Biohybrid morphing tail aerial robot

Eric Chang* and David Lentink
Department of Mechanical Engineering, Stanford University
*echang7@stanford.edu

1 Introduction

Birds change their tail shape and pose in flight to adjust their flight dynamics, but little work has been done to quantify the force production of morphing tails. Previous experimental studies on avian tails have mostly focused on quantifying lift production [1–4]. However, these studies all consider discrete tail areas, and do not consider span-morphing tails that can continuously change their shape. Fewer studies have quantified the effects of tail tilt (figure 1) and have found that tail tilt produces lateral forces that contribute to yawing moments [2, 3]. No study to date has investigated the effects of lateral motion in bird tails, even though bird tail anatomy and observations in nature suggest that birds are capable of this movement [5]. Additionally, no existing study has considered a morphing tail in free flight, which can produce 3D position and orientation responses to tail motion which is difficult to reproduce in a wind tunnel.

We present a morphing feathered robot inspired by the rock pigeon (*Columba livia*) capable of these four degrees of freedom: spreading/furling, elevation/depression, tilt, and lateral deviation. Tail morphing is accomplished by the coordination of 12 individual feathers that change tail area during untethered outdoor flight. The morphing tail robot serves two functions— first, as a platform to study flight control in an aerial vehicle using lateral tail deviation, and second, to study how combining the four degrees of freedom in the tail may enable supermaneuverability.

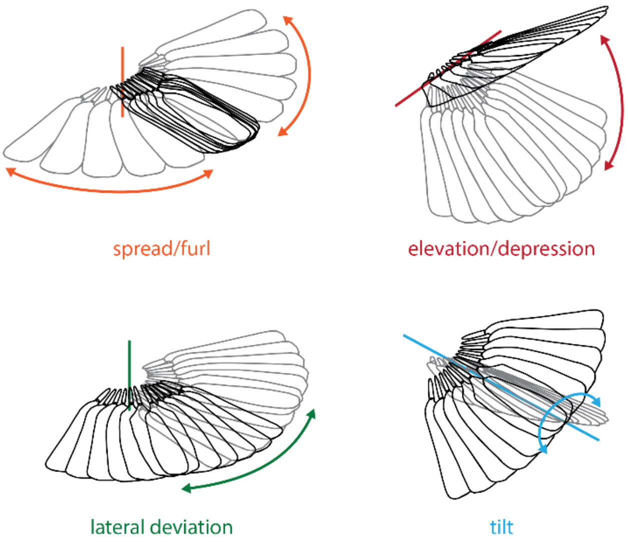

Figure 1: The four avian-inspired degrees of freedom in the biohybrid morphing tail robot.

2 Tail mechanism design

The tail mechanism consists of a suite of rotary servos in the body of the robot that remotely actuates an assembly of revolute joints that control the angular position of 12 rock pigeon tail feathers (Figure 2A). The servos drive elevation/depression, lateral deviation, and spreading/furling using Bowden cables in a push-pull configuration (Figure 2B). An additional servo directly actuates the tilt.

The feathers are glued to 3D printed revolute joints to interface the biological material with our mechanism. The left- and right-most lateral feathers are actively actuated with independent servomotors through the Bowden system, while the remaining feathers are connected to each other with elastic bands. The elastic bands underactuate all feather motion based on the distal feather positions. A mechanical stop limits the motion of the medial two feathers, inspired by the pygostyle, a rigid structure in avian tails that attaches to the medial tail feathers.

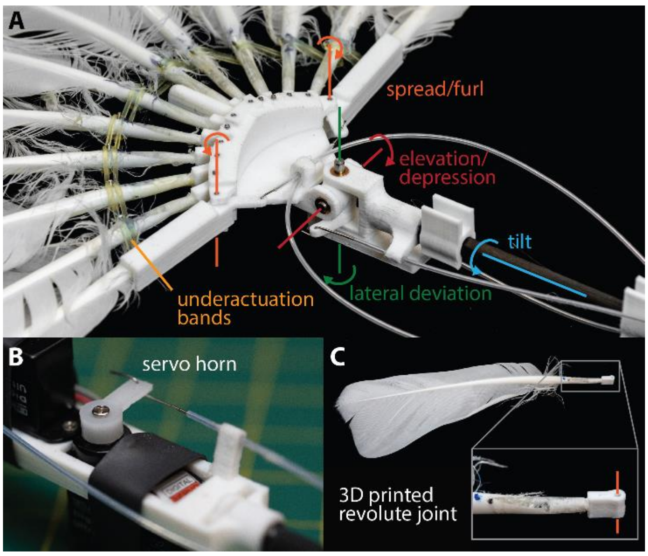

Figure 2: (A) The biohybrid robotic mechanism is capable of four degrees of freedom, while underactuating the motion of 12 pigeon tail feathers using elastic bands. (B) Servos actuate elevation/depression, lateral deviation, and spreading/furling through Bowden cables. (C) 3D printed revolute joints interface with the pigeon tail feathers.

3 Feather kinematics

To quantify how the feathers move during spreading/furling, we use a digital camera and colored tape adhered to each feather to identify and track the orientations of each feather as we sweep through many distal feather spread angles (Figure 3). Since the tail is designed to morph symmetrically, we mirror and combine data from opposite sides of the tail. We compare the results from the robot with a pigeon tail in three poses. These results show that feather angles move linearly with respect to the spread angle. Comparing the robot and pigeon tail feather angles shows that the robot produces feather kinematics very close to its biological counterpart.

4 Flight Testing

To test the tail mechanism in flight, we housed it in a foamboard body equipped with an autopilot with position and orientation sensing and datalogging. The robot has a propeller and electric motor for thrust, and a gliding pigeon-derived flat plate wing [6]. We adhere custom cut cardstock to the dorsal side of the tail mechanism to cover gaps in between feathers that are normally covered by covert feathers in birds.

The robot first flew in outdoor untethered flight under manual teleoperated control, where we piloted the robot using a radio-control transmitter with joystick motion directly mapped to tail motion. While difficult to control, the robot was stable and the degrees of freedom in the tail functioned as we assumed; elevation/depression pitched the robot while tilt and lateral deviation rolled and yawed the robot. Spreading the tail resulted in higher sensitivity to control inputs. Using all the degrees of freedom simultaneously allowed for controlled dynamic maneuvers (Figure 4A).

We also implemented closed-loop fly-by-wire control. We used the measured pitch and roll angles as inputs to PID controllers that map to elevation/depression and tilt/lateral deviation respectively. This allowed the pilot to still command high-level pitch and roll trajectory commands, while letting the autopilot handle the fast dynamics and wind perturbations. 30 seconds of a top-down trajectory of a sample flight under fly-by-wire control is shown in Figure 4B, demonstrating the ability for the robot to turn using this control scheme.

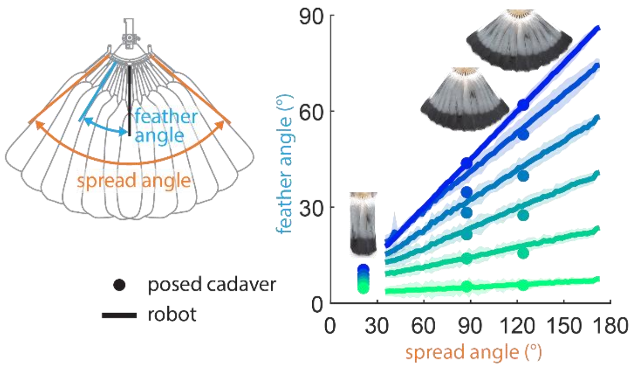

Figure 3: The underactuated system coordinates feather motion as a function of the spread angle. The measured robot feather angles are comparable with pigeon tails.

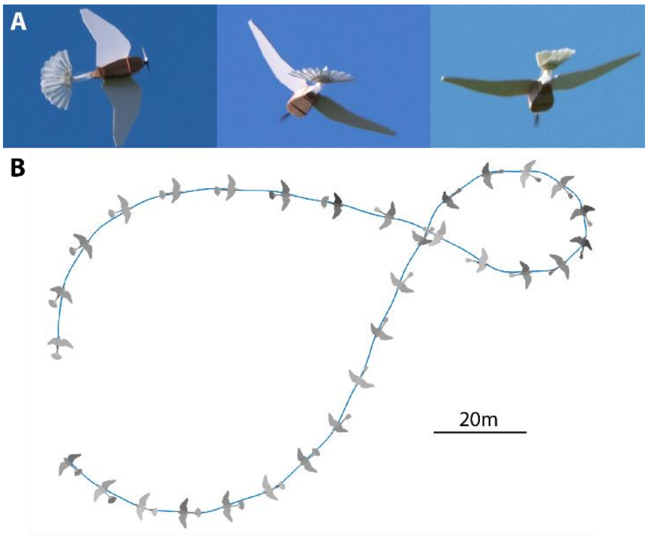

Figure 4: (A) The biohybrid tail robot maneuvers with novel combinations of tail motion and morphing. (B) Using closed-loop fly-by-wire control, the robot flies stably and can track high-level flight trajectories. Avatars scaled 10:1 for readability.

5 Conclusions

Our biohybrid morphing tail robot is the first flying robot to successfully demonstrate the ability to maneuver using avian-inspired lateral tail deviation. It accomplishes its maneuverability by dynamically switching between a rich continuous array of tail shapes and poses in flight.

The combination of the biohybrid design and similarity to a real pigeon tail makes this platform uniquely suited to study supermaneuvrability in biology and robotics. In biology, this robot can be used to study how birds can use their tails to dynamically maneuver, fly more efficiently, and navigate gusty environments in a way that is not feasible to study with birds. In robotics, this robot can be a testbed for novel control schemes for vertical tail-less flight and morphing control surfaces.

References

[1] M. R. Evans, "Birds' tails do act like delta wings but delta-wing theory does not always predict the forces they generate," 2003.

[2] L. L. Gamble and D. J. Inman, "A tale of two tails: developing an avian inspired morphing actuator for yaw control and stability," *Bioinspir. Biomim.*, vol. 13, no. 2, p. 026008, Feb. 2018.

[3] D. Hummel, "Aerodynamic investigations on tail effects in birds," *Z. Flugwiss. Weltraumforsch.*, vol. 16, no. 3, pp. 159–168, 1992.

[4] W. J. Maybury, J. M. V. Rayner, and L. B. Couldrick, "Lift generation by the avian tail," *Proc. R. Soc. London. Ser. B Biol. Sci.*, vol. 268, no. 1475, pp. 1443–1448, Jul. 2001.

[5] J. J. Baumel, *Functional Morphology of the Tail Apparatus of the Pigeon (Columba livia)*. Springer-Verlag Berlin Heidelberg, 1988.

[6] C. J. Pennycuick, "A Wind-Tunnel Study of Gliding Flight in the Pigeon Columba Livia," *J. Exp. Biol.*, vol. 49, no. 3, 1968.