Analysis of Kinematics and Dynamics of Butterflies in Natural Flight, with Estimation of Occluded Data

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I. Introduction

The aerospace and biology communities are increasingly interested in the flight mechanics [1] and dynamics of micro air vehicles (MAV) and natural organisms in the low Reynolds number regime. Flight measurements for biological systems are available; however, a meaningful, concise, record of existing data remains a work-in-progress. Furthermore, most data is collected in precise, experimental environments. Comprehensive data on insect flying in a natural environment are extremely rare.

This paper presents a work in progress in developing experimental techniques used to collect live flight data from Lepidoptera (butterflies) in their natural environment, and develop models to describe the mechanics of their flight. All flight measurements were performed at the Butterfly Rainforest at the McGuire Center for Lepidoptera and Biodiversity, a 6,400 square foot screened vivarium at the Florida Natural History Museum in Gainesville, FL, USA. The center houses over 460 species of plants and 2,000 free-flying butterflies representing 120 different species. From this initial data set, inferences of flight mechanics will be proposed.

Natural fliers demonstrate a diverse array of flight capabilities, many of which are poorly understood. NASA has established a research project to explore and exploit flight technologies inspired by biological systems [2]. From an engineering standpoint, this interest is driven by design of MAV's [3]. Much of the research regarding insect flight comes from the biology community. Organisms that have been previously studied include desert locusts, dragonflies, damselflies and blowflies [3]–[6]. Much of this research was collected in artificial settings, such as wind tunnels.

Preliminary flight data gathered in this project focused on Idea Leuconoe (Tree Nymph) butterflies, and showed an apparently significant abdomen activity in certain flying phases with a possible correlation with the flapping wing and body dynamics. The objective of the proposed work is to differentiate the main insect elements and effectively decouple their dynamics from the main body with the intent of finding any correlation between single body parts, external stimuli and the overall flight mechanics. The experimental estimate of the main elements of the insects' kinematics will be attempted while seeking a frequency-response data that will characterize the dynamics of the specimen as a complete input-to-output system. The frequency-response methodology is a very well known technique used in the rotorcraft community. Rotorcraft are characterized by complicating factors such as very low signal-to-noise ratio, unstable pitch and roll dynamics and high level of noise in the measurements. The above features are typical of insects' flight; therefore this technique seems particularly suited for butterflies' flight-mechanics characterization.

II. The Experimental Set Up

The data acquisition system was designed to be non-obtrusive and allow measurements in the specimens' natural environment. A vision-based estimation method is used to study the insect flight with as little interference to the natural behavior as possible. The visual system is composed of two high-speed digital cameras synchronized as a stereo pair, seen in Fig. 1. The stereo pair are calibrated to resolve intrinsic and extrinsic parameters of the camera, allowing estimation of 3D position of points in space [7]. The measurements were performed under natural sunlight conditions at 100-200 frames per second and resolutions of 800x600 pixels. Points on the butterfly, such as head, thorax, abdomen and wing tips, are tracked by hand in each video frame, and converted using a modified version of open source stereo estimation software [8].

One of the main concerns of this research is to validate our results and provide accurate error estimates. To this end, we have designed an artificial, articulated target mounted on pendulum+shaker capable of precise motions with disturbance signals, seen in Fig. 2. All data analysis routines developed for use on butterfly data can be validated by performing them on video of the artificial target. It is possible to determine the position trajectory of the fiducial pattern on this artificial body, quite reliably using the VIC software. The VIC is however capable of tracking only fiducial patterns and therefore cannot be used directly to obtain butterfly position data. Figure 3 shows a comparison of the position data of a fiducial pattern on the spring mass body, using both the VIC and the tracking software. Measurements along the direction perpendicular to the camera plane are generally more susceptible to errors, and this is borne out by the relatively larger error along the z axis in the figure (the z axis comprises most of the out of plane motion). The in-plane motion (along the x and y axes) shows relatively smaller error values. At this

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Fig. 1. Stereo camera rig at the McGuire Center

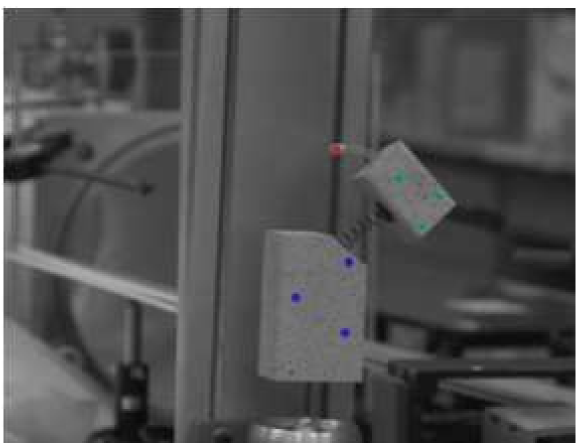

Fig. 2. The artificial target, with points tracked on the body (blue), head (green) and antenna (red).

point, motion estimation from the stereo reconstruction is accurate within ± 0.5 mm for motion components parallel to the image plane, and within ± 2mm for motion perpendicular to the image plane. The estimation error due to noise is currently addressed through filtering. Future efforts will seek to address it through nonlinear optimization of the estimate (i.e. bundle adjustment).

III. Kinematics Data Processing

The 3D position estimates are used to determine the trajectories of the various body parts both in an inertial camera-fixed frame, as well as in a moving body-fixed frame. One ultimate objective is to obtain correlations between these individual motions with the overall flight trajectory of the insect, and such correlations are sought during different flight phases. For the purposes of this paper, we shall focus on the take-off segment and look at the motion of the wing tips, the abdomen tip and the head-thorax system.

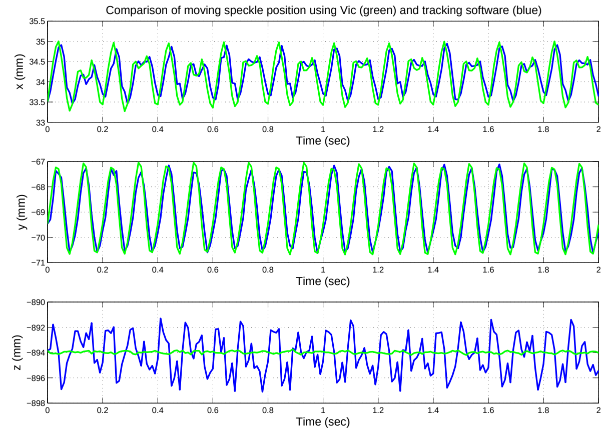

Fig. 3. Comparison of position trajectory of a fiducial pattern on the artificial spring mass body using the VIC (green) and tracking software (blue).

Data is initially filtered using a cubic spline fitting to remove noise, with filtering being carefully tuned to strike a balance between removing noise and leaving apparent motion data. Occlusions of the tracked body parts are unavoidable, and the wings often obscure the head and abdomen. To address this issue, we propose a method to fill missing spans data when at least one point is visible on the same body. For body parts such as the abdomen, points on both ends are tracked. We fill in each missing data point based on the assumption that the body part is rigid and does not change shape (data analyzed thus far indicates this is true for the abdomen within the expected position error of the tracked points).

Consider a sequence of 3D measurement of two points on a rigid body, $p_k,\ q_k \in \mathbb{R}^3$, $k \in \{1 \dots T\}$, where T is the length of the data sequence, i.e. the number of measurements. Assume point q_k is visible for all k, but point p_k is obscured for samples $k \in \{M \dots N\}$. Since they lie on a rigid body, it is known that points p_k and q_k lie a constant scalar distance R from each other. We make the assumption that the missing point will move the least distance possible during the obscured time period. Given that q_k is always visible, and R is known we estimate the coordinates of p_k by finding the estimate $\hat{p}_k$ that minimize the following constrained equation

$$\text{minimize: } f(\hat{p}_k) = \frac{1}{2}\left\|p_k - p_M\right\|^2 + \frac{1}{2}\left\|p_k - p_N\right\|^2$$

$$\text{constraints 1-3 : } h_1(\hat{p}_k) = \frac{1}{2}\left\|\hat{p}_k - q_k\right\|^2 = R$$

$$h_2(\hat{p}_{M+1}) = \frac{1}{2}\left\|(\hat{p}_{M+1} - p_M) - (p_M - p_{M-1})\right\|^2 \leq d$$

$$h_3(\hat{p}_{N-1}) = \frac{1}{2}\left\|(p_N - \hat{p}_{N-1}) - (p_{N+1} - p_N)\right\|^2 \leq d$$

where d is some constant that will need to be tuned. Constraint h_1 constrains the position of the estimate relative to the measured position of the visible body point. Constraints h_2 and h_3 constrain only the first and final estimates of the

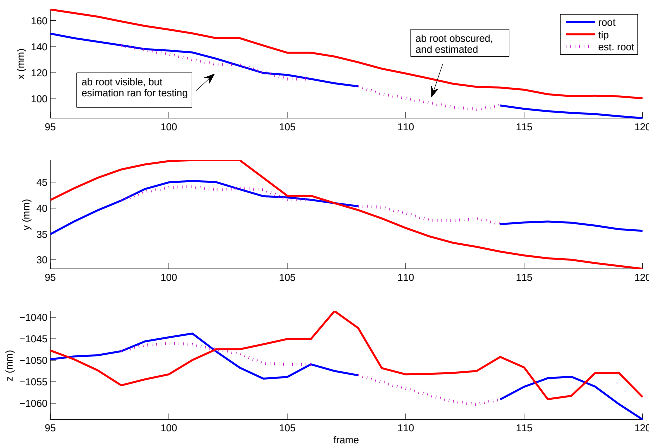

Fig. 4. Example of estimating an obscured data sequence.

missing such that there is not an abrupt change in velocity for the point. The solution is found numerically for each missing point.

An example of this method can be seen in Fig. 4. Video was captured of a butterfly and points were tracked on the abdomen tip and abdomen root. The abdomen tip is visible through the entire time window, but the ab root is briefly obscured from frames 109-114. The proposed method is used to estimate the unknown position of the ab root during this interval. To test the strength of the method, it is also used to estimate the ab root position from frame 98-106. The ab root is visible in the interval, so can provide a comparison. The average error between estimation and measurement during this time is 3.8582 mm, with standard deviation of 1.4233mm. The majority of this noise is along the z-axis (optical axis of the camera), which is a notably noisy estimate.

Fig. III shows three snapshots of a movie taken of a butterfly during take-off. During this segment, a significant amount of motion of the head-thorax system, as well as the abdomen tip was observed. The pair of red lines shown on each figure is drawn from the abdomen root to the abdomen tip and the head. We attempt to obtain quantitative estimates of the angular displacements of these body parts on the pitch plane. The pitch plane is defined as the plane comprising of three points – a point on the abdomen tip, a point on the abdomen root and a point on the head. The 3D estimates of these three points are tracked successively in each frame, and the pitch plane orientation is updated at each frame. It is understood that there is some inherent error in this process owing to the fact that it may not be possible to track exactly the same point on the abdomen tip (or the abdomen root and head) from one frame to the next.

Fig. 6 demonstrates the above-mentioned angular data, as a function of time. There is significant amount of head-thorax activity, as evidenced by the fact that it exhibits an angular displacement of close to 90 degrees, over a span

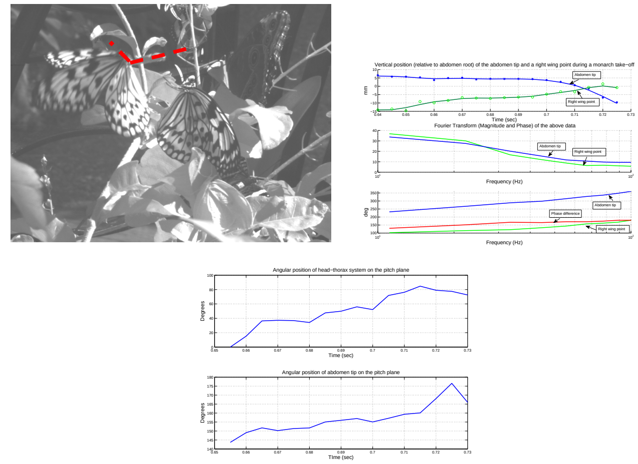

Fig. 5. Three different snapshots during a take-off segment demonstrating variable angular positions of the head-thorax system and the abdomen root.

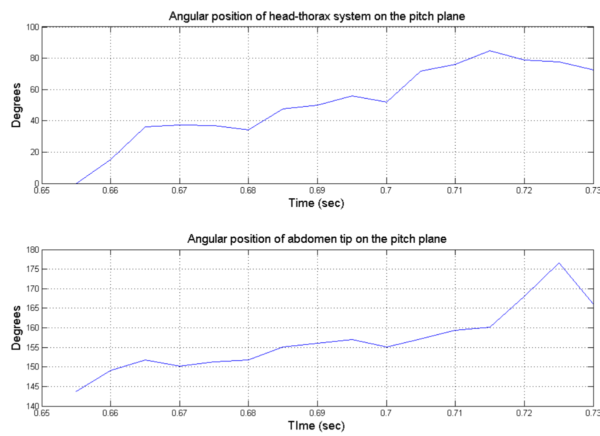

Fig. 6. Angular positions of the head-thorax system and the abdomen tip on the pitch plane

of about 0.07 sec. During this same time, the abdomen tip deflected about 35 degrees. The included angle between the line joining the abdomen root to the head and the line joining the abdomen root to the abdomen tip varies from around 140 deg to around 70 deg, within this short time span. Fig. 7 then shows the corresponding Fourier transforms, demonstrating the relative activity of the head-thorax system as compared to the abdomen tip.

Fig. 8 then demonstrates the vertical displacement of the abdomen tip (measured relative to the abdomen root) in conjunction with the vertical displacement of a point on the right wing. Both these points show a net displacement of about 15 mm (over the same time interval) demonstrating the significant motion of the abdomen tip, as compared to the wing. The Fourier transforms demonstrate that both the wing and the abdomen tip have almost identical magnitude content, and the phase difference between their motions is almost constant over a range of frequencies.

Fig. 9 then shows a time history of several body parts

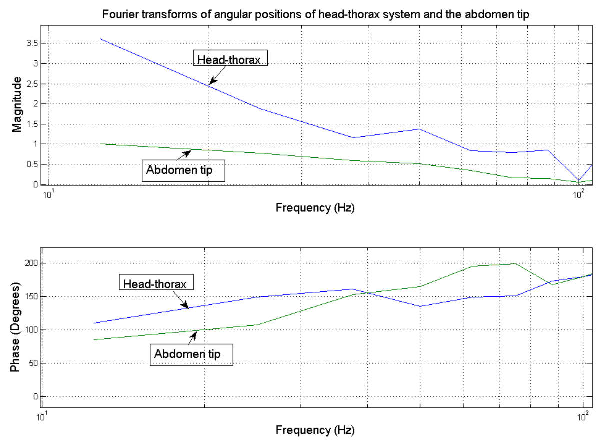

Fig. 7. Fourier transforms of angular positions of head-thorax system and abdomen tip

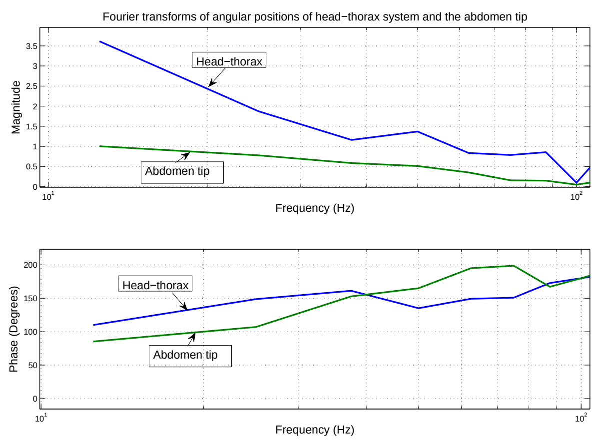

Fig. 8. Vertical displacement of abdomen root and a right wing point (during a take-off segment) along with the corresponding Fourier transforms

(along the vertical axis) during a take-off and a comparison of those with the vertical displacement of the abdomen root during the same time-segment. The figure demonstrates significant movement of the head-thorax system (about 10 mm), along with simultaneous abdomen tip movement (about 20 mm) and right wing tip movement (about 10 mm). During this time, the abdomen root is vertically displaced by about 7 mm.

IV. Future Work

This is a work in progress. Early efforts points have focused on collecting data and necessary data processing to improve signal fidelity and recover missing data. Initial data analysis has determined some interesting phenomena that may not have been previously understood. For example, it appears that butterfly take-off involves significant motion of the abdomen and relative motion of abdomen and head. This may indicate the use of center of gravity for stabilization and control. Future efforts will include refining data collection

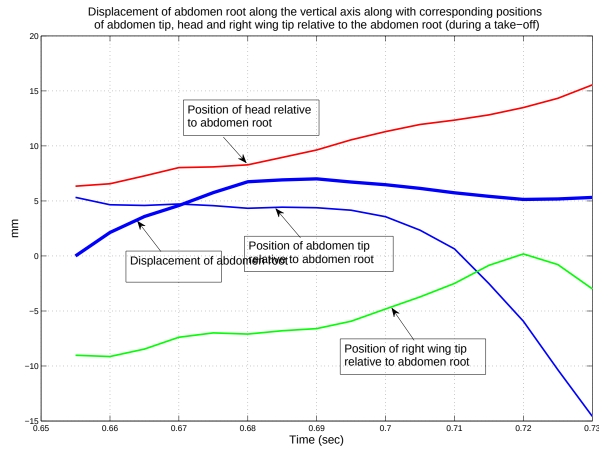

Fig. 9. Displacement of abdomen root along the vertical axis along with corresponding positions of abdomen tip, head and right wing tip relative to the abdomen root (during a take-off)

and processing, along with establishing error estimates for all analysis. However, primary future efforts will focus on using collected data to formulate a mathematical model of butterfly flight in multiple flight regimes.

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