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Butterflies

Flexible Flapping-Wing Robots

Nature-Inspired Inventions

Volume 008 of 255

WealthSphere Labs

Butterflies: Flexible Flapping-Wing Robots

Nature-Inspired Inventions, Volume 008

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About this book. This is an educational guide to biologically inspired engineering. The invention concepts in it are design ideas for study and experimentation, not tested or certified products. Worked numbers illustrate methods unless a source is named. Nothing here is engineering certification, legal advice on patents, or a substitute for qualified professional review of anything that will carry people, loads or risk.

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Introduction: Flying With Soft Wings

A butterfly seems an unlikely engineering model. It flaps slowly, flutters erratically and looks fragile. Yet butterflies fly well enough to escape birds, to land precisely on flowers in the wind and, in the case of the monarch butterfly, to migrate thousands of kilometres. They do it with very large, very light wings that bend and twist with every stroke.

Most aircraft are designed to be stiff. Flexibility is treated as a problem to be controlled. Butterflies show a different approach: wings whose flexibility is part of how they work, storing and releasing energy, shaping the airflow, and making flight robust to collisions and gusts.

This volume explores how butterflies fly, the physics of flexible flapping wings, and how engineers can build flapping-wing robots that use flexibility deliberately. It covers materials and manufacturing for soft wings, control of erratic but effective flight, and practical concepts for robots in research, education, displays and gentle indoor operation.

How this book is organized

Chapters 1 and 2 cover butterfly flight and anatomy. Chapter 3 explains the physics of flexible flapping. Chapter 4 surveys the history of butterfly and flexible-wing robots. Chapters 5 to 7 cover translation, materials and control. Chapter 8 presents ten design concepts. Chapters 9 to 12 cover testing, failure modes, approval and a design workbook.

Figures for real insects and robots are rounded and typical.
Worked numbers are illustrations unless a source is named.

Chapter 1: How Butterflies Fly

The butterfly body plan

Butterflies and moths form the order Lepidoptera, with well over 150,000 known species, most of them moths. Butterflies typically have large wings relative to their bodies, low wing loading and low wingbeat frequencies — often in the range of roughly 5 to 15 beats per second, much slower than flies or bees.

Flight style

Butterfly flight is often described as erratic or fluttering. The body bobs up and down with each wingbeat, and the path zigzags. This irregularity may help butterflies escape predators, because birds find their path hard to predict. It also reflects the physics of large, slow-beating wings on a light body: each wingbeat produces a large force relative to body weight, causing visible body motion.

Long-distance migration

The monarch butterfly of North America migrates up to several thousand kilometres from the United States and Canada to overwintering sites in central Mexico. Over such distances, monarchs combine flapping with gliding and soaring on thermals and favorable winds — showing that butterflies can fly efficiently when they need to.

Unconventional lift

Research by Robert Srygley and Adrian Thomas, published in *Nature* in 2002, used smoke visualization to study free-flying red admiral butterflies trained to fly in a wind tunnel. They found that the butterflies used a variety of unsteady mechanisms — leading-edge vortices, clap-and-fling, and others — and switched between them from stroke to stroke. Butterflies are not limited to one way of producing lift.

The clap

Research by Christoffer Johansson and Per Henningsson at Lund University, published in the *Journal of the Royal Society Interface* in 2021, found that butterflies clap their wings together at the top of the upstroke, and that the flexibility of the wings lets them form a cupped shape during the clap, trapping air and expelling it backward as a jet. The flexible wings made the clap more effective than rigid wings would be.

Chapter takeaways

- Butterflies have large, light wings and slow wingbeats.
- Their erratic flight may help evade predators.
- They use several unsteady lift mechanisms, switching between them.
- Wing flexibility enhances the clap, producing useful thrust.

Chapter 2: Anatomy of a Flexible Flyer

Wing structure

Butterfly wings are thin membranes supported by tubular veins, with most of the veins concentrated toward the leading edge and the wing base. The leading edge is therefore stiffer, and the trailing regions are more flexible. Under load, the wing bends and twists, with the trailing edge lagging behind the leading edge.

Scales

Butterfly wings are covered in tiny overlapping scales that give them their colors. Scales may also affect airflow over the wing surface and add a small amount of water repellency. Their aerodynamic role is still being studied; some research suggests they help with lift or efficiency.

Coupled wings

The forewing and hindwing on each side overlap and move largely together, acting as a single large wing. This differs from dragonflies, whose four wings move independently.

Flight muscles and body

Butterflies use indirect flight muscles that deform the thorax. They also move the abdomen during flight, and research suggests that abdominal motion contributes to pitch control, shifting the center of mass in coordination with wingbeats.

Chapter takeaways

- Stiff leading edges and flexible trailing regions produce passive bending and twisting.
- Forewing and hindwing act together as one large wing.