Inertial redirection of thrust forces for flight stabilization

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Insects are highly maneuverable fliers. Naturally, engineers have focused much of their efforts on understanding the role of insect wing design and actuation for maneuvering and control of bio-inspired micro air vehicles. However, many insects exhibit strong visually mediated abdominal reflexes. The hawkmoth, *Manduca sexta*, has a particularly large abdomen, and recent evidence suggests that these visuo-abdominal reflexes are used to inertially redirect thrust forces for control. In a biologically inspired control framework, we show that the stability of a quadrotor can be categorically improved by redirecting aerodynamic forces using appendage inertia.

Keywords: insect flight control, flight stabilization, pitch control, inertia, dynamics, flexible airframe

1. Introduction

Absent aerodynamic forces, terrestrial animals and robots have little affordance over their net angular momentum during flight, e.g. after a jump. Nevertheless, adjustments to internal configuration degrees of freedom (*i.e.* motions in the "shape-space" of the locomotor system[11]) can capitalize on momentum conservation to orient the body during free flight maneuvers. Based on this idea, Libby *et al.*[9] recently discovered that the tail on certain animals such as the gecko—and possibly dinosaurs—helps keep the animal upright after it jumps. The mechanism involved is remarkably simple: any net angular momentum imparted to the animal during lift-off can be counteracted by counter-rotating the tail at the appropriate speed. This principle was demonstrated on a robot where, following a jump, the robot simply controlled its tail using feedback from an internal sensor to maintain its body angle while in midair.

How might this principle—intersegmental reorientation via inertial forces—be used in flight control? To sharpen this broad question, we focus here on insect flight control. An insect has three primary body segments: the head, thorax, and abdomen with actively controlled joints between each segment. For example, head motions are critical components of the visual tracking control system in insect flight.[13] The motion of the abdomen relative to the middle thoracic segment has been implicated in adjustments of the center of pressure.[3] But, given that the abdomen constitutes at least 50% of the mass of the flying animal suggests that inertial effects could be substantial.[7] This is particularly true in large flying insects such as the hawkmoth *Manduca sexta*. Indeed, these animals produce sensory mediated abdominal responses,[2,8,10] but the role they play in flight control has been unclear. Recently Dyhr *et al.*[4,6] reported evidence that the hawkmoth might use its abdomen to reorient its thorax, much like a gecko uses its tail to reorient its body as described above.

In the case of the hawkmoth, however, there is an interesting twist. As described by Dyhr et al.,[4,6] as the abdomen and thorax are reoriented in space, the flight apparatus—which is attached to the thorax—is also reoriented in space, and therefore subsequent thrust forces are redirected. Dyhr *et al.* modeled the biomechanical flight control "plant," and performed system identification of the moth sensorimotor controller. They determined that the visuo-abdominal reflex[2] is consistent with the hypothesis that the moth uses its abdomen to help stabilize flight.

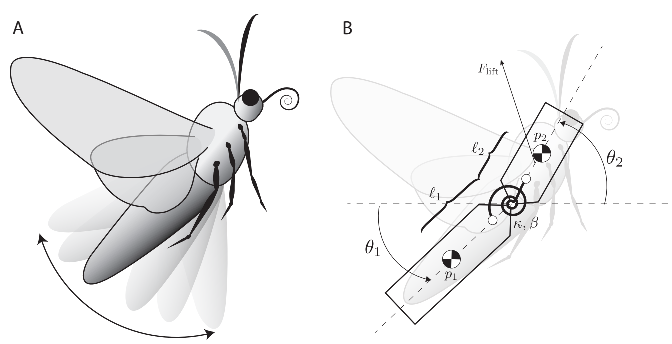

Fig. 1. **(A)** The abdomen of a moth comprises 50% of the mass of the animal. It was recently discovered that strong visually mediated abdominal reflexes of the moth may serve to redirect flight forces for control.[4,6] **(B)** A two-link rigid-body model of sagittal plane dynamics can be used to describe how rapid adjustments of the thoracic abdominal angle, namely $\theta_2 - \theta_1$, can be used to redirect wing forces for control.

Can flexible frames such as those observed in the moth enhance robotic flight control[5]? We devised a mechanism that enables us to test the ideas proposed by Dyhr et al.[4–6] in a robot. The mechanism is similar to that presented by Bouabdallah *et al.*[1] for a coaxial helicopter, for which the battery pack was moved to adjust the center of mass position relative to the center of lift. In that work, strong gyroscopic effects from large counter-rotating propellers[12] may limit the connection to insect flight. Here, we focus on building on the ideas above to enhance stability of a flying robot via actuation of an abdomen-like appendage.

2. Methods

2.1. *Aircraft: The X-3D-BL ResearchPilot*

Our tests were performed with an *X-3D-BL ResearchPilot* quadrotor by *Ascending Technologies, Inc.* The aircraft, composed of a magnesium chassis with carbon-fiber sandwiched balsa arms, is approximately $50\,\text{cm} \times 50\,\text{cm}$ and weighs approximately 450 g with the battery. It is capable of carrying a payload weighing approximately 400 g for about 10 minutes.

The X-3D-BL has onboard roll and pitch stabilization facilitated by three piezo gyroscopes and a triaxial accelerometer. Data from these sensors are fused onboard and filtered to give accurate absolute roll, ρ, and pitch, ϕ, angles and their rates, $\dot{\rho}$ and $\dot{\phi}$, respectively. These computed measurements are then utilized by separate onboard PD controllers whose gains can be set prior to each flight test.

The quadrotor is piloted via a radio frequency (RF) remote controller (RC) unit (DX7se by *Spektrum*), which gives roll, pitch and yaw control in absolute angles and a dimensionless thrust magnitude control with adjustable resolution. Piloting functions of the RC were partially transferred to our ground computer. This separate communication channel also carried all sensor data from the quadrotor. In addition, we used this channel to remotely set internal stability gains and other flight parameters as well as to conduct sensor calibration and to map remote control functions. The manufacturer provided the specifications of the serial protocol API necessary for our in-house designed flight control software.

2.2. *Inertial Appendage: Servo-Actuated Battery*

We attached the quadrotor's own battery below its chassis in a manner similar to the mechanism proposed by Bouabdallah et al.[1] The battery of the X-3D-BL is a rectangular prism weighing about 150 g, *i.e.* one third of

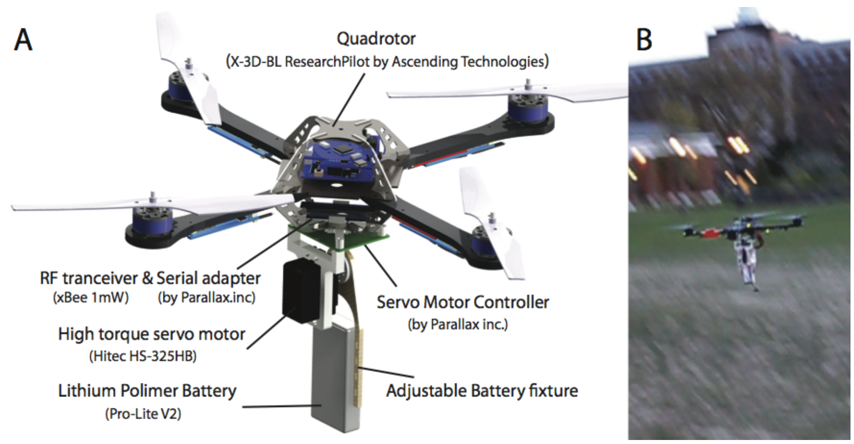

Fig. 2. **(A)** Quadrotor abdomen design and integration.**(B)** Stable flight of the abdomen integrated quadrotor.

the entire quadrotor mass (including battery).

The full quadrotor assembly and relevant components are depicted in Figure 2A. The battery angle, θ, with respect to the quadrotor chassis's z-axis (the yaw axis) is set by an available high-torque (3.7 kg/cm) servo motor that has a range of about -90° to $+90^\circ$ and a maximum angular rate of 400 deg/sec at no load.

The battery pivots about the servo shaft at an adjustable distance via a laser-cut balsa fixture. A separate 1 mW 100 m range RF module (XBee 802.15.4 by Digi) is used for data transmission between the ground station and the "abdomen" assembly. The servo motor, servo controller, and RF module are powered by the quadrotor battery through a voltage converter.

Attaching this assembly on the bottom of the X-3D-BL increases the total mass by 110 g and lowers the center of mass by 6 cm. The inertia about the pitch axis is also increased by about 70% (from 0.26 to 0.44 kg m^2).

2.3. *Simple Abdominal Controller*

In our experiments, the abdominal angle, θ_{ctrl}, was controlled via PD feedback from the pitch angle and pitch rate:

$$\theta_{\text{ctrl}}(t) = K_P \cdot \phi(t) + K_D \cdot \dot{\phi}(t). \quad (1)$$

The gains K_P and K_D were hand tuned such that the controller output led to significant stabilization but at same time stayed within the bandwidth limitations of our servo motor. The gains for the final data collection were 0.25 for K_P and 0.07 for K_D.

2.4. *Gain Settings for Onboard Controller*

We used two distinct sets of onboard pitch-control gains for the propellers, separate from the abdomen pitch gains in (1). From the point of view of abdominal pitch control, the plant includes the propeller gains, and we use two different settings for these gains. The first set of propeller gains were set so that the quadrotor was stable but highly oscillatory, which we call the "Stable Plant" gains. The second set of propeller gains were insufficient to stabilize pitch, which we call the "Unstable Plant" gains.

2.5. *Perturbation Experiments*

During our experiments, the human pilot provided thrust control through the RC. The pilot did not adjust pitch, roll or yaw during the experiment. The quadrotor abdomen assembly was tethered from top and below to define the indoor "no-fly zone" for safety reasons. A soft stick was used to perturb the aircraft. The perturbations were provided directly beneath the front or back propeller, creating a large sagittal-plane pitching moment. The perturbations were spaced approximately 10 seconds apart in two consecutive 120 second long trials. Before each trial, the quadrotor sensors were recalibrated. We compared perturbation responses between the trials where the abdominal control was on (closed-loop) and off (open-loop).

The pitch responses to each perturbations were normalized to 15° at their first peak, and then the responses were averaged. The resulting decaying oscillatory signal was fit assuming a second-order response, *i.e.* $\ddot{\phi} + 2\zeta\omega_n\dot{\phi} + \omega_n^2\phi = 0$. The damping ratio, ζ, was calculated via logarithmic decrement, and the period was estimated to recover the the natural frequency $\omega_n = \frac{2\pi}{T\sqrt{1-\zeta^2}}$. This yielded an almost perfect fit (depicted as dashed black line of Fig 3) to the averaged curve.

3. Results

As depicted in Figure 3, the performance of the quadrotor can be enhanced with the complementary inertial redirection of aerodynamic forces provided by the PD-controlled abdomen. In these experiments, the system was open-loop stable (that is, it was stable in the absence of abdominal feedback), but the performance improved significantly in the presence of abdominal feedback. The first two columns of Table 1 show the change in poles for this experiment.

Our second result shows that a pitch-wise unstable quadrotor (X-3D-BL pitch derivative gain is set to 0) can be stabilized with the same feedback controller (same PD gains). Fig 4A shows a sample unstable response curve of the pitch angle upon the initial 15 degree perturbation. Fig 4B shows of the same configuration with the active abdominal control. The parameters of the second order model and the associated eigenvalues (poles) are presented in the third column of Table 1.

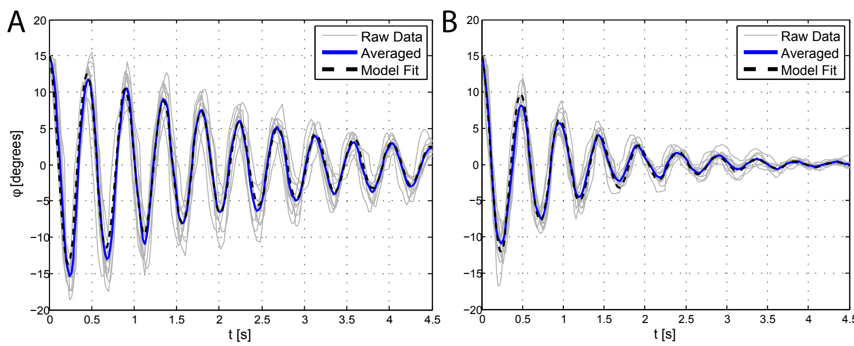

Fig. 3. Pitch angle versus time after pitch perturbations, where the quadrotor propeller gains were "de-tuned" so that pitch was stable but highly oscillatory. **(A)** The open loop (no abdominal control—the abdominal servo-angle is held fixed). **(B)** The servo is controlled in closed-loop via the simple PD scheme described controller (1).

	(A) Stable Plant		**(B) Unstable Plant**
	Open-loop (abdomen off)	*Closed-loop* (abdomen on)	*Closed-loop* (abdomen on)
$\lambda_{1,2}$	$-0.40 \pm 14.02j$	$-0.90 \pm 13.03j$	$-0.76 \pm 13.38j$
ω_n	14.03 rad/s	13.061 rad/s	13.40 rad/s
ω_d	14.02 rad/s	13.03 rad/s	13.38 rad/s
ζ	0.028	0.069	0.057

Table 1: Characterization of stability improvement with abdominal control. **(A) Stable Plant:** *Open-loop* refers to the abdominal control being turned off, and *Closed-loop* refers to the abdominal control being turned on. As can be seen, the damping increases significantly when the abdominal control is turned on. **(B) Unstable Plant:** Stability is recovered in *Closed-Loop* (with abdominal feedback).

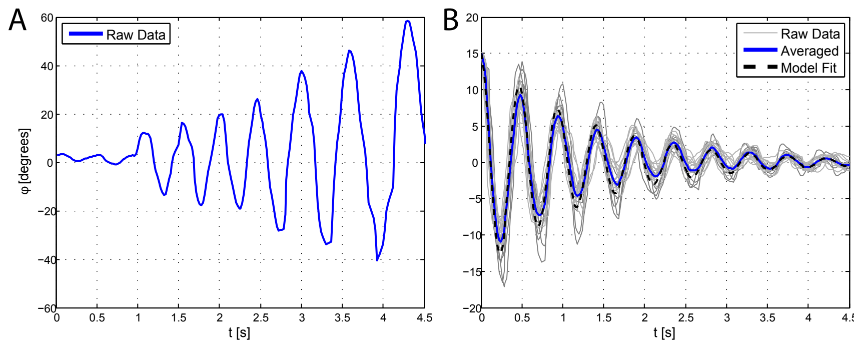

Fig. 4. Pitch angle versus time after pitch perturbations, where the quadrotor propeller gains were "de-tuned" so that pitch was unstable. **(A)** Response with no abdominal control. **(B)** Response with abdominal control.

4. Discussion

Dyhr *et al.*[4] hypothesized that active feedback control of an inertial appendage could be used to enhance the stability of a moth during flight and suggested this effect could be used for artificial machines.[5] Here, we instantiated their biological hypothesis as an engineering design concept: flexible airframes for active inertial redirection of aerodynamic forces. In our experiments, lift forces generated by propellers were redirected by changes in the pitch angle of the main chassis (analogous to the thorax of the hawkmoth). The pitch angle of the main chassis of the quadrotor was itself mediated by PD-controlled abdominal articulation in the sagittal plane.

There are obvious limitations of our quadrotor aircraft as a physical model of insect flight: the robot and animal operate at dramatically different physical scales and employ radically different propulsion mechanisms. Yet, the combination of mathematical analysis and biological modeling presented by Dyhr *et al.*[4] and physical experiments put forth in this paper, lay a foundation for future work in flexible frames for flight control.

There remain many engineering improvements before us. First, implementing absolute position control would enable tetherless testing of abdomen-mediated maneuvers involving flips and rolls, which is a worthwhile future direction. Most importantly, the controllers we have implemented are ad hoc, and more systematic controller design should greatly enhance the performance of the system.

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References

1. S. Bouabdallah, R. Siegwart, and G. Caprari. Design and control of an indoor coaxial helicopter. In *Proc. IEEE Int. Conf. Robot. Autom.*, pages 2930–2935, Oct. 2006.
2. J. Camhi. Sensory control of abdomen posture in flying locusts. *J. Exp. Biol.*, 52(3):533, 1970.
3. J. Camhi. Yaw-correcting postural changes in locusts. *J. Exp. Biol.*, 52(3):519–531, 1970.
4. J. Dyhr, K. A. Morgansen, T. Daniel, and N. Cowan. Flexible strategies for flight control: an active role for the abdomen. *J. Exp. Biol.*, in prep.
5. J. P. Dyhr, N. J. Cowan, D. J. Colmenares, K. A. Morgansen, and T. L. Daniel. Autostabilizing airframe articulation: Animal inspired air vehicle control. In *Proc. IEEE Int. Conf. on Decision Control*, 2012. Submitted.
6. J. P. Dyhr, N. J. Cowan, A. J. Hinterwirth, K. A. Morgansen, and T. L. Daniel. Flexible frames for flight. In *Soc. Int. and Comp. Biol.*, 2012.
7. T. L. Hedrick and T. L. Daniel. Flight control in the hawkmoth manduca sexta: the inverse problem of hovering. *J. Exp. Biol.*, 209(16):3114–3130, Aug 2006.
8. A. J. Hinterwirth and T. L. Daniel. Antennae in the hawkmoth Manduca sexta (Lepidoptera, Sphingidae) mediate abdominal flexion in response to mechanical stimuli. *J. Comp. Physiol. A*, 196(12):947–956, Dec 2010.
9. T. Libby, T. Y. Moore, E. Chang-Siu, D. Li, D. J. Cohen, A. Jusufi, and R. J. Full. Tail-assisted pitch control in lizards, robots and dinosaurs. *Nature*, 481:181–184, Jan. 2012.
10. T. Luu, A. Cheung, D. Ball, and M. V. Srinivasan. Honeybee flight: a novel streamlining response. *J. Exp. Biol.*, 214(13):22152225, July 2011.
11. J. Ostrowski. Computing reduced equations for robotic systems with constraints and symmetries. *IEEE Trans. Robot. Automat.*, 15(1):111–123, 1999.
12. C. Pradalier. pers. comm., 2012.
13. G. Taylor and H. Krapp. Sensory systems and flight stability: what do insects measure and why? *Advances in Insect Physiology*, 34:231–316, 2007.