Simulation and Visualization of Air Flow Around Bat Wings During Flight

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Problem

We present a method for simulating and visualizing air flow around a static bat (order Chiroptera) wing geometry. This demonstration serves as proof-of-concept for simulating and visualizing air flow around a time-varying geometry in order to understand the aerodynamic principles behind bat flight. By understanding the mechanics of bat flight, we hope to make discoveries in areas such as biomechanics, aerodynamics, and evolutionary biology.

Geometric Model Construction

We have taken one time step of bat flight motion capture data from the wind tunnel to the CAVE. After obtaining motion capture data in wind tunnels using high-speed digital cameras [1], we created a time-varying polygonal geometric model. Wings are represented by infinitely thin tessellations of triangles. The triangles provide an approximation of the normally rounded surface of the bat wing. An example of the model is shown in Figure 1.

By using specially formatted text files to represent the geometry, the program facilitates the user's ability to load geometries from different bats of very diverse wing form. This research focuses on data from an individual from a small-bodied (3-5 *g*) species, Rhinolophus megaphyllus. The number of points tracked on bats varied. For the bat used in this research, markers were placed on the bat's left side only and mirrored across the animal's midline to yield the complete geometry. Animations from this model were exported to Quicktime and could also be viewed in the CAVE.

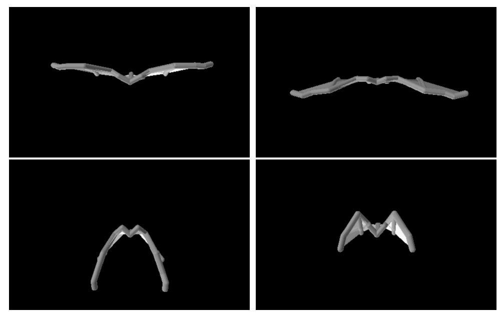

Figure 1: Frames from an animation of the polygonal geometric model of the bat shows the skin represented by infinitely thin polygons as well as the deformation which the model undergoes.

Mesh Generation

We imported different positions of the model into the grid-generating program Gridgen [2]. A volume of 10 by 10 by 20 non-dimensional units was defined around the bat geometry, which had a wing span of approximately 3 non-dimensional units at its widest. We triangulated at a rate of 2 non-dimensional units on the surfaces of the volume and a rate of 0.1 non-dimensional units on the bat geometry. This provided a focus on the more interesting flow patterns near the bat. The triangulation was used to subdivide the volume into tetrahedral spaces.

The mesh for the bat changes significantly over a given wing beat. As a result, multiple meshes are necessary and must be interpolated together in order to achieve a simulation of an entire wing beat. After a mesh is created, a preliminary simulation is run to determine how many frames later the next mesh should be created. Once all necessary meshes are created, a time-varying simulation of the flow through an entire wing beat of the bat can be carried out.

Simulation and Visualization

The fluid-simulation program, NekTar [3], used the aforementioned meshes to calculate velocity field data of the volume surrounding the bat geometry. We visualized the flow data in the CAVE, a 3D, stereo immersive environment. The flow visualization software was previously developed to view blood flow in an artery [4] and worked well to demonstrate the flow of air within the volume surrounding the bat. An example of this visualization tool

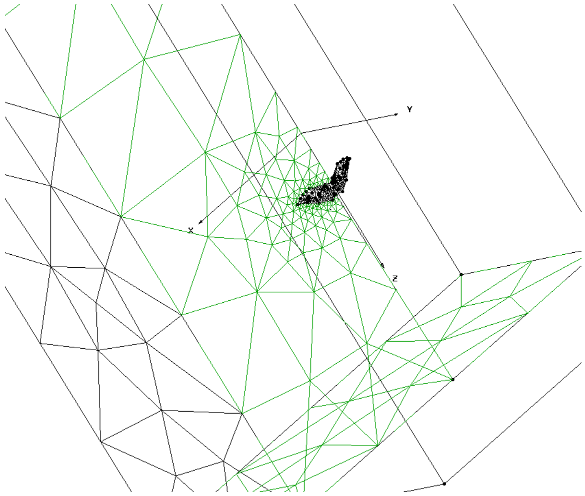

Figure 2: A Gridgen screengrab. Here, a user specifies which surfaces should be triangulated.

can be seen in Figure 3. Pathlines representing the path of massless particles demonstrate the air flow. The length of a given pathline indicates velocity where longer paths have faster velocities. Using this tool, we were able to see interesting flow patterns around the static bat geometry, such as small vortices coming off the back of the wings.

Discussion and Conclusions

The simulation and visualization of bat flight in 3D represents an important step in simulating biomechanical behavior. One area that could use further investigation is the source of the bat's lift. Information about the pressure distribution on the wing's surface could yield interesting discoveries about the mechanics of bat flight in relation to aerodynamics. On the static model initial tests show pressure that is relatively invariant in a single time-step of an intrinsically time-varying process; more novel and informative patterns are expected in analysis of the realistic time-varying simulation.

From the visualization of air flow around the static geometry, we learned that the shape of a bat's wing generates unique air flow patterns. Analysis of the visualization of the recently completed simulation of a full wing beat will hopefully shed more light on the mechanics of bat flight. This represents an important development in evolutionary biology with regards to simulating animal flight. This simulation is an important step not only towards simulating and visualizing the air flow around a flying bat, but also towards learning to simulate and visualize highly-deforming, time-varying geometries.

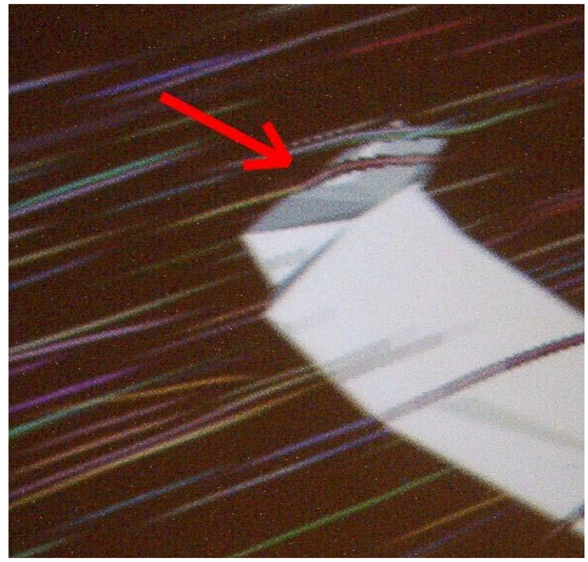

Figure 3: The red arrow in this photo taken in the CAVE points to particles moving along curved pathlines as they move over the bat geometry.

Acknowledgments

Thanks to Maryem-Fama Ismael Aguirre and Kristin Bishop for their knowledge of bats. Thanks to Jason Sobel for his assistance with the visualization. Thanks to Andy Forsberg for additional visualization. This work is partially funded by the National Science Foundation (CCR-0086065 and NSF-IBN 9874563 to SMS).

References

[1] Sharon M. Swartz, Maryem-Fama Ismael Aguirre, and Kristin Bishop. "Dynamic Complexity of Wing Form in Bats: Implications for Flight Performance." Functional and Evolutionary Ecology of Bats. Eds. Z. Akbar, G. F. McCracken, and T. H. Kunz. Oxford University Press, at press.

[2] Pointwise, Inc. 213 S. Jennings Ave. Fort Worth, Texas 76104-1107, USA. 1996-2001.

[3] Tim Warburton. *Spectral/hp Methods on Polymorphic Multi-Domains: Algorithms and Applications*. Ph.D. Thesis, Brown University, RI, 1999.

[4] Jason S. Sobel. *Particle Flurries for Visualizing 3D Pulsatile Flow*. Honors Thesis, Brown University, Providence, RI, 2002.

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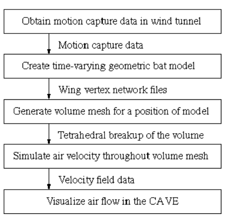
Problem

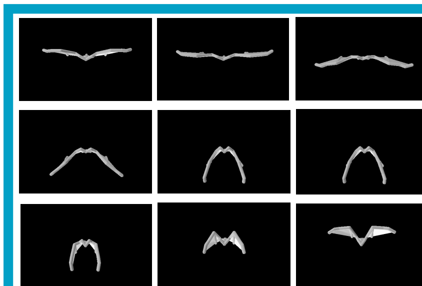
When bats fly, their wings undergo large amplitude motions and deformations. As a consequence, simulating and visualizing the way air flows around the bat is extremely complex, and biologists have yet to gain a full understanding of the aerodynamics and mechanics of bat flight. We present a method for simulating and visualizing air flow around a static bat wing geometry. This demonstration serves as proof-of-concept for simulating air flow around a time-varying geometry in order to understand the aerodynamic principles behind bat flight. This poster illustrates the steps taken to arrive at this simulation. By understanding the mechanics of bat flight, we hope to make discoveries in areas such as biomechanics and aerodynamics.



Right, a flow chart diagrams the steps taken to arrive at the final simulation and visualization.

Data Acquisition

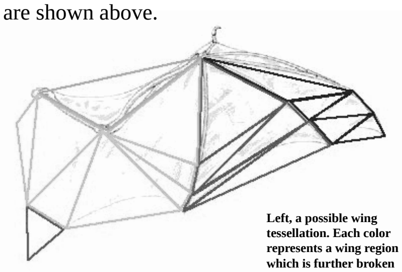
The Swartz Lab acquired motion capture data of bat flight by flying more than 20 individuals of several species through wind tunnels [1]. This research focuses on the data from one individual of a small-bodied (3-5 *g*) species, Rhinolophus megaphyllus. Two high-speed digital cameras tracked infrared markers on the bat. Software interpolated the camera data to arrive at 3D coordinates and converted them to a coordinate system centered at the bat's sternum marker.



Above, shots of a wing beat taken at every 6th frame demonstrate the significant amount of deformation which occurs to the model's wings during flight.

Geometric Model

We created a polygonal geometric model of the bat using the motion capture data. Each wing was represented as a tessellation of triangles. By storing the geometry definition in specially formatted text files, the program facilitates the user's ability to load geometries from different bats of very diverse wing forms. In the case of the bat used for this simulation, markers were placed on the bat's left side only and mirrored across the animal's midline to yield the complete geometry. We built the model using WorldToolKit, allowing it to be ported to the CAVE. Animations of the bat can also be exported to Quicktime; sample frames are shown above.

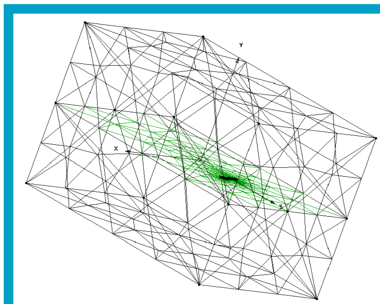


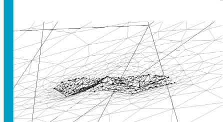
Left, a possible wing tessellation. Each color represents a wing region which is further broken down to triangles.

Visualization

Top, a photo taken in the CAVE shows cylinders representing the paths of particles in the air flow. Bottom, a screengrab in the CAVE shows orange kelp highlighting flow patterns of selected particles.

We manipulated velocity field output from NekTar to produce a 3D visualization of simulated airflow around the bat geometry in the CAVE. We used a visualization tool previously developed for viewing blood flow in an artery [4], shown in the top photo. We also visualized the velocity path of some particles using a technique known as kelp [4], shown in the bottom photo. The color of the kelp indicates the pressure at that point. The uniform color of the kelp suggests that pressure is relatively invariant in this single time-step of an intrinsically time-varying process; more novel and informative patterns are expected in realistic time-varying simulations.





Above, a mesh of the entire volume around the bat. Left, a detailed view of the increased triangulation near the bat geometry.

Mesh Generation

The fluid-simulation code used, NekTar [2], requires meshes to represent the bat and the surrounding space within the volume in order to simulate the air flow around the bat. By importing the model into Gridgen [3], a commercial grid-generation program, we created a mesh within a defined volume of 10 by 10 by 20 non-dimensional units, where the bat has a wing span of approximately 3 units at its widest point. The surfaces are triangulated such that a vertex exists every 0.1 non-dimensional units on the bat, but only every 2 non-dimensional units on the volume surfaces in order to focus on the more interesting events which occur closer to the bat.

Summary and Conclusions

- At this point we have taken one time step of bat flight motion capture data from the wind tunnel to the CAVE
  - demonstrative that we can repeat steps for a full wing beat
- Simulation and visualization of bat flight in 3D represents an important step in simulating biomechanical behavior.
  - kelp may yield more information on the source of the bat's lift, particularly on the pressure distribution
- Work is continuing on simulation and analysis of a full wing beat, including:
  - creating more meshes
  - refining visualization techniques

References

[1] Sharon M. Swartz, Maryem-Fama Ismael Aguirre, and Kristin Bishop. ``Dynamic Complexity of Wing Form in Bats: Implications forFlight Performance." Functional and Evolutionary Ecology of Bats. Eds. Z. Akbar, G. F. McCracken, and T. H. Kunz. Oxford University Press, at press.

[2] Tim Warburton. *Spectral/hp Methods on Polymorphic Multi-Domains: Algorithms and Applications*. Ph.D. Thesis, Brown University, RI, 1999. *http://www.cfm.brown.edu/people/tcew/nektar.html*

[3] Pointwise, Inc. 213 S. Jennings Ave. Fort Worth, Texas 76104-1107, USA. 1-888-GRDIGEN. 1996-2001. *gridgen@pointwise.com http://www.pointwise.com/*

[4] Jason S. Sobel. *Particle Flurries for Visualizing 3D Pulsatile Flow*. Honors Thesis, Brown University, Providence, RI, 2002.

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