Visualization of Vortices in Simulated Airflow around Bat Wings During Flight

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Introduction:
We present visualizations that emphasize vortices in simulated airflow around a motion-captured bat model. These visualizations aim to help biologists gain understanding on the mechanics of bat flight. As suggested by our fluid dynamics collaborators, studying the formation and shedding of vortices in the flight of bats will help scientists understand the efficient mechanisms bats employ in generating lift. By understanding bat flight, we hope to make discoveries in areas such as biomechanics, aerodynamics, and evolutionary biology. This work is the time varying extension of R. Weinstein's simulation and visualization of a still bat [7].

Data Acquisition:
The Swartz Lab acquired motion-capture data of bat flight by flying more than 20 individuals of several species through a wind tunnel [1]. This research focuses on the data from one individual of a large-bodied (600-1000 g) species, *Pteropus poliocephalus*. Two high-speed digital cameras tracked infrared markers on the bat. Software triangulated the camera data to arrive at 3D coordinates and converted them to a coordinate system centered at the bat's sternum marker. Additional processing and smoothing made the raw motion data simulation-ready.

Simulation:
A polygonal model that spatially interpolates the motion markers along a whole wing beat cycle is fed to Gridgen [2], a simulation mesh generation package. Up to 60 tetrahedral meshes of the volume around the bat are generated and interpolated over time. These grids are used by our simulation package Nektar [3] to produce time varying vector and scalar fields that describe the airflow within a box-shape volume around the bat.

Pre-visualization:
The size and complexity of the time varying fields generated by the simulation makes them unfit for real-time visualization. To overcome this limitation, our method pre-computes and stores sets of pathlines and streamlines that can later be visualized interactively. The line sampling and visualization methods used on the bat flow data is a variation of the one presented in Particle Flurries [4] for the visualization of blood flow in a coronary artery.
In order to emphasize vortices we sample Hussein's λ_2 values [5] in a high-resolution grid covering the whole simulation volume. Negative values of λ_2 indicate the presence of a vortex. The best samples, which are the most negative ones, are used as seeds for flow-lines. Redundancy is avoided by skipping seeds that are close to previously computed lines. The result of this process is a set of flow-lines sorted by lowest λ_2 point, which preserves a Poisson-disc distribution in space/time.
This sequential approach to computing pathlines requires loading all time-steps of data into main memory simultaneously. Memory addressing limits of our Pentium/Linux systems prompted the development of a multi-process data server that keeps each time-step of flow data in it's own process. By running both our flow-line computation process and the data server on a single machine with enough RAM we avoided the overhead of inter-process communication through a network.

Visualization:
We visualized the flow data in the CAVE [6], an immersive, 3D, stereo display environment which scientists found more engaging than our less sophisticated desktop displays.
One of our visualizations shows massless particles that flow down pre-computed pathlines, which resemble eels of variable length, color and opacity.
A second visualization relies on animated streamlines, represented with lines of variable color and opacity.
The user has interactive control over the number of lines that are displayed, how randomly they are picked from the sorted line set and the mapping of opacity to flow quantities. These controls allow users to explore a continuum between localized visualization of detected vortices, and the contextual flow around them.

Discussion and Conclusions:
We completed a full iteration of simulation and visualization of unsteady flow around unsteady geometry.
Streamlines, with their instantaneous nature, proved to be better than pathlines at showing vortices, however, our visualizations based on particles were better at showing the signature of vortices in the wake of the bat.
The user is given control over how much the representation of numerically detected features blend in with their surrounding contextual flow. We believe that the use of this kind of fuzzy representation of features helps engage the human's vision system in the detection and validation of vortices as well as finding the relation of vortices with the rest of the flow.

Even though the low Reynolds number (Re = 100) of our simulations is far from a physically accurate one, they allowed us to develop visualizations that show vortices and that will extend to higher, more realistic Re numbers. Due to the interdisciplinary nature of this project, these forms of visualization in a 3D environment like the CAVE have been effective in allowing experts from varied fields to collaborate in new and exciting ways.

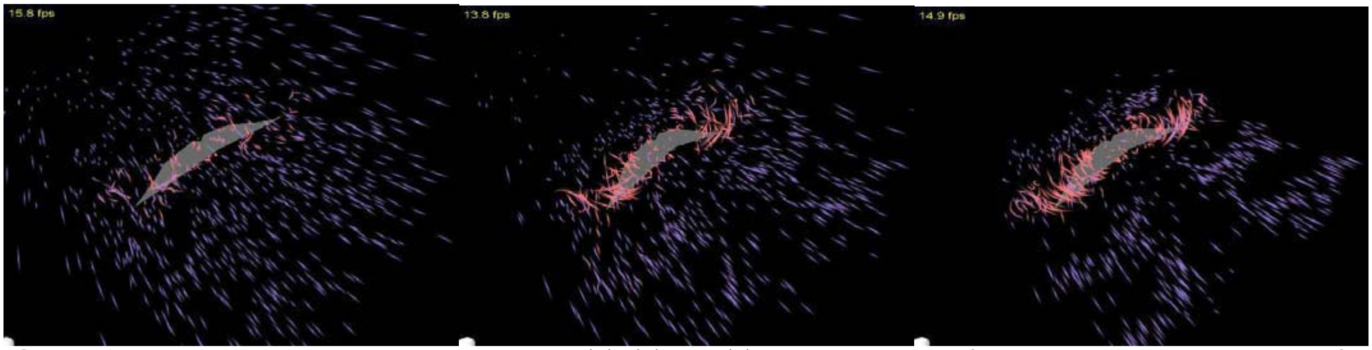

Figure 1: Particle eels turn red in low λ_2 regions. (a), (b) and (c) show variations of randomness in the selection of pathlines. (a) shows random selection of pathlines, (c) shows only pathlines with negative λ_2 .

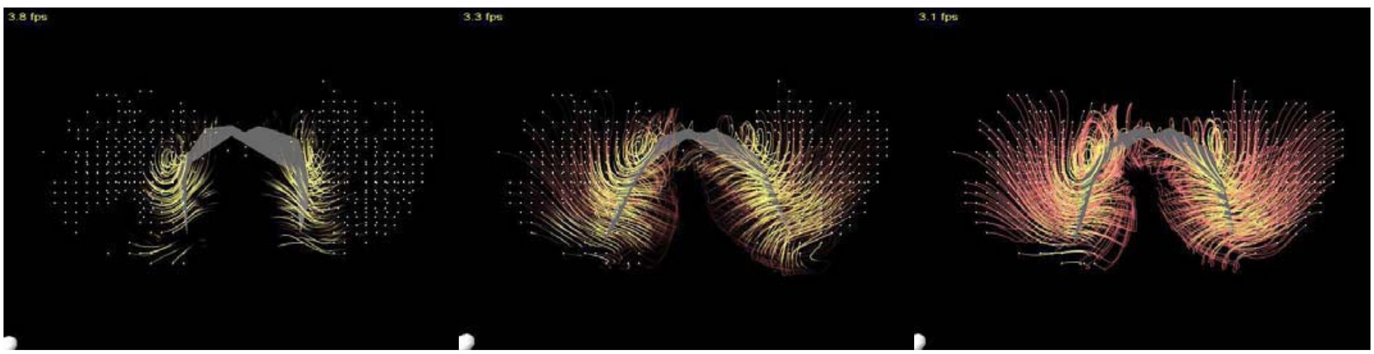

Figure 2 Streamlines seeded at low λ_2 regions. (a), (b), (c) show variations of the mapping of transparency to $\boldsymbol{\lambda_2}$. White dots represent the seeds of streamlines. Yellow color maps to low λ_2 values.

Movies:
http://www.cs.brown.edu/research/vis/areas/projects/bat.html

Figure 3: White dots, “snow flakes”, are used to represent particles at low $\lambda_{2,}$ regions. High number of particles can be rendered due to their graphical simplicity.

References:

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