presence of wind is less than 90º. (C) Observed thermal circling (solid red line) around the inclined thermal core (black dashed line). (D) Thermalling behaviour (solid red line) around the center of the trajectory (dashed black line) in the absence of compensation (blue arrow). The necessary position for successful thermalling is shown by the "real" thermal core (dashed gray line).

as current users unable to send or receive emails, unable to access their scientific data or past emails, and inaccessible projects and personal webpages. Along with Prof. Péter Pollner, I was responsible for the migration of this server to a new machine. This included the recovery of data from the disks on the old machine and the secure setup of user accesses, email server and web server on the new machine, all of which had to be adapted to the new system.

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.

During this semester András Zábó joined our research group as a MSc student. The decomposition algorithm and synthetic data present in this and my previous reports will be at the basis of his project. Consequently, I have dedicated part of my time in assisting András Zábó understand the details of my project which gives the opportunity to improve my mentorship skills.

7 References

Buldyrev, S. V., Havlin, S., Kertész, J., Stanley, H. E., & Vicsek, T. (1991). Ballistic deposition with power-law noise: A variant of the Zhang model. Physical Review A, 43(12), 7113.