One Flew Over the Chaos Nest

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Received 06.04.2022, accepted 20.02.2023, published 13.04.2023

We present experimental observations of the flight pattern of a normal fly in a rectangular room driven by its own natural (as we believe) motives. Experimental technique involves utilizing a commercial cellphone-based videocamera in the high frame-rate regime. The recorded data are frame-wise analyzed in order to unravel the hidden structure in the complicated flight pattern.

Introduction

Everyone has seen that: A fly flies into a room through the window and starts meandering around chaotically – at first sight. Is this motion really chaotic? Is there some hidden structure? Or is it maybe the chaos that gives rise to the structure formation?

There is a class of states that are far from equilibrium and stability[1] appearing in nonlinear dissipative systems also related to chaos that is present in many different areas, from pure abstract mathematics to real world. And in the field of chaos there seemed to be no laws, and, hence, no place for science. One of the examples is the Belousov–Zhabotinsky chemical reaction shown in Fig. 1. Billions of cyclic reactions happening simultaneously at various points of the solution create an *autowave* pattern.

Figure 1: Belousov-Zhabotinsky reaction as an example of the chaotic state representing hidden structure. Taken from Ref. [1].

In such chaotic phenomena, there should be no causality and therefore no order – at first sight! However, some of these states can be described mathematically, one of the examples is the so-called *strange attractor*.[2,3] It turned out that such mathematical models can be applied to a number of chaotically-looking nonlinear processes related to climate, economics, society and indeed natural science and reveal the fine structure hidden inside.

Edward Lorenz was the first who obtained the strange attractor mathematically in 1963 solving nonlinear differential equations describing his weather model.[4] The initial set consisted of 12 equations inherently reflecting the complex nature of non-equilibrium processes. After simplifying the model Lorenz ended up with a set of three nonlinear equations that were possible to solve:

$$\begin{aligned} dx/dt &= P(y-x) \\ dy/dt &= Rx - y - xz \\ dz/dt &= xy - Bx \end{aligned} \tag{1}$$

where the *P*, *R* and *B* are the parameters of the considered system and x, y and z are the variables forming the phase space. Employed to describe the time evolution of a system, it was possible to calculate the state of the system at any given time point. Clearly, this seemed to be very attractive for practical purposes, with the potential to predict the future (weather, stock market etc).

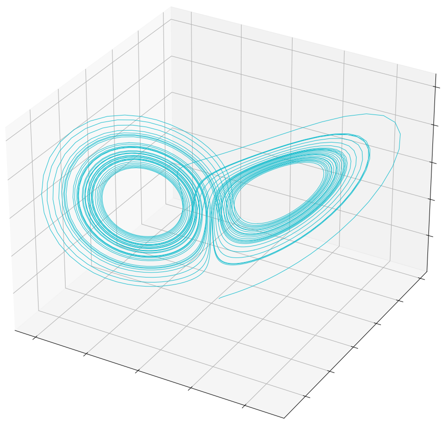

Figure 2: Lorenz's strange attractor in xyz projection.

In Fig. 2, the solutions of equations 1 – or the Lorenz strange attractor – are presented. One can see that even if

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the two starting conditions are *almost* identical, after evolution in time, the system ends up in two states completely apart from each other – in contrast to *normal attractor* – time-asymptotic deterministic final state of a system. This means that even a small uncertainty in our knowledge about the initial state of the system can lead to dramatically distinct predictions about its future (that's why we cannot trust the weather forecasts).

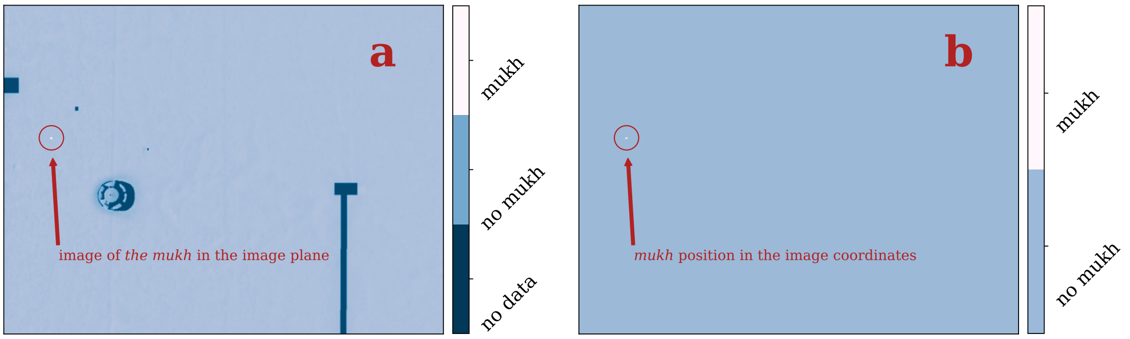

Figure 3: Capturing *the mukh* (in the red circle). (a) Raw image with masked out compromised regions (b) Processed image.

Watching the *mukh**

NB: Here and further the word "fly" is substituted by* ***mukh* *to avoid possible syntactic interference with the verb (like in the first line of the previous Section).*

Mukh observation was performed in a standard bedroom with horizontal dimensions of $\approx$ 250 $\times$ 550 cm^2 and the ceiling height of $\approx$ 300 cm. Preliminary visual observations showed that *the mukh* flies in a plane parallel to the room's ceiling being displaced from it by $\approx$ 30 cm, only slowly shifting its vertical position within several centimeters. This fact simplified the experiment and further data processing, and *the mukh*'s trajectory was recorded by taking a usual 2D video from below. We used a smartphone camera with a resolution of 1920$\times$1080 pixels placed at $\approx$ 230 cm from the ceiling to take videos with a static frame and the image plane parallel to the ground. The camera field of view projected onto an image plane resulted in the available image area after cropping in real space of $\approx$ 200 $\times$ 150 cm^2.

A few videos were taken, in one of them *the mukh* trajectory was localized in the image area not leaving the boundaries (Fig. 4) and this frame sequence consisting of N_{fr} =1600 frames was used for further analysis. Available frame rate of 120 frames/s of the slow-motion regime turned out to have enough resolution of *the mukh* trajectory allowing for tracking the changes in *the mukh* speed $\vec{v}$. Fortunately, the white ceiling was a perfect background for the black *mukh* providing high contrast of the image without the necessity of attaching an LED to *the mukh* that could affect *the mukh*'s flying style.

Frame sequences were imported in PYTHON using the inverted gray scale for frame-wise processing (one of such frames is represented in Fig. 3a). There were some "bad" regions on the ceiling, e.g. a wire or a fire alarm module, so we had to mask out the data points in those regions. The mean brightness was equalized over the entire picture with a Gaussian filter. The brightness of *the mukh* (in the inverted contrast) was found to be $\geq$ 20% higher than the background, and after applying threshold filtering, each frame turned into an array containing only a few pixels with nonzero brightness. To get rid of handling of 1544 arrays each containing almost 1920$\times$1080 of zeros and only few meaningful points we replaced each frame-array with coordinates (x_i, y_i) of the bright pixels (Fig. 3b) resulting in a data array $\sum_{i=1}^{N_{\text{fr}}}(x_i, y_i)$.

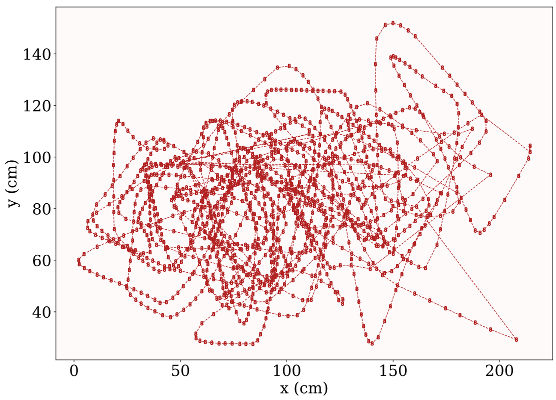

Figure 4: *Mukh*'s trajectory within 1 minute of observation.

The entire continuous *mukh* trajectory after $\approx$ 1 minute of observation is represented in Fig. 4. At first sight, it corresponds to an initial feeling - the motion is chaotic. However, one can observe the intrinsic feature of *the mukh*'s flying style - it moves along a straight line for a while and then makes a turn. This fact is actually consistent with the physiology of *mukh*s. Several studies[5,6] showed that there are two groups of muscles involved in the flight control of a *mukh*. One group is in charge of permanent flight control, making tiny adjustments of the direction to compensate for weak perturbations caused by air turbulence, wind etc. Another strong muscle group is not active most of the time, being involved only for a short time to make fast maneuvers requiring a lot of instant effort.

Let's pick some sequences from the tangled clew depicted above. Six continuous and consequent trajectories are represented in Fig. 5. Here, the character of the motion is seen more clearly - we can distinguish closed polygonal (tetragonal in most cases) trajectories roughly centered around a certain point. The polygonality of the trajectory itself seems to originate from the mechanism of flight control considered above. We can assume that *the mukh* tries to optimize the energy consumption and approximates a circular trajectory (that would be optimal from basic symmetry considerations) with a polygon, for example, with a quadrilateral. The latter can be considered as a distorted projection of the room geometry perceived by *the mukh*.

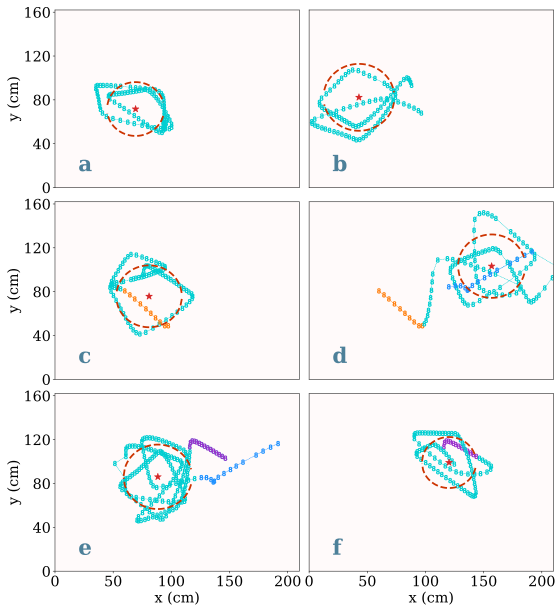

Figure 5: Selected *mukh*'s trajectories. Turquoise points represent the *mukh*'s positions, red dashed circles - the fits with the center point marked with a star. Overlapping last ten points in panel **c** and first ten in **d** are shown with orange dots.

Let us have a closer look at the *the mukh* flying pattern. In the first three panels **a, b, c** *the mukh* moves quasi-concentrically in the left side of the image, however, at some moment (panel **d**) it flies away from one quasi-localized state to start a new bunch of loops in the right side of the scene. Afterwards, *the mukh* repeats such behavior: it makes a few loops on the right, flies to the left and makes a few loops there (panels **e** and **f**) etc.

To reveal the underlying structure of the *mukh* behavior we choose consequent closed loops in *the mukh* trajectory and fit each loop with a circle O^i according to the formula

$$R_i^2 = (x_i - x_{c_i})^2 + (y_i - y_{c_i})^2 \tag{2}$$

using SCIPY.OPTIMIZE.CURVE_FIT method. Each of these fitting circles is thus characterized with the two parameters: the circle radius R_i and the coordinates of the center $C_i = (x_{c_i}, y_{c_i})$.

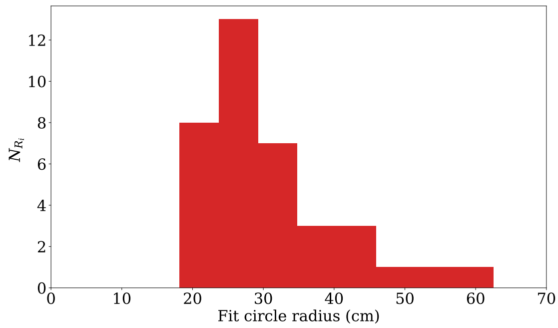

Figure 6: Distribution of the circle fit radii.

We found out that the radius of the circle R_i remains approximately constant (Fig. 6) being equal to ≈ 25 cm and seems to represent some intrinsic geometrical property either of *the mukh* or the room. However, the time evolution of the circle center position C_i reflects the changes in *the mukh* localization. Figure. 7 represents the space distribution of the fit circle center positions C_i with the color gradient showing the time axis. We can see that the circle centers are localized in two clusters – left and right – highlighted with the grey circles.

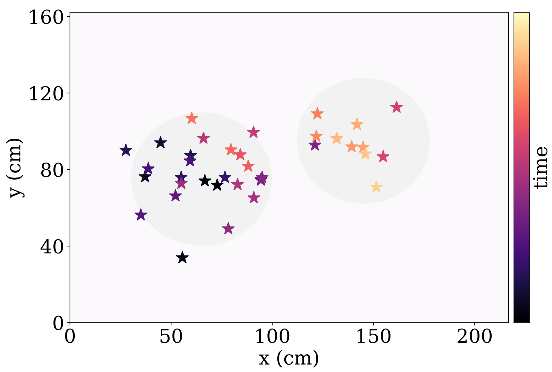

Figure 7: Time evolution of the center position (star marks) of closed *mukh* trajectories. Grey circles are the guides to the eye.

Discussion and conclusion

Lorenz obtained his strange attractor modeling the convective flows of the heated air. And some studies[7-10] on the different types of *mukh*s describe their sensitivity to thermal gradients. Perhaps, *the mukh* tries to follow the air temperature gradients and the errors (uncertainties), accumulating every time it makes a turn, result in forming in its motion a pattern that resembles the strange attractor (with some imagination).

Additional experiments on studying the thermal distribution in a room with an open window on a sunny summer day could clarify if there exist correlations between the well-known *mukh* flight pattern and air temperature gradients. It should be noted that if the number of *mukh*s in the room is > 1, also *mukh-mukh* interaction may occur leading to an even more complicated picture.

In conclusion, we started from a chaotic picture of *the mukh* trajectories shown in Fig. 4, selectively analyzed it and found a consistent pattern. As a result of the fitting procedure described in the previous Section we obtained the time evolution of the center coordinates C_i for each loop within the observation period. Interestingly, the set of the center coordinates C_i manifests splitting into two spatial clusters as shown in Fig. 7. Is it the chaos that gives rise to structure formation?

Read more:

[1] https://www.youtube.com/watch?v=2uVrBqFxnV8&ab_channel=TersetBrayan date of access: 01.05.2022, title: "Searching for the unity (*Rus*: V poiskakh edinstva (Lennauchfilm))", published on 27.08.2020, language – Russian, moment in Fig. 1 – 14:37

[2] Grebogi C., Ott E., Yorke J. A. Chaos, Strange Attractors, and Fractal Basin Boundaries in Nonlinear Dynamics, 1987, Science Vol 238, Issue 4827 632-638 DOI:10.1126/science.238.4827.632.

[3] Grebogi C., Ott E., Pelikan S., Yorke J. A., Strange attractors that are not chaotic, Physica D: Nonlinear Phenomena **13**, 261-268 (1984). https://doi.org/10.1016/0167-2789(84)90282-3.

[4] Lorenz E.N., Deterministic Nonperiodic Flow, Journal of the Atmospheric Sciences **20**, 130 (1963).

[5] Schönbauer, C., Distler, J., Jährling, N. et al. Spalt mediates an evolutionarily conserved switch to fibrillar muscle fate in insects. Nature 479, 406–409 (2011). https://doi.org/10.1038/nature10559.

[6] Lindsay T., Sustar A., Dickinson M. The Function and Organization of the Motor System Controlling Flight Maneuvers in Flies. Current Biology **27**, 345-358 (2017).

[7] Simões J.M., Levy J.I., Zaharieva E.E. et al. Robustness and plasticity in Drosophila heat avoidance. Nat Commun **12**, 2044 (2021). https://doi.org/10.1038/s41467-021-22322-w

[8] https://biology.ucdavis.edu/news/flight-turbulence-new-study-explores-how-flies-navigate-unstable-convective-air date of access: 01.05.2022

[9] Anantanawat K., Papanicolaou A., Hill K., Xu W., Molecular Response of the Mediterranean Fruit Fly (Diptera: Tephritidae) to Heat, Journal of Economic Entomology **113**, 2495–2504 (2020). https://doi.org/10.1093/jee/toaa147.

[10] Timchenko S., Bimatov V., Kuznecov P., Sidorenko Yu., Multiobjective asynchrone parallel genetic algorithm for reentry trajectory optimization, Parallel Computational Fluid Dynamics 2003, Elsevier, 2004, Pages 447-454.