Designing feathered morphing wings for biohybrid aerial robots

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1 Introduction

The surface of an avian wing is primarily comprised of feathers, soft individual panels that stitch together, yet slide past each other, to form a variety of aerodynamic airfoils [1–3]. Feathers enable birds to morph, or drastically change the shapes of their wings mid-flight, adapting to cluttered environments or turbulent conditions. Although some advantages of morphing are understood [4], how feathers are coordinated within a morphing wing is less known. Previously designed avian-inspired robots with morphing wings use either wide panels or membranes, and do not derive robotic motion from biological feather motion [5–8]. We study the skeletal wing and feather motion of the common pigeon, Columba livia, to gain insight into the underlying mechanisms. From biomechanical measurements, we create a mechanistic model underpinning the construction of robotic feathered morphing wings. Inspired by biological principles, we designed soft feathered morphing wings that can push aerial robotics towards more robust and maneuverable flight. The feathered robotic design is validated through testing continuous morphing in a wind tunnel and during outdoor flight, proving that a feathered biohybrid robot can successfully achieve robust and controllable morphing in free flight.

2 Biomechanical measurements inform an underactuated linear spring model

The pigeon wing is composed of a skeleton powered by muscles and feathers that shape the airfoil. The twenty stiff primary and secondary flight feathers that form the majority of the wing planform lie against the ulna and carpometacarpus bones, between which we define the wrist angle (figure 1A). To determine the underlying mechanisms that coordinate flight feathers, we track the three-dimensional kinematics of feathers and bones within the morphing wing of a pigeon cadaver using a high-resolution motion capture system (figure 1B). Retroreflective marker clusters are rigidly affixed via carbon-fiber rods inserted directly into each of the bones. Additionally, pairs of markers are adhered to every feather along the rachis, the stiff central shaft of the feather. We sweep the wing through a cycle from flexion, fully tucked, to extension, fully outspread, and back, along the path of least resistance, and track a total of 52 moving markers for each trial. Three birds were each tracked for 12 cycles of flexion and extension. From these measurements, we calculate the input wrist angles and the resulting feather angles, the angles between each feather and the ulna.

The results show that each of the flight feathers moves linearly with respect to the wrist angle, with no hysteresis between extension and flexion. Since a single input, the wrist angle, can control the angles of all of the feathers, we can consider the feathered wing an underactuated system controlled by skeletal motion. This underactuation arises mostly from the elastic tissue intertwaving the base of flight feathers. We then model the morphing wing as an underactuated system using a linear elastic spring model. Using the known displacements of the feathers through flexion and extension and normalizing with the wing extension force, we use Hooke’s law to calculate the relative elastic stiffness between each flight feather for every wrist angle (figure 1C). Except for the estimated stiffness at the wrist joint between feathers P1 and S1, the elastic stiffness does not vary much for different wrist angles, suggesting that linear springs suffice, but there is some non-linear behavior at the wrist.
3 Building a biohybrid multi-element morphing wing

We implemented the underactuated spring model into a physical feathered robotic wing design that morphs through the same flexion and extension wrist angles as a pigeon. Each pigeon feather is attached to the 3D printed skeleton via a pin joint connection and is able to rotate in plane. Individual elastic bands couple adjacent feathers together, and set a different stiffness between each feather while servos drive the skeletal motion (figure 2A). We coordinate a total of 40 underactuated feathers, 20 in each wing, on the complete robot. Results from tracking the wrist and feather angles of the robotic wing found that feather motion in the underactuated biohybrid robot closely follows those in a bird wing for the same wrist angle input (figure 2B), mis able to sweep from a fully extended to a tucked planform, reducing its wingspan by almost half from 80cm to 42cm and bringing the overall wing area from 0.1058 m² to a tucked area of 0.0780 m². Wind tunnel tests of the biohybrid wing in both laminar and highly turbulent flow confirm that an underactuated elastically-driven mechanism robustly transfers motion from the skeleton to the feathers, coordinating morphing in concert.

After wind tunnel testing, we mounted the wing to a test platform for outdoor flight, a propeller powered fuselage with a programmable autopilot and a suite of sensors including an inertial measurement unit, airflow sensor, and GPS. In the outdoor flights, we fly the robot using both automatic and remote manual control of wing morphing. The biohybrid robot sustains flight while extensively morphing through continuous aerodynamic planforms.

4 Conclusions

By studying the skeletal and feather motion of an avian wing, we found that birds control their feathers in an underactuated manner through their wrist angles. Based on these measurements, we designed a bioinspired underactuated mechanism to coordinate feather motion in a biohybrid aerial robot with morphing wings. Such a biohybrid robotic model of a morphing wing allows biologists to ask questions and perform manipulations that are difficult to perform on birds, such as specific molting patterns and changes in morphology such as removing elasticity or modifying skeletal structure. Additionally, a robot rooted in biology opens a new underactuated design paradigm of controlling a plethora of feathers with just a few actuators. For future work, roboticists can adjust the body plan of the generalist pigeon to optimize for performance in different areas, such as longer wings for gliding or lower wing loading for efficiency and range. The underactuated feathered design template can be altered to fit to different bird species since the avian body plan is scalable [11]. We have demonstrated that a soft feathered underactuated wing design derived from biomechanical measurements of a morphing wing can both answer biological questions about avian flight as well as further robust flight in aerial robotic designs.

Figure 2: (A) A robotic biohybrid wing with underactuated elastic springs smoothly coordinates 20 feathers. (B) Measured robotic feather motion closely tracks the motion of a pigeon wing during morphing. (C) Outdoor flight sequence shows the biohybrid robot morphing continuously.

References