Literature Survey

for ButterFlight

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CIS 6600
Advanced Topics in Computer Graphics and Animation

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Introduction

Realistic modeling and simulation of living things has found numerous applications in entertainment, virtual worlds, education, and behavioral analysis. In recent years, various efforts have been attempted to model and animate a variety of flying creatures, including birds [WP03][Ju13], dragonflies, bats, and insects [WJDZ14][WRJM15]. However, realistically simulating butterfly flights for real-time graphics and animation applications remains an under-explored problem. Experiment-based methods have difficulty acquiring full trajectories of real-world butterflies; CFD-based methods are computationally too expensive for real-time simulation; and, unlike many flying insects, a butterfly flies with small flapping frequencies and exhibits closely coupled wing-body interaction that cannot be ignored.

Our authoring tool, ButterFlight, is based on the practical force-based model proposed by Chen et al. [CLTL22]. This approach first models a butterfly with parametric maneuvering functions including wing-abdomen interaction, then simulates dynamic maneuvering control through a force model that includes both a simplified aerodynamics force and a curl-noise vortex force.

In this literature survey, we trace three converging research threads that lead to [CLTL22]: (1) from the seminal quasi-steady aerodynamic theory for insect flight [Ell84], through bird and butterfly flight animation, to the parametric maneuvering functions for butterfly wing-body motion; (2) from the seminal Boids flocking model [Rey87], through biologically-plausible insect swarm simulation, to the chaotic trajectory generation for flying insects; and (3) from Perlin noise [Per02] and curl-noise [BHN07], to the vortex force model that drives inherent noisy behavior in butterfly flight.

Content

The research evolution is shown in the following graph:

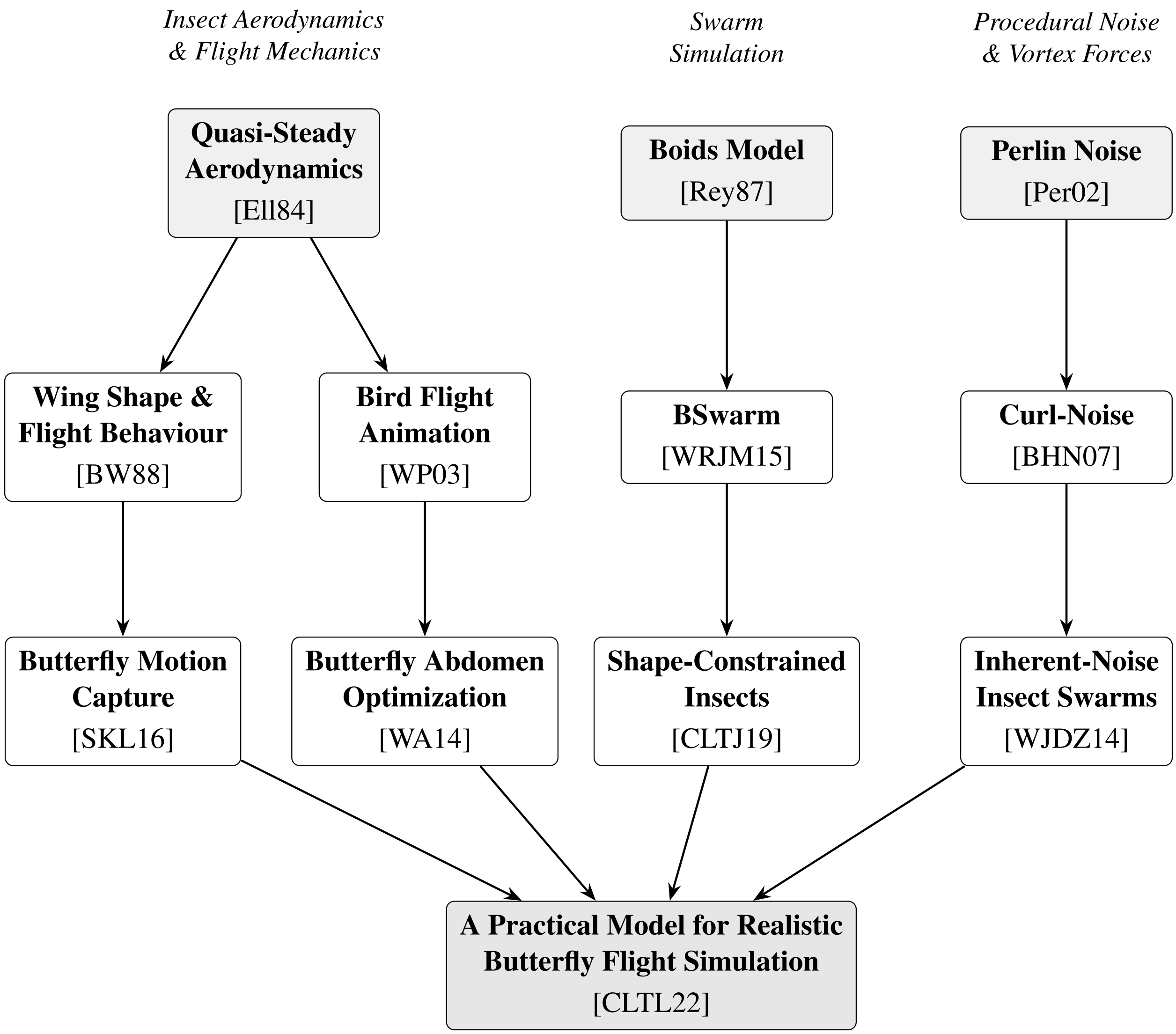

Figure 1: Research Evolution Graph

[Ell84] In this seminal work, Ellington establishes the quasi-steady aerodynamic theory for analyzing hovering insect flight. The framework computes instantaneous lift and drag forces on insect wings based on the angle of attack, wing area, and air velocity, using empirically derived lift and drag coefficients. This quasi-steady analysis became the standard approach for modeling the aerodynamic forces of flapping insect wings without resorting to computationally expensive CFD solvers. In Chen et al. [CLTL22], the simplified aerodynamic force equations (Equations 4–6) are built directly on this theory.

[Rey87] Reynolds introduced the Boids model, a seminal distributed behavioral model for simulating flocks, herds, and schools. Each agent follows three simple local rules—separation, alignment, and cohesion—to produce emergent collective behavior. This work laid the foundation for all subsequent swarm simulation methods. However, the basic Boids model does not support physical forces for realistic simulation. Later works extended these ideas with biologically-motivated spatial zones (repulsion, alignment, attraction), which in turn led to the insect swarm models that feed into [CLTL22].

[Per02] Perlin improved his original noise function with better gradient computation and reduced directional artifacts. This procedural noise generation technique became fundamental to many graphics applications, from terrain generation to texture synthesis. In the context of butterfly simulation, Perlin noise is integrated into the curl-noise vortex force (Equation 7 in [CLTL22]) to produce the time-varying, spatially coherent noise field that drives the inherent chaotic behavior of butterfly flight.

[BW88] Betts and Wootton present the first detailed kinematic investigation of butterflies performing varied patterns of natural flight. Six butterfly species flying freely in the field were filmed with a high-speed ciné camera and subjected to kinematic and morphometric analysis. They characterized flight modes—fast forward, slow forward, hovering, and climbing—and found correlations between flight performance and wing shape parameters including aspect ratio, wing loading, and moments of wing inertia. Their finding that butterflies exhibit great flight versatility through startling shifts in frequency, amplitude, and stroke plane angle motivates the parametric maneuvering approach used in [CLTL22].

[WP03] Wu and Popović apply aerodynamic theory to animate realistic bird wing flapping. They introduce parametric maneuvering functions to control wing motion during flight and optimize the maneuvering parameters of both wings and feathers through an offline method. This was the first work to bridge aerodynamic force models with computer graphics animation of flapping flight. The periodic maneuvering function design used in Chen et al. [CLTL22] (Equation 1) is directly inspired by this work and by [WA14].

[BHN07] Bridson, Houriham, and Nordenstam propose curl-noise as a procedural approach for generating divergence-free velocity fields for fluid flow simulation. By taking the curl of a potential field constructed from Perlin noise, the method produces incompressible, collision-free flow fields. Chen et al. [CLTL22] extends this approach to compute an artificial vortex force acting on the butterfly thorax (Equation 7), simulating the wake influence of wing flapping and the inherent noisy behavior observed in real butterflies.

[WRJM15] Wang et al. propose BSwarm, a biologically-plausible dynamics model for insect swarms. This work, from the same research group (co-authors Jin and Manocha) as [CLTL22], established the framework for biologically-grounded insect swarm animation. However, BSwarm and similar swarm methods focus on macro-level swarm trajectories, using pre-created cycle-frames for individual insect motion—a limitation that [CLTL22] addresses with its micro-level force-based model.

[WJDZ14] Wang et al. apply a curl-noise field to compute collision-free trajectories for flying insects, capturing the inherent noisy dynamics of insect swarms. This was the first work to combine procedural curl-noise with swarm simulation for flying insects, establishing the use of curl-noise in insect animation. From the same research group (co-authors Jin and Deng) as [CLTL22], this work focused on macro-level swarm trajectories. Chen et al. [CLTL22] extends the curl-noise idea from macro-level swarm trajectories to micro-level individual butterfly motion via the vortex force applied to the thorax.

[SKL16] Sridhar, Kang, and Landrum use 12 high-resolution VICON motion-tracking cameras to capture the free flight of Monarch butterflies. They quantify body orientation—thorax and abdomen separately—and wing kinematics as a six-degree-of-freedom system, along with instantaneous lift coefficient during climbing flight. Critically, they show that the wing flapping frequency and body oscillation frequency match at approximately 9.5 Hz, confirming the close coupling between wing and body motion. They also provide key morphological data (wing area, body mass) that are used as simulation parameters in [CLTL22] (Table 2). The finding that the abdomen rotates with opposite phase to wing flapping directly informs the phase angle settings in Equation 1 of [CLTL22].

[WA14] Wilson and Albertani optimize wing-flapping and abdomen actuation parameters for hovering in the butterfly *Idea leuconoe*. They model the butterfly as a rigid body while integrating the abdomen's inertia and moment, and design periodic functions for the coupled wing and abdomen motion. Along with [WP03], this work directly inspires the periodic maneuvering function design in Chen et al. [CLTL22] (Equation 1). A related work by Sridhar, Kang, and Lee (2020) further develops a geometric formulation for Monarch butterfly dynamics with abdomen undulation effects, confirming that the abdomen moves with opposite phase to wing flapping during hovering and climbing.

[CLTJ19] Chen et al. extend the chaotic behavior of flying insects to generate special-effect animations with shape constraints. Building on the swarm simulation foundation of [WRJM15] and [WJDZ14], this work demonstrates artistically controllable insect swarm motion. It serves as a direct predecessor to [CLTL22], which shifts focus from macro-level swarm effects to a physically-grounded, micro-level individual butterfly flight model with wing-body interaction.

[CLTL22] Chen et al. propose a first-of-its-kind, practical model to simulate realistic butterfly flights. The approach consists of three inter-connected modules: (1) butterfly modeling with a hierarchical skeleton and parametric maneuvering functions including wing-abdomen interaction, inspired by [WP03] and [WA14]; (2) forces computation combining simplified aerodynamic forces based on quasi-steady theory [Ell84] with a curl-noise vortex force [BHN07] for inherent noisy behavior; and (3) maneuvering control through body motion decoupling that generates both inherently noisy trajectories and rapidly-adjusted body postures. The approach is validated through simulations of various scenarios (path following, wind interaction, chasing, aggregation, traveling) and user studies, demonstrating real-time performance at 60 FPS for single butterflies and 25 FPS for swarms of 100.

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