Open-loop roll, pitch and yaw torques for a robotic bee

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Abstract—This paper presents measurements of open-loop roll, pitch and yaw torques, and open-loop flight experiments for an insect-sized robotic bee. Torques are generated entirely with flapping wings via an actuation scheme that uses a single, central power actuator and two smaller control actuators that fine-tune wing motion. We present an initial 110mg design used for torque measurements and a lighter 83mg prototype that is capable of liftoff with external power and can execute open loop pitching and rolling maneuvers.

I. INTRODUCTION

Inspired by agile natural flyers, in the last decade engineers have pursued the development of flapping-wing micro air vehicles (FWMAVs) on the scale of insects and small birds. Such vehicles rely on flapping wings for propulsion, rather than more traditional mechanisms such as propellers or jet engines. Recent successes include the DelFly [1], which uses a tail to steer, the smallest of which has a mass of 3g and a 10cm wingspan; and the Aerovironment Nano Hummingbird [2], which has a mass of 19g, a 16.5cm wingspan and steers by modulating wing angle of attack. Several orders of magnitude less massive is the Harvard RoboBee, with a mass of approximately 100mg and wingspan of 3cm.

The RoboBee project has evolved since the original version of the vehicle [3] was developed in 2007 (Fig. 1). The first prototype could lift off with external power, but was attached to guide rails for stability and had no mechanism for active attitude control. A mechanism to control body torques using a central power actuator and smaller control actuators was originally proposed in [4]. In [4], wing kinematics were measured, but aerodynamic torques were only predicted using a quasi-steady blade-element aerodynamic model [5] and not measured directly. Several years later, the development of a custom micro torque sensor [6] allowed direct measurement of body torques, and this was tested on pitch torques (which do not require control actuators). In this work, we describe a proof-of-concept RoboBee with control actuators used to measure roll and yaw torques. Finally, we introduce a lighter, 83mg vehicle for open-loop flight experiments. Much additional work is currently in progress, including system identification and trajectory tracking of open loop flights, and...
closed-loop controlled flight experiments; these experiments are beyond the scope of this paper.

II. MECHANISM

The detailed mechanical design of the vehicle is presented in [4] but summarized briefly here. The original RoboBee vehicle consisted of a single piezoelectric actuator [7] that flapped both wings symmetrically through a four-bar transmission. The design in [4] added two smaller piezoelectric actuators that could independently tune the transmission ratio between the power actuator and the left and right wings, allowing independent modulation of stroke amplitude without changing the motion of the power actuator. This is similar to the thoracic structure of Dipteran insects [8], which use large power muscles (dorsoventral and dorsolongitudinal) at resonance with the thorax and wings, and smaller control muscles to fine-tune wing motion for steering.

III. TORQUE GENERATION

The principles for controlling roll and pitch torques were originally introduced in [4]. Here we briefly review those principles and introduce a method for controlling yaw torques with this design. An important principle for torque control is that the wingbeat dynamics are roughly an order of magnitude faster than the body dynamics - thus, body attitude can be controlled by controlling time-averaged, not instantaneous, forces and torques. This has been observed both in biological systems [9] and FWMAV experiments [10], [11]. This section addresses the general wing motions, and actuator signals specific to this design, required to generate all three torques. A schematic top-down view of the vehicle in hover with roll, pitch and yaw axes defined is shown in Fig. 2a for reference.

A. Wing Kinematics

Pitch torque can be controlled simply by shifting the mean stroke angle forward or backward. This can be accomplished with a single power actuator and does not require control actuators, and is depicted schematically in Fig. 2b. Measurements of pitch torque generated with this method were originally presented in [6], and used for single-DOF pitch attitude control in [11].

Roll torques are controlled via differential stroke amplitude - the control actuators are excited out-of-phase to increase the amplitude of one wing while decreasing the amplitude of the opposite wing. This has the advantage of generating a torque while keeping the total lift, and net load seen by the power actuator, approximately the same. This is depicted in Fig. 2c.

While roll and pitch torques can be controlled with parameters that can be varied slowly over several wingbeat periods, yaw torques require use of the control actuators on a sub-period basis to achieve split-cycle flapping ([12], [13] present a method for control with split-cycle flapping using independent wing actuation). When control actuators are used to change wing amplitude at a fixed power actuator frequency, this also changes wing velocity - i.e., in Fig. 2c,
the left wing will have a higher velocity than the right wing since it is sweeping through a larger amplitude at the same frequency. If this amplitude differential is switched on the upstroke and the downstroke, then one wing will have a higher velocity on the upstroke, and the opposite wing will have a higher velocity on the downstroke. This creates an asymmetry in drag force on each wing over the wingbeat cycle, resulting in a net yaw torque. This is illustrated in Fig. 2d.

B. Actuator Signals

Each piezoelectric actuator is voltage-driven with a unipolar signal, typically ranging up to 300V (drawing about 100mW for the power actuator and several milliwatts for the control actuators). Each actuator has three electrical terminals: a positive “bias” voltage, a signal voltage, and ground. Note that for a bimorph actuator with a unipolar drive, zero displacement will occur when the signal voltage is equal to one-half the bias voltage. Thus, for drive signal \( V_i \) and bias voltage \( V_b \), we can parameterize the drive signal of the \( i \)th actuator as

\[
V_i = A_i \sin (\omega t + \phi_i) + \beta_i
\]

where \( A_i \) is referred to as the amplitude and \( \beta_i \) as the offset. The parameters necessary for a constant time-averaged torque are defined for the power \( (V_1) \) and control \( (V_2 \& V_3) \) actuators in Table I and depicted graphically in Fig. 3. Note that only the phases \( \phi_i \) and offsets \( \beta_i \) are relevant for determining which torque is generated - the amplitudes \( A_i \) will simply scale the magnitude of the torque, and the frequency \( \omega \) is the same for all three actuators.

For convenience, we define the following “control” voltages for each torque. For pitch,

\[
V_p = \beta_1 - \frac{V_b}{2}
\]

for roll

\[
V_r = \beta_2 - \frac{V_b}{2}
\]

and for yaw

\[
V_y = A_2.
\]

Note that for roll and yaw, the control actuator signals are always mirrored about \( V_b/2 \), so it is mathematically redundant to define another voltage based on \( V_3 \).

IV. TORQUE MEASUREMENTS

The single-axis torque sensor from [6] was used to measure roll, pitch and yaw torques individually for the 110mg prototype. The pitch torque data from [6] is reproduced here for completeness, and for the first time we present roll and yaw torque data for an insect-sized FWMAV. Torques in the range of \( \pm 1\mu \text{Nm} \) can be achieved about each axis, and these are compared to torques measured in several commonly studied insect species in Fig 4. Note that since testing conditions varied for the data collected on different insects in [14], [17], [15], [16], this is only an order-of-magnitude comparison for torques generated by insects of different sizes. It is not intended to indicate any definitive trend or scaling law, or claim that the RoboBee will be controllable based on its relative location on this plot. However, the torque generated by the RoboBee seems consistent with its mass when compared to biological data.

The experimental data is shown in Fig. 5 for time-averaged torques over a period of several seconds. All three torques show a fairly linear relationship with their respective control voltages \( V_p \), \( V_r \) and \( V_y \) - surprising due to the nonlinear nature of the aerodynamic forces, but potentially beneficial for controller design. An additional test, varying the control actuator phase \( \phi_2 \) with constant signal \( V_y \) (and the relationship \( \phi_3 = \phi_2 + \pi \)), shows that the values \( \phi_2 = \pi/2 \) and \( \phi_3 = 3\pi/2 \) maximize yaw torque (Fig. 5d). The amount of data presented here is limited primarily due to the limited lifespan of experimental devices (flexure hinges tend to fatigue and piezoelectric actuators are subject to brittle failure) - however improving fabrication methods [18], [19] continue to help mitigate these issues, and closed-loop system identification of the voltage-torque input-output systems is currently in progress.
V. OPEN-LOOP FLIGHT MANEUVERS

The 110mg proof-of-concept vehicle used to measure torques proved too heavy for successful liftoff, so a redesigned 83mg vehicle was developed and used for free flight experiments. The primary weight reduction came from downsizing the control actuators (from 20mg each to 10mg each), along with slight reduction in airframe mass (from 13mg to 8mg). This results in a sacrifice of maximum torque output, as torque scales with actuator displacement, which scales with actuator size (see [4] for details), however the sacrifice was necessary in order to achieve liftoff. The power actuator, wings and transmission remained the same (other miscellaneous components, like glue used for assembly, make up the remainder of the mass). The lighter vehicle is shown in Fig. 6. Open-loop tests confirmed the ability to perform liftoff, pitch and roll maneuvers. Figure 7 shows combined frames from high-speed videos of open-loop “vertical liftoff”, “roll left” and “roll right” trajectories. The full videos are available as supplemental material. These initial results show that roll and pitch motions are not entirely decoupled; and attempts
VI. Conclusions

This paper has presented the first roll and yaw torque measurements for a RoboBee prototype, as well as the first flight experiments that were not mechanically tethered for stability. This is just one step on the path to a vehicle capable of untethered, controlled hover. All of the experiments presented in this paper were open-loop and did not make use of system identification or feedback control. Due to the lack of a six-axis force/torque sensor with appropriate range and resolution, we also cannot claim that the torques measured were entirely decoupled. However, the preliminary flight experiments give a qualitative sense that the vehicle has a reasonable ability to independently control body torques, and thus should be capable of free flight with a sufficient controller. System identification of both torque data and free flight data, as well as controlled flight experiments, are currently in progress and will be the subject of future publications.

REFERENCES

Fig. 7. High-speed video frames showing open-loop flight maneuvers (filmed at 1000 frames per second with a Phantom V7.10 high-speed camera from Vision Research). Vertical liftoff (center column), roll left (left column), and roll right (right column) trajectories are shown. The trajectory history is overlayed on each frame, with a dot representing the approximate center of mass. See electronic supplemental material for the full videos, including open-loop pitch maneuvers.


