A Body Reorientation Strategy in Insect Takeoff Flight

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Fast and efficient recovery of flight orientation during takeoff or after a severe disturbance is desirable for micro flapping fliers. Navigating body through desired path in limited space and time needs fast and accurate control mechanisms to modulate flight moments. In this work we shot high-speed videos from dragonflies taking off starting from various initial orientations. Modifying equations of motion of a rigid flying body, we introduced governing equations for fast turns of dragonflies. Results suggest that there are other levels of maneuver planning rather than manipulating aerodynamic moments to accomplish fast and efficient turn maneuvers. Rapid change (within few wing beats) in flight course was accomplished through efficient kinetic energy transfer between pitching and yawing motion via body rolling velocity.

Nomenclature

\begin{align*}
\ddot{\omega}_\text{cpl} & \quad \text{Coupling induced yaw acceleration vector, rad/s}^2 \\
\ddot{\omega}_\text{aero} & \quad \text{Aerodynamic induced yaw acceleration vector, rad/s}^2 \\
\dot{\omega} & \quad \text{Body rotational velocity vector} \\
\dot{V} & \quad \text{Body translational speed vector} \\
P & \quad \text{Roll velocity, rad/s} \\
Q & \quad \text{Pitch velocity, rad/s} \\
R & \quad \text{Yaw velocity, rad/s} \\
I_b & \quad \text{Moment of inertia matrix, Kg.m}^2 \\
\dot{F} & \quad \text{Flight forces vector} \\
\dot{\tau} & \quad \text{Flight moments vector} \\
L & \quad \text{Flight moment in x direction} \\
M & \quad \text{Flight moment in y direction} \\
N & \quad \text{Flight moment in z direction}
\end{align*}

I. Introduction

Insect flight, as the most agile flight in micro aviation, was always inspiring for flapping wing micro air vehicles (MAV) design. Although numerous research has been done on aerodynamics of flapping flight \([1-3]\), flight forces control and flapping mechanisms of the insects, it’s still not possible to design effective robot flies which can achieve biological levels of aerial performance. While research has been done on understanding and mimicking control mechanisms \([4]\), hinge morphology \([5]\) or body torque modulation technique \([6, 7]\) of insect flights and their applications to MAV design, there remains a lack of knowledge on how insects navigate the motion and reorient their flight in fast turn maneuvers especially after taking off or any major loss of desired flight course. Research on flight navigation and control of insects is usually focused on flight stabilization or obstacle avoidance.

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strategies and sensory and data processing techniques [8]. But less attention is being attracted to maneuver planning and motion management techniques although these kinds of knowledge can be extensively useful in designing high maneuverable flying robots and may help us understand how nature resolved complexities and difficulties involved with designing such systems in limited size and weights.

As one of the fastest maneuvers in the insect world, dragonflies are able to quickly take off and change flight orientation in few wing beats. In this work, we study strategies used in dragonflies’ takeoff and flight reorientation by using a combined high-speed photogrammetry and equation of motion analysis. Our results suggest that effective energy exchange between various components of rotational motions is used by dragonflies to accomplish desired maneuver without delicate manipulation of flight moments in yaw and pitch direction.

In following sections, general governing equations of turns of a flying rigid body is simplified for analyzing dragonfly’s fast turns using its specific wing-body configuration. Discussion will be continued introducing two kinds of energy agents serving in the system to manage level and distribution of kinetic energy. Fast turn maneuver of two different dragonflies, after taking off to reorient the flight in limited time and space, are analyzed in current paper. Our studies suggest the existence of an unknown level of maneuver planning and navigation in dragonflies’ flight which can be potentially used for effective maneuver planner designs applicable high maneuverable micro air vehicles.

II. Methodology

A. Equations of motion

Equations of motion for a rigid body motion with non-zero flight forces and moments can be written as following

\[
\begin{bmatrix}
ml & 0 & \omega \\
0 & I_b \omega & \omega \times m \vec{V} \\
\omega \times I_b \omega & \omega \times m \vec{V} & \vec{F}
\end{bmatrix} = \begin{bmatrix}
\vec{F} \\
\vec{M}
\end{bmatrix}
\]

(1)

Here, \( F \) and \( M \) are the total flight forces and moments respectively. \( I_b \) is the inertial tensor and \( \vec{V} \) and \( \vec{\omega} \) represent translational and rotational velocity vectors, respectively.

From lab observation, following its takeoff, dragonfly usually uses a turning motion to achieve desired flight orientation. In this work, we are interested in rotational motion and we’ll focus last line of equations (1). This will not affect our conclusions as importance of coupling between translation and rotation shows up when we are concern with flight stability or aerodynamic mechanisms. Expanding rotational term in Equation (1) we get

\[
\begin{align*}
\dot{P} + C_1 RQ - D_1 (\dot{R} + PQ) &= l \\
\dot{Q} + C_2 PR + D_2 (P^2 - R^2) &= m \\
\dot{R} + C_3 PQ - D_3 (\dot{P} - QR) &= n
\end{align*}
\]

(2)

\[
\begin{align*}
C_1 &= I_{zz} - I_{yy}, & C_2 &= I_{xx} - I_{zz}, & C_3 &= I_{yy} - I_{xx}, \\
\frac{D_1}{I_{xx}} &= I_{zz} - I_{yy}, & \frac{D_2}{I_{yy}} &= I_{xx} - I_{zz}, & \frac{D_3}{I_{zz}} &= I_{yy} - I_{xx},
\end{align*}
\]

where P, Q, R are roll, pitch and yaw velocities (Figure 1a) about the longitudinal, lateral and normal axes of the body coordinates respectively. l, m and n are the corresponding flight rolling, pitching and yawing moments divided by moment of inertia in respective direction. \( C_i \) and \( D_i \), configuration parameters, define wing body configuration from mass distribution point of view. Specifying these values, behavior of the rigid body can be characterized and compared for different configurations using similar analysis provided in this study. The other important parameter in
analyzing motion and dynamic behavior is connection between the aerodynamic moments and the motion variables which is outside of the scope of this research but will be left for future work.

| Table 1. Total weight and body length for each of dragonflies in the experiment. |
|-----------------------------------|----------------|--------|
|                                  |   |        |
| **Dragonfly I**                  | .256 | 43.95  |
| **Dragonfly II**                 | .166 | 39.02  |

B. Moment of Inertia (MOI)

The data presented in this paper is from Eastern Pondhawk, *Erythimus Simplicicollis*, dragonflies, which were taken from a lake near the research lab during the period of August–September 2010. Weight and body length were measured for each individuals before the lab test. Two flights of two different individuals (Table 1) are analyzed and discussed in this paper.

In order to calculate the moment of inertia of each dragonfly, we cut bodies into three major parts, head, thorax and tail. Then the length and weight of each part were measure. Thorax and frontal section of tail, closer to thorax, are approximated with an ellipsoid while head and aft tail are estimated as two half ellipsoids, matched to their real shape (Figure 1).

![Figure 1. (a) Dragonfly’s body is approximated with 3 ellipsoids and one half ellipsoid for head. (b) definition of dimensions of ellipsoids.](image)

Dimensions of each of the sections and their contribution in moment of inertia (MOI) plus the whole wing-body MOI are shown in Table 1.

| Table 2. Weight, dimensions and MOI for wings and each of the body sections. |
|-----------------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
|                                  | Weight (g) | a (mm) | b (mm) | c (mm) | Roll MOI (Kg.m^2) | Yaw MOI (Kg.m^2) | Pitch MOI (Kg.m^2) |
| Head                             | .0184      | 4.46   | 3.7    | 4.5    | 6.03e-11           | 1.52e-9           | 1.54e-9           |
| Thorax                           | .1846      | 5.4    | 2.7    | 3.4    | 7.05e-10           | 6.85e-9           | 7.02e-9           |
| Tail Part I                      | .0308      | 2.7    | 1.7    | 2.4    | 2.95e-11           | 7.18e-10          | 7.28e-10          |
| Tail Part II                     | .0214      | 11.6   | 1.2    | .75    | 1.51e-11           | 1.53e-8           | 1.53e-8           |
| Fore Wings                       | .0030      |        |        |        | 6.70e-10           | 2.26e-11          | 2.26e-11          |
| Hind Wings                       | .0031      |        |        |        | 6.10e-10           | 5.02e-12          | 5.02e-12          |
| Body+Wings                       | .256       |        |        |        | 2.09e-9            | 2.44e-8           | 2.46e-8           |

The dragonfly body is assumed non-deflectable for current cases although in some flights the body deflection might be significant. Contribution of the wings on the location of the center of mass and yawing and
pitching moment of inertia is negligible (1% and 2%). Because of the slim cylindrical shape of the body, rolling moment of inertia is significantly lower and two pair of wings can increase it by about 60% assuming that the center of mass of the wings are located in 30% of the wing length measured from root. Change in rolling moment inertia due to the wing flapping is negligible assuming that wing center of mass moves on an arc which its center is close to center of mass. Also wings are almost symmetrically distributed around the center of mass therefore their effect on the product moment of inertia, $I_{xz}$, is negligible. MOI tensor can be written as below

$$I_b = 10^{-9} \begin{bmatrix} 2.09 & 0 & -1.02 \\ 0 & 24.40 & 0 \\ 0 & 0 & 24.60 \end{bmatrix}$$

To calculated similar tensor for Dragonfly II, a scaling parameter is used. It is listed as below

$$\frac{m_i}{M'} \times \left( \frac{l_i}{L'} \right)^2$$

(3)

Here, $M'$ and $L'$ represent the first dragonfly’s mass and length respectively and $m_i$ and $l_i$ are the mass and length of the $i^{th}$ dragonfly. Configuration parameters which show importance of each of the terms in equations of motion and their corresponding term are shown in Table 3.

### Table 3. Configuration parameters for Dragonfly I.

<table>
<thead>
<tr>
<th></th>
<th>Value for Dragonfly I</th>
<th>Corresponding Term in EOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>-.09</td>
<td>$RQ$</td>
</tr>
<tr>
<td>$C_2$</td>
<td>-.90</td>
<td>$PR$</td>
</tr>
<tr>
<td>$C_3$</td>
<td>.90</td>
<td>$PQ$</td>
</tr>
<tr>
<td>$D_1$</td>
<td>-.48</td>
<td>$-(R+PQ)$</td>
</tr>
<tr>
<td>$D_2$</td>
<td>-.04</td>
<td>$(P^2-R^2)$</td>
</tr>
<tr>
<td>$D_3$</td>
<td>-.04</td>
<td>$-(P-QR)$</td>
</tr>
</tbody>
</table>

### C. Simplified equations of motion for dragonfly’s turning motion

Based on the moment of inertia calculations presented in the previous section, yaw and pitch moments are found out to have almost equal values. Since $I_{xz}$ is much smaller than pitch and yaw MOI, Equation 3 can be further simplified as below,

$$\ddot{P} = I + \frac{(\dot{R} + PQ)}{2}$$

(4)

$$\dot{Q} = m + PR$$

$$\dot{R} = n - PQ$$

Based on the equations above, we divided the total rotational acceleration vector to two components (Equation 5). These two terms represent contribution of aerodynamic and coupling terms in accelerating the motion, respectively.

$$\ddot{\omega} = \ddot{\omega}_{aero} + \ddot{\omega}_{cpl}$$

(5)

$$\ddot{\omega}_{cpl} = \begin{bmatrix} \frac{(\dot{R} + PQ)}{2} \\ PR \\ -PQ \end{bmatrix}$$
where \( \hat{\omega} = \begin{bmatrix} \dot{P} & \dot{Q} & \dot{R} \end{bmatrix} \) is the measured rotational acceleration vector in the body coordinate system.

To emphasize the importance of studying equations of motion in body coordinate system, it needs to be pointed out that insect’s ability to rotate body depends on its ability to use specific flapping and aerodynamic mechanisms. This means that insect needs to use its flight muscles in a specific way for instance to increase longitudinal forces and yaw the body. Body motion, due to the change of whole relative velocity, also affects flight forces and moments. Although final orientation and position might remain the same from point of view of an observer on earth-fixed coordinate system, the path that insect takes to go through can be managed optimally based on the least time, space or energy consumption.

III. Results

A photogrammetry system consisting of three synchronized Photron FASTCAM SA3 60K high-speed cameras with 1024×1024 pixel resolution is used for data collection of dragonfly flights. These cameras were aligned orthogonally to each other on an optical table and operated at 1000 Hz to capture freely flying dragonfly taking off from a paper stool (Figure 1b) in the filming area. Motion of body of each dragonfly was then reconstructed for videos using an accurate surface reconstruction method [9].

![Figure 2. (a) Body coordinate systems and definition of rotational velocities; (b) shooting area in lab test.](image)

A. Body motion of dragonfly’s takeoff flight

Dragonflies with different initial body orientations were recorded from the rest on a paper stool (Figure 2b) and then moving to a direction with lights on. We didn’t observe any high jumps caused by legs in flight initiation phase, but wings were always involved in the motion even before legs detach from the stool. Although sometimes dragonfly moved its legs on the stool to partially reorient the body or to justify the jumping direction, but always initiation of flight was followed by combined rotational motions of the body in a manner to get to cruise or climbing orientation in few wing beats.

![Figure 3. Body motion during the takeoff turn for dragonflies in experiment. Initial orientation is shown with black color. (a) dragonfly I, (b) dragonfly II.](image)
B. Body angular orientation measurement

To measure angular orientation of the body with respect to the earth fixed coordinate system, insect’s real body was replaced by a reconstructed rigid model. This model body which was built matched to Dragonfly I’s body is a grid containing thousands of points with known 3D distance measured from the body fixed coordinate system. Origin of this coordinate system is placed at estimated center of mass. Center of mass is assumed to be located at the middle of the four wing hinge points similar to [10]. Accuracy of location of the center of mass is not a sever matter of concern as in real life it can change because of feeding, mating or carrying the prey. Also the only parameter in our analysis which is sensitive to this value is product moment of inertia which doesn’t affect accuracy of conclusion severely. X-axis of body fixed coordinate system is along the body from center of mass to nose, Y-axis is normal to X pointing to the right and Z-axis points downward in vertical plane. This coordinate system follows right hand rule (Figure 2a).

At each frame four points on the wing hinges of the reconstructed body were matched to the real insect’s body. Doing this, body fixed coordinate system will be known at each frame. Transferring origin of this coordinate system to the origin of the earth fixed coordinate system, relative orientation of body (Euler angles) can be measured. Instruction for measuring Euler angles can be found in numerous text books. We followed the method in [11]. Angular velocities and accelerations were calculated taking time derivatives from discrete data.

C. Motion analysis

Previous studied on the dragonfly’s turn maneuver suggests that they roll their body to reorient flight forces [12]. Although this might be part of the reason, we observed that they combine high rotational speeds to accomplish a turn. Besides having four wings which can flap anti-phase, braking mechanisms for decelerating such high speed rotations is totally unknown in dragonflies. Many studies were done on the wing kinematics during maneuver [13, 14] but less attention was attracted to motion strategies. In current research, studying body motion during free takeoffs, which contain large rotations in all 3D space, we hope to get closer to understanding body acceleration/deceleration strategies which dragonflies might take advantage of.

In this stage of study, we need to introduce concept of energy management in the system. Kinetic energy can be calculated by multiplying each of the equations of motion to its characteristic velocity and by a subsequent integration (Equation 6).

\[
\begin{align*}
\frac{1}{2} I_{xx} P^2 &= \int [L P + \int I_{xx} (\dot{R} P + P^2 Q)] dt \\
\frac{1}{2} I_{yy} Q^2 &= \int [M Q dt + \int I_{yy} PRQ dt] \\
\frac{1}{2} I_{zz} R^2 &= \int [N R dt + \int I_{yy} PQR dt]
\end{align*}
\]

Energy added or distracted from motion should be the result of work done by aerodynamic forces on rotating the body. Similar to acceleration, there are two energy agents in each direction, one which injects the added energy from aerodynamic moments and affects the total energy level of the system and the other one which transfers energy through the system and affects energy distribution in the system (first and second term in the right hand side of Equation 6, respectively). We are going to show that dragonflies are able to take advantage of this latter one to rearrange the added energy via aerodynamic work through the system and manage maneuver in desired way.

Term in the left hand side of set of equations in (6) and aerodynamic work are shown in Figure 3 (a,d) with solid and dashed lines respectively. Difference between these two lines, sharing the same color, represents the role of coupling term in rearranging energy distribution between different variables of body motion. For instance in takeoff of first dragonfly (Figure 3a), aerodynamic moment would inject enough energy to this motion to maintain almost constant yaw velocity if there was no leak of energy to pitching direction. Similar phenomenon is observable in second dragonfly’s turn. After about 2 wing beats, adjusting roll velocity, insect was able to pitch body rather than yaw using the same energy that is added to the system through production of yaw moments. Interestingly, in both cases yaw and pitch motions both settled down through these kinds of energy rearrangements in the system (Figure 4b and e).

Noting that in both dragonflies, roll velocity remained under the control of aerodynamic moments in that
respective direction, this phenomenon can be interpreted as an energy rearrangement strategy in flight via adjusting roll velocity, rather than roll angle, which manipulates the motion to accomplish desired maneuver while yaw and pitch moments don’t need to be modulated significantly. Although kinetic energy stored in rolling motion is about an order of magnitude less than pitch and yaw, because of its lower moment of inertia, sensitivity of yaw acceleration to pitch velocity and vice versa is proportional to magnitude of roll velocity itself (Equation 5 and Figure 4). This makes a desirable combination for system, to use this velocity as the energy carrier between pitch and yaw motion and manage energy distribution in the system. We should note here that ability of the insect to produce aerodynamic forces in each of the individual directions is limited while desired maneuver might need different accelerations and velocities. Problem becomes even worse when motion is more complicated and all three components of aerodynamic moments are needed to be modulated at the same time in a specific way, which in many situations is probably even impossible. That’s where these kinds of energy rearrangements in the system can be definitely helpful.

![Figure 4. Kinetic energy (a,d), cumulative angular orientation (b,e) and angular velocity about body axes. Dragonfly I is shown in (a-c), and dragonfly II in (d-f). Solid lines represent values measured in the experiment. Dashed line show contribution of aerodynamic moments to the respective term. Red, blue and green represent pitch, yaw and roll directions, respectively.](image)

Figure 5 shows how the body orientation is being affected form point of view of an observer on the fixed earth coordinate system, using this energy rearrangement strategy. Dashed lines represent the motion that could have been produced by aerodynamic moments while solid lines are the measured orientations. It’s clear from these figures that planned motion can be totally different from what is produced by aerodynamic moments. Thus our study suggests that besides controlling flight forces and moments to perform a maneuver, dragonfly plans the motion in a higher level. The goal of this strategy might be minimizing the required power, time or space which will be investigated in future studies.
Figure 5. Instantaneous angular orientation of the body with respect to the earth fixed coordinate system for dragonflies in experiment: Dragonfly I (a), dragonfly II (b). Solid lines represent values measured in the experiment. Dashed lines show contribution of aerodynamic moments to the respective term. Red, blue and green represent pitch, yaw and roll directions, respectively.

D. Limitations and error sources in current study

Error involved in measuring angular orientation is most pronounced in measuring roll angle of the body which needs accurate measurement of wings roots location. Although dragonfly is comparatively big insect which makes this measurement easier compared to smaller insects like flies, but inclined wing hinge plane and difficulty in accurate measurement of the angle between this plane and body horizontal plane is another source of error. Body horizontal plane is defined with 3 points in that plane. These points have to belong to the grid that made the reconstructed body. Choosing these three points, they can be tracked easily in each frame afterward, because each point on the body has a specific number tag which remains the same independent of the body orientation. While we minimized error via this latter source, error in accurate measurement of wing hinge points is not easy to be quantified. Measurement error can be amplified calculating angular velocities and accelerations based on the measured angular position data. To reduce these fluctuations we smoothed measured angular orientations using “Tecplot 360” smoothing method. Each pass of smoothing shifts the value of a variable at a data point towards an average of the values at its neighboring data points.

Another source of error arises from estimations and assumptions made in calculating moment of inertia. Because this study relies on comparative values of moment of inertia components, authors believe its effect is not substantial and doesn’t change final results significantly.

Despite these possible sources of error, we consider they have limited effects on our results and do not affect final conclusion. Especially because our analysis concerns more with yaw and pitch velocities which were suffered less from the measurement error.

IV. Summary and Future Work

Dragonflies’ takeoff flight and following fast reorientation of flight are digitized using high speed photogrammetry, and analyzed through modified equations of motion. It is found that dragonflies are able to combine different motions effectively to perform a fast and sharp turn and reorient the flight to the desired direction in a few wing beats. Our results suggest that to perform a fast turn, dragonfly is not only able to decide on wing kinematics and control flight moments but also it plans the maneuver in a higher level to manage aerodynamic energy effectively. These kinds of strategies can teach us a lot about sensing and processing data in dragonflies and the control strategies they use. Most importantly, this study suggests that instead of accurately controlling wing motion and aerodynamic moments, which might not be even possible for many complicated maneuvers, it’s possible to navigate through desired maneuver rearranging added energy to the system from the same set of aerodynamic
moments. This mechanism can decrease required control effort, as roll velocity is much easier to be manipulated than the other two rotations, and simplify navigation system design.

As a future work, coupling between the motion and flight aerodynamic forces needs to be studied. Due to its small turning radius to wing span ratio, insect maneuver is much more complicated than conventional aircrafts. This is not just because of their flapping wings and complexity in control mechanisms but also because of their low translational and high rotational speeds which as a result wing-wake interaction gets more important during the maneuver. Also optimizing technique behind these kinds of strategies should be studied further.

Acknowledgement

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References