3D Reconstruction and Analysis of Bat Flight Maneuvers from Sparse Multiple View Video

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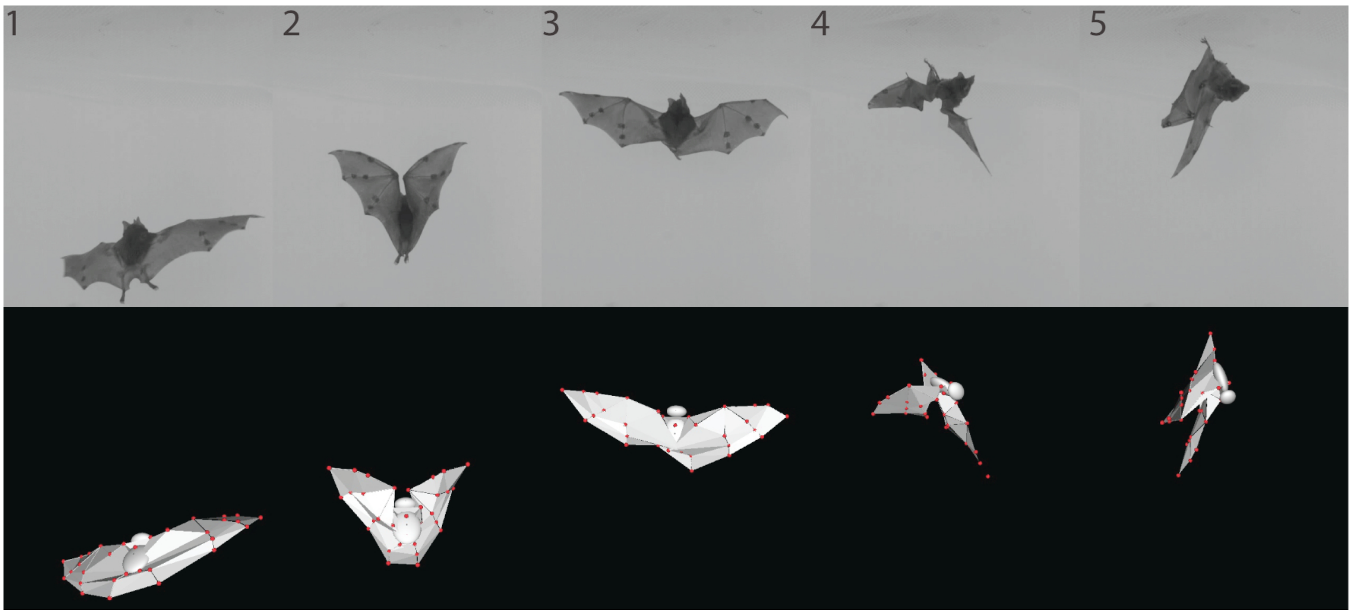

Figure 1: Real world tracking results of a bat using a 52 degree of freedom articulated model. Shown on top are frames extracted from high speed video of a landing bat. Shown on the bottom are the corresponding frames of the reconstructed three-dimensional wing and body kinematics.

ABSTRACT

We present a novel framework for the 3D reconstruction and analysis of complex flight maneuvers performed by bats. By incorporating biomechanical and geometric knowledge about bats into an articulated model, we are able to recover the time varying posture of freely flying bats from sparse multiple view high speed video. We apply this tracking method, in conjunction with a simulation framework we developed, to analyze how bats perform complex aerial rotations during landing and takeoff.

Index Terms: I.4.8 [Image Processing and Computer Vision]: Scene Analysis—Tracking; I.6.m [Simulation and Modeling]: Miscellaneous—; J.3 [Life and Medical Sciences]: Biology and genetics—; J.2 [Physical Sciences and Engineering]: Physics—

Motion is ubiquitous in Biology: all living organisms exhibit motions at some level from the cellular to the macroscopic. For animals in particular, motion determines how they forage, migrate, mate, where they live and how they escape predators. Because of the biological significance of animal movement and the increased availability of high quality cameras for motion capture, there is growing interest in quantifying animal locomotion from multiple view video. Despite this interest, 3D motion reconstruction methods predominantly focus on the capture and reconstruction of human motion. As such, there are fewer sophisticated methods for analysis of animal locomotion.

In this work, we detail a method to measure and analyze the flight kinematics of freely flying bats. Bats have recently garnered interest from both the engineering and biological communities because of the exceptional flight characteristics they demonstrate. They have evolved a particularly impressive capacity to control their flight resulting in these animals being adept at maneuvering while being highly efficient fliers [1, 6]. This adeptness is, in part, determined by bats ability to modulate their wing shape in detail through more than 24 independently controlled wing joints [3]. This intricacy of bat kinematics greatly complicates their motion analysis relative to other animals. We develop a framework for the extraction of detailed wing and body kinematics of bats from multiple view video and computational models to investigate the link between a bats wing movements and the resulting complex flight maneuvers.

The primary contribution of this work is two-fold. First, we detail the development of a practical and versatile tracking framework to estimate the posture of the highly articulated flight kinematics of bats. Our method demonstrates the feasibility of tracking highly articulated motions by detecting only a sparse set of image features.

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Because our approach is quite general, we believe that it can be widely applied to study animal and human locomotion. Second, we apply our framework to develop a dynamical model of a bat and explore how bats are able to help control flight maneuvers. We apply our motion reconstruction method to analyze particularly striking aerial maneuvers - complex aerial rotations performed by bats during landing and take-off - to show how their wing movements quantitatively lead to changes in their body kinematics.

1 Tracking of Freely Flying Bats

We extract the detailed three-dimensional wing and body kinematics of bats from videos taken by multiple calibrated high-speed cameras. Previous investigations of bat flight kinematics have relied on hand digitizing video markers and direct triangulation of their 3D positions (e.g. [7, 5]). Due to the relatively sparse camera arrays used to reconstruct these kinematics and the large scale motions that bat wings exhibit in-flight, the reconstructed kinematic data often contain gaps where insufficient information exists to directly triangulate marker positions. To increase the accuracy and simplify the task of tracking, we developed a model-based tracking method where known biomechanical constraints can be incorporated into tracking. Our tracking method will be used to reconstruct the flight kinematics of a variety of bat species, consequently, we accommodate models that are quite general.

We phrase tracking as a non-linear state estimation problem. That is, we estimate the time-varying *state* of an articulated bat model from a set of *measurements* of known markers in a sequence of images from a number of calibrated cameras. The markers can be synthetic - drawn to the bat - or natural - formed by the texture on the bat's own skin. The model state is parametrized by body position, orientation, wing joint angles, and geometric parameters specifying the dimensions of the model. We approximate the model's dynamics and the mapping from state to measurements by stochastic functions. To track, we estimate the most likely model's state at each time-step given measurements at the current and all prior time-steps. We use the infrastructure provided by the Square Root Unscented Kalman filtering (SRUKF) method to determine this estimate[2].

In figure 1 we show real world tracking results achieved using our tracker. We used image sequences (show on top of figure) from three calibrated high-speed cameras to track the wing and body kinematics of a landing bat using a 52 degree model (results shown on bottom of figure).

2 Complex Aerial Maneuvers Performed by Bats

By leveraging the detailed wing and body kinematics provided by our motion tracking method, we investigate how bats modulate their wings' motion to perform flight maneuvers. Here, we focus on a particular flight maneuver and ask: how do bats reorient themselves during landing and take-off? Many species of bats roost head-under-heels [4]. Since bats are unable to fly upside down, they must perform a complex aerial rotation when transition between flying and roosting (see figure 1).

To investigate how bats perform this complex maneuver, we build a detailed dynamical model of a bat. Using this model in conjunction with the measured wing kinematics, we then show that surprisingly modulation of wing inertia plays the dominant role of reorienting the bat with little or no reliance on aerodynamic forces. Thus, much like a falling cat, a bat is able to change its bodys orientation mid-flight without relying on aerodynamic forces and instead by changing the mass distribution of its body and wings

Acknowledgements

The authors wish to thank Daniel K. Riskin, Lauren Reimnitz, and Jorn Cheney for help with experiments and valuable discussions. This work was supported by the AFOSR MURI program on bio-inspired flight and NSF grants numbers CCF-0729126, IIS-0808718, and CCF-0915661.

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