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Book Review

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Morphing Aerospace Vehicles and Structures

John Valasek, Wiley, Hoboken, NJ, 2012, 306 pp., $135.

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In biology, a *morph* is one of many forms that an organism can take. Every insect, bird, and bat morphs (i.e., changes its shape to control its speed, direction, angular position, and location). Wings bend, twist, fold, flap, and sweep; tail surfaces fan out and deflect; heads turn; and claws extend to grab unsuspecting prey. What, then, is a morphing aircraft? The very notion of controlled flight dictates that devices move to generate forces and moments that produce useful motions. Every controlled aircraft morphs to some degree. In the present context, a "morphing air vehicle" is one that undergoes large changes in shape or structure, not only for immediate stability and control, but also to further mission objectives.

Morphing Aerospace Vehicles and Structures, a book edited by John Valasek, provides a good introduction to the elements of morphing vehicle design. It has 12 chapters with three principal parts: bioinspiration, control and dynamics, and smart materials and structures. Although some aspects of the text apply to aircraft of all sizes, the book implicitly focuses on smaller uninhabited air vehicles (UAVs) that benefit most from analogies to flying animals. For reference, flying vertebrates range from 2 g to 21 kg in mass, 5 cm to 3.6 m in wingspan, and 0 to 160 km/h in speed (hovering and level flight). UAV analogies are most appropriate in this design space.

Valasek presents a brief history of early aviation and its reference to bird flight in Chapter 1. He identifies a middle era when variable geometry was adopted to allow aircraft to fly efficiently at both subsonic and supersonic speeds without particular reference to biology. More recently, flying animals that morph to accomplish higher level objectives like foraging, perching, and migration have provided new paradigms for optimizing the mission performance of small UAVs.

"Part 1: Bio-Inspiration" leads off with a discussion of natural flyers. Taylor, Carruthers, Hubel, and Walker, of Oxford's Department of Zoology, provide a very readable introduction to distinctive features of animal flight. Insects have deformable-membrane wings that flap at high-frequency for lift, propulsion, and control. The flow about their wings is unsteady and extremely complex. The bones of a bird's wings are analogous to those in the human arm and hand. The skin and feathers provide significant chord thickness, and the wing planform can be altered rapidly and asymmetrically. The tail provides stability and control, although morphing wing effects are dominant. A bat's wings have similar skeletal components, but the "fingers" extend to the trailing edge, supporting a muscularized membrane that contributes to propulsion as well as to rapid planform variation. The muscles that control insect and bird flight are located primarily in the body and at the root of each wing; the bat wing's distributed actuation provides complex aerodynamic effects that are still not well understood.

Abate and Shyy review a variety of micro and nano air vehicle concepts in Chapter 3, noting their high potential for performing surveillance in limited spaces. Although not limiting the discussion to bioinspired designs, they point out the aerodynamic scaling issues that are encountered in the development of vehicles with wingspans of 10 cm or less.

"Part II: Control and Dynamics" contains five chapters. Animals' intuitive high-bandwidth sensing and control of nonlinear time-varying dynamics are worth mimicking. In Chapter 4, Valasek, Kirkpatrick, and Lampton introduce reinforcement learning for gross configuration modification in response to changing mission requirements. This wide-ranging chapter covers Q learning, a panel method for modeling aerodynamics of arbitrary shapes, the rigid-body equations of motion, an introduction to shape-memory-alloy (SMA) control actuation, and an adaptive inverse-dynamic approach for nonlinear control. Though not biomimetic, numerical examples illustrate a trapezoidal wing morphing symmetrically to generate maximum and minimum lift via changes in root and tip chords, wingspan, and sweep angle.

Obradovic and Subbarao consider an alternative scheme in which a straight wing morphs between planar- and gull-wing shapes (Chapter 5). The wing is capable of asymmetric morphing for turning by differential extensions of the left and right segments. Conventional control surfaces also are simulated, allowing comparisons to be made between maneuvering by morphing or control surface deflection. Aerodynamic modeling and rigid-body equations of motion are modified to account for morphing motions, forces, and moments. The authors conclude that gull-wing morphing is effective but that it requires higher actuator loads for maneuvering than conventional control surfaces or in-plane morphing of the wing.

A multibody flapping-wing UAV is analyzed by Grauer and Hubbard in Chapter 6. Parameters for a mathematical model of the airplane are identified in laboratory and flight tests of a model, and a feedback control law is applied to the simulated vehicle. Their calculations reveal the periodic heaving and pitching that the body experiences when the wings flap.

Grant, Sorley, Chakravarthy, and Lind describe an experimental UAV with variable inboard and outboard wing sweep (Chapter 7). The UAV can sweep its wings asymmetrically, but only the symmetric case is considered. With the development of equations that address time-varying inertias, discussion switches to modal analysis of linear systems with time-varying poles. The limitations of such analysis are well known [1], and it is unclear what advantages derive from applying it to morphing UAVs. The chapter ends without a summary or conclusions.

Wickenheiser and Garcia have contributed a very interesting study of optimal perching maneuvers for a morphing aircraft (Chapter 8). The morphing UAV is based on the NASA ARES vehicle proposed for Martian exploration. Wings can be rotated about a spanwise axis relative to the fuselage, and the tailplane can be pitched and heaved to alter forces and pitching moment. Aerodynamics are modeled by lifting-line theory, with modifications for viscous flow. A series of longitudinal multibody simulations for both optimal and nonoptimal maneuvers provides insight into the effects of morphing, initial conditions, and constraints. The analysis is consistent with the perching behavior that you see at your backyard bird feeder.

"Part III: Smart Materials and Structures" moves away from biological analogies to discuss supporting technology. Chapter 9, "Morphing Smart Material Actuator Control Using Reinforcement Learning," is a recapitulation and expansion of the discussion of reinforcement learning and SMA actuators found in Chapter 4, also coauthored by Kirkpatrick and Valasek. It reviews other intelligent control methods that could be applied to the highly nonlinear, slow SMA actuators, and it ultimately focuses on additional details and examples of Q learning. Although repetitive, the chapter is nicely written and would be at home in a book about intelligent control applications.

Schick, Hartl, and Lagoudas review a number of morphing applications of SMA actuators (Chapter 10). Results are presented for changing wing contours and surfaces, engine inlet shaping for supersonic flight, and active alteration of engine bypass flow. Shape-memory-alloy mechanisms and effects, experimental procedures, and analysis are discussed. It is noted here and in previous chapters that SMA actuators have high power-to-weight ratio and solid-state simplicity, although they also possess low-energy efficiency, slow response, hysteresis, degradation, and fatigue. For control system design, more information about response bandwidth, nonlinearity, and reliability is warranted.

In Chapter 11, Kumar and Chakravorty portray morphing as a hierarchical control and planning problem using graph theory to find the best paths between interconnecting nodes. High-level planning is accomplished by numerical search (e.g., the A* algorithm) and values of the nodes are determined by subjective metrics (e.g., quadratic cost functions). A Kagomé truss structure that positions a plate, such as an element of a deformable wing's surface, is analyzed. Aircraft typically are built with semimonocoque structures (i.e., with load-bearing surfaces); the chapter does not address how the truss would be actuated and how it would handle such loads.

Valasek presents a brief epilogue in Chapter 12, suggesting that there is a bright future for research in morphing air vehicles.

Together with the reference lists, the chapters illustrate that much research and some development has been directed at morphing air vehicles. The benefits must outweigh the added weight, complexity, and cost of implementation for morphing to be attractive. For example, retractable landing gear is 10% heavier than fixed gear; that is a small price to pay for jet-transport drag reduction, but an undesirable complication for a primary trainer [2]. One exemplar of morphing technology, the variable-sweep wing of fighter aircraft, achieved its goals but has come and gone, with no aircraft of the type in current production.

The economics and utility of morphing for small UAVs are unique and may lead to efficient innovative designs. Promising ideas for rapid morphing include asymmetric wing incidence, sweep, dihedral, and twist; rotation, heaving, and variable sweep of tail surfaces; and center-of-mass shifting for attitude control. Slow morphing for mission optimization may be achieved by combining these concepts with variable wing chord section (thickness, camber, and profile), boundary-layer control, adaptive propulsion (direct lift, retractable powerplants, variable-contour propellers), and overall configuration change.

Morphing Aerospace Vehicles and Structures is an ambitious book that covers a variety of technologies associated primarily with small aircraft design. The chapters revolve around a central theme seen from different perspectives. The book is a useful source for ideas and should be read by engineers and students with an interest in UAV development.

References

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