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# Development of Gyroscopic Thrust Vectoring system in Flapping Wing MAVs without Empennage

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***Abstract***—Improvement in inherent agility, gust wind resistance of Flapping Wing Micro Air Vehicles (FWMAV) and morphological, visual closeness to natural flyers has been historically constrained due to the usage of conventional empennage constituting a control-surface based directional control apparatus. This paper discusses a novel mechanism wherein the directional control is achieved by vectoring the thrust force generated by the flapping wings. This eliminates the presence of the empennage, thus making the FWMAV open to morphological and cosmetic developments, besides contributing to the stability. This mechanism harnesses the advantages of Gimbal-mounting of the propulsion unit, similar to rocket engines, permitting individual and independent regulation of pitch, roll and yaw components. The control schema can be utilized in any FWMAV independent of the form factor and nature of the propulsion mechanism.

***Keywords***—Flapping wing control, thrust vectoring, gyroscopic control, biomimetics.

## I. Introduction

ADVANCES in sensor, data processing and actuation technologies over the past decade have brought biomimetics to a whole new frontier, where all known forms of locomotion observed in nature have been successfully implemented by man-made systems. Flight in nature, continues to be the most problematic as well as the most exciting form as it involves an elevated level of spatial, sensory perception, path-planning, body kinematics, besides the exclusive ability to forage in locations that are otherwise inaccessible to other forms of locomotion. Flapping flight offers the unique advantage of agile motion with unmatched precision, which has been identified as one of the major targets of the Micro Air Vehicle revolution that is now being well fueled by the academia and industries alike [5].

While the influx of rotorcrafts in MAV domain has satisfied the plain need for agility in flight, they have an aggressive displacement from the nature's flight morphology. The current Flapping wing MAVs also feature an empennage based control surface setup that is used to impart directional control over the vehicle, making them functionally and morphologically distant from their biological counterparts. This research paper presents a minimalistic control schema through which the conventional empennage control surfaces can be eliminated; paving way for wing based directional control, a scope for manifold increase in agility, while also increasing the avenues for morphological and cosmetic developments. As the control schema consists of three servomotors that control the gimbal-mounted wing structure, there is enormous scope for the design and development of self-stabilizing ornithopters, just like rotorcrafts, working only by the data obtained from their on-board Inertial Measurement Unit.

## II. Background and Motivation

The growth envisioned for Flapping wing MAV consist majorly of development in the mechanical design and control sectors rather than electronics and communications primarily because there is a large gap between what is being offered by the electronics section and how much of that is being put to efficient use by the mechanical design and control design. For the current state of sensing, data processing and actuation technology, a fiercer conceptual, mechanical and control design would yield better results.

Most of the Flapping Wing MAVs in the present day utilize a tail unit consisting of one or more control surfaces for directional control [1][9][11]. Emphasizing on the directional control through dynamic changes in the wing morphology, like in nature, could lead to MAVs that would be more compact, agile and less susceptible to external disturbances like gust. The Flapping wing research is yet to embark on a truly hovering, agile vehicle with an ability to maneuver in the three dimensional space without appendages such as the empennage. In the case of hover-capable insects of the order Diptera such as the houseflies, bees, wasps, etc., no external control surfaces are present and the directional control depends solely on the manipulation of the basic wing geometry parameters [2][4].

With such an approach, the primary idea presented in this paper is the elimination of the empennage via the design and development of a gimbal mechanism that is readily applicable to any Flapping wing transmission unit, which vectors the thrust force produced by the single pair of wings to create directional vectors resulting in pitch, roll and yaw components

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that are independent on one another. Key wing geometry parameters namely Wing twist and Root chord inclination are dynamically adjusted to control the Flapping wing MAV in three-dimensional space.

## III. CONTROL HYPOTHESIS

A well-defined body axes system that is compatible with the conventional aircraft geometry is necessary to lend a clearer perspective of the control perspective presented here. In the case of a vertical takeoff flapping wing MAV, the longitudinal axis is perpendicular to the surface of the earth as opposed to the normal axis of the conventional aircraft. The body axes system of the MAV is described in **Figure 1**.

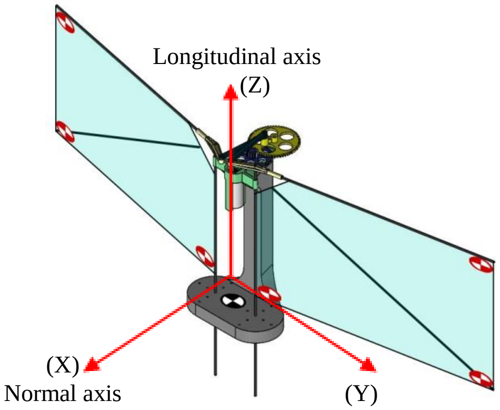


**Figure 1 Body axes of the flapping wing MAV**

Vectoring of thrust in a system like a rocket is basically inclining the net reaction force with respect to the body of the craft, in desired directions so as to generate moments about the body with an objective to control the pitch, roll and yaw of the vehicle. In the same way, inclining the net resultant force generated by the flapping wings will give rise to moments about the body axes of the MAV giving rise to directional motion. Considering the case of a hovering VTOL Flapping wing MAV, the line of action of the net thrust is equal and opposite to the weight of the MAV, thus facilitating a stable hover. If the magnitude of the thrust force is maintained and direction is altered, there will be a change in the status quo of MAV, as the change in direction will not provide sufficient downward thrust force for hovering while a component of the directional force will induce a directional motion.

In the system taken for consideration to describe the control hypothesis, the hovering VTOL flapping wing MAV features a flapping unit that flaps the wings about their root chords that are separated by a distance ‘*d*’ units from each other where, d≠0. In this system the lateral axis, normal axis and the longitudinal axis are aligned to the X, Y and Z axes respectively and the Center of Gravity (CG) lies on the origin. The hypothesis states that manipulating the direction of the net thrust force that keeps the MAV airborne, it is possible to control the vehicle in three-dimensional space.

According to the hypothesis:

1. Forward motion can be achieved by negative displacement of the root chords’ trailing ends along the X axis, thus providing a forward tilt to the mean position of the flapping wings with respect to the longitudinal axis of the vehicle and consequentially the net thrust force of the flapping wings. The net thrust so generated will have upward as well as forward component enabling the MAV to move forward. Backward tilt can be achieved by positive displacement of the root chords’ trailing ends along the X axis will have the reverse effect and will enable the MAV to move backwards. The force components generated by root chord morphing induce moments about the lateral axis, lie on the XZ plane and can thus be considered pitching moments.
2. Asymmetric displacement of the starboard and port root chords’ trailing ends on the XZ plane induces moments about the longitudinal axis due to opposing directions of the reaction force of each wing. Along the X axis, positive displacement of the starboard root chord’s trailing end and negative displacement of the port root chord’s trailing end gives rise to a clockwise moment about the Z axis, as observed from above. The vice versa is valid and the moments thus generated can be considered as rolling moments as they act about the longitudinal axis, lie on the XY plane.
3. Displacing both the root chord’s trailing ends along the Y direction induces tension in the flapping wings and the wings generate varying thrust with variation in flexural stiffness [10]. When the root chords’ trailing edge are displaced positively along the Y direction, the starboard wing membrane stretches, increasing the tension on it and thus producing a thrust force of larger magnitude. Whereas, the membrane of the port wing slackens, reducing the tension on it and thus producing a thrust force of lesser magnitude. Due to asymmetry in the thrust generated by the starboard and port wings, the starboard wing overpowers its counterpart, resulting in a turning moment about the X axis. The vice versa is valid and the moments thus generated can be considered as yawing moments as they act about the normal axis, lie on the YZ plane. However, equally displacing the root chords’ trailing ends in opposite directions along the Y axis give rise to no net moment as the opposing forces are equal and tend to mutually cancel out.

## IV. EXPERIMENTAL VALIDATION

An experimental setup was conceived and developed to validate the control hypothesis by way of operating the apparatus at 6 different configurations of root chord positions and observing the directions of forces so generated from each of them. The apparatus consists of an unmodified Golden snitch*[10] flapping wing unit mounted atop a custom-built test stand with a layout of holes on the bottom support. The root chord from the flapping wings are inserted into the designated holes to form different inclinations with respect to longitudinal axis of the test stand which represents the body of the MAV as it houses both the flapping unit and wings. The holes constrain the trailing ends of the root chords and maintain the desired displacement along X and Y axes.

The wings were fabricated from a 10um Mylar sheet with 0.5mm carbon rods as the frame. A basic rectangular planform with a single diagonally running spar was used for simplicity. The flapping unit driven by 6 mm motor [3], was remotely activated via a Lithium Polymer battery powered Micro Radio receiver with a provision to control the motor thrust and hence the flap rate of the wings [9]. **Figure 2**, **Figure 3** and **Figure 4** refer to the test setup and simplified configuration diagram. The different root chord configurations are tabulated in **TABLE I**.

TABLE I ROOT CHORD CONFIGURATIONS

| Sl. No | Root chord configuration | Intended purpose |
|---|---|---|
| 1 | ◑ ¦ ◑<br>○ ◐ ○ ¦ ○ ◐ ○<br>○ ¦ ○ | Pitch Forward |
| 2 | ○ ¦ ○<br>○ ◐ ○ ¦ ○ ◐ ○<br>◑ ¦ ◑ | Pitch Backward |
| 3 | ○ ¦ ◑<br>○ ◐ ○ ¦ ○ ◐ ○<br>◑ ¦ ○ | Roll Clockwise |
| 4 | ◑ ¦ ○<br>○ ◐ ○ ¦ ○ ◐ ○<br>○ ¦ ◑ | Roll Counter clockwise |
| 5 | ○ ¦ ○<br>◑ ◐ ○ ¦ ◑ ◐ ○<br>○ ¦ ○ | Yaw Left |
| 6 | ○ ¦ ○<br>○ ◐ ◑ ¦ ○ ◐ ◑<br>○ ¦ ○ | Yaw Right |

The apparatus was suspended along its longitudinal axis using 0.3mm carbon rod and all the configurations mentioned in **TABLE II** were tested and the direction of the net thrust was observed and recorded. The observations are tabulated in **TABLE III**. **Figure 5** shows the free suspension test performed using Configuration III.

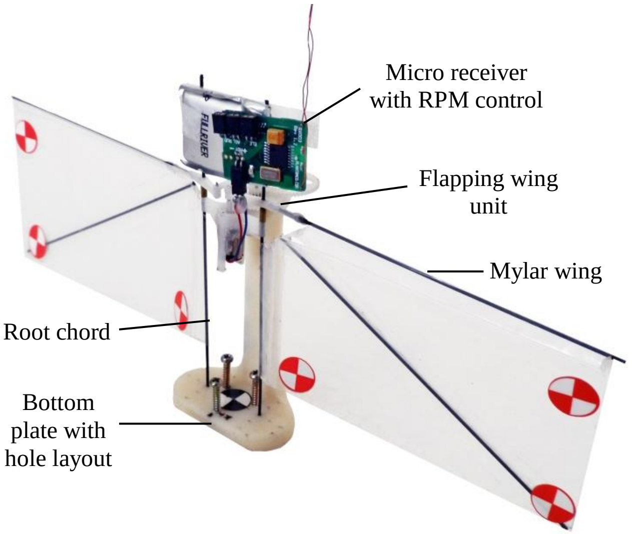


**Figure 2 Developed test setup**

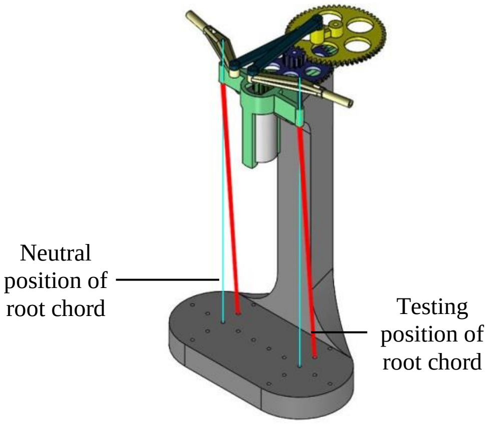
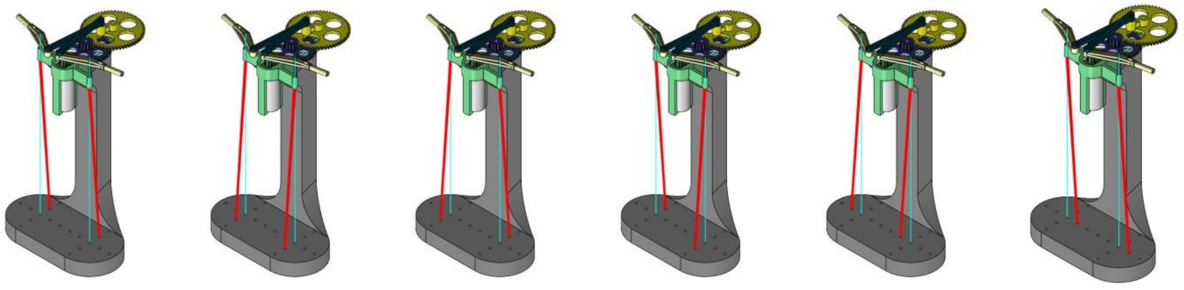


**Figure 3 Sample testing configuration**

TABLE II CORRESPONDING TEST CONFIGURATIONS



Config. I Config. II Config. III Config. IV Config. V Config. VI

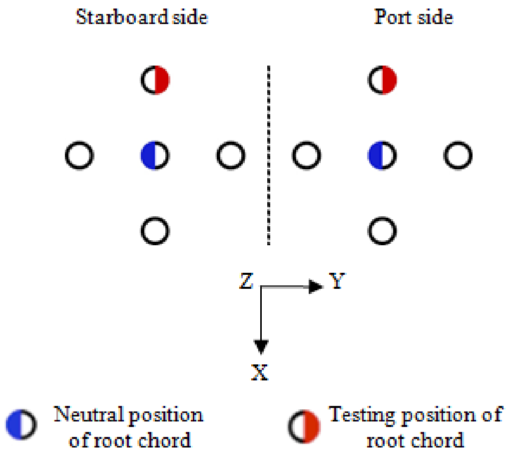


Figure 4 Sample root chord configuration

From the results obtained from the experiment, it can be concluded that inclining the root chord of flapping wings to the body of the MAV has a great influence on the direction of thrust generated and that this influence can be manipulated to produce pitching, rolling and yawing moments to control the direction of flight. With this as a base, a mechanism designed to control the root chord inclination would be successful in controlling the MAV's flight direction.

TABLE III OBSERVATION FROM FREE SUSPENSION TEST

| Config. | Results | |
|---|---|---|
| | Predicted by hypothesis | Experimental observation |
| **I** | Pitch forward | Pitch forward |
| **II** | Pitch Backward | Pitch Backward |
| **III** | Roll CW | Roll CW |
| **IV** | Roll CCW | Roll CCW |
| **V** | Yaw left | Yaw left |
| **VI** | Yaw right | Yaw right |

## V. THE PROPOSED TVC SYSTEM

As far as the control of pitch, roll and yaw are concerned; individual control modules can be designed to modify each of them without having any effect on one another. Given that there are strict boundaries in both volume and weight, an integrated module that occupies less volume and weighs less would be ideal and best suited for the context of MAVs.

The idea of gimbal mounting was derived from rockets where the engine nozzle is gimbal mounted, permitting individual and independent control of pitch, roll and yaw components, to vector the reaction force in order to dynamically alter the pose of the rocket and guide it along predefined trajectory. Similarly, a control mechanism with each control module mounted on a gimbal would provide independent control of the components on the same gimbal while being mechanically simple and compact.

### A. *Pitch control*

The developed mechanism consists of a gear setup mounted about the lateral axis, with a control rod like structure along the longitudinal direction connecting the base plate that harbors the trailing ends of the starboard and port wing root chords. The gear setup is actuated via a servo and the operation of it results in the positive or negative inclination of the root chord with respect to the longitudinal axis, on the XZ plane creating the pitching moments.

### B. *Roll control*

The design of the roll mechanism features a servomechanism capable of rotating the base plate about the longitudinal axis, on the XY plane leading to asymmetric displacement of root chords' trailing ends and thus creating the rolling moment. The operating of the servomechanism leads to clockwise or counterclockwise rotation of the base plate. Actuation of the servo setup is independent of the pitching mechanism and can also be used in combination with it.

### C. *Yaw control*

The pitching setup is mounted on to another independent component mounted about the normal axis, capable of displacing the rood chords' trailing ends on the YZ plane. This isolates the yawing mechanism from the pitching setup, while also enabling simultaneous operation of both in combination.

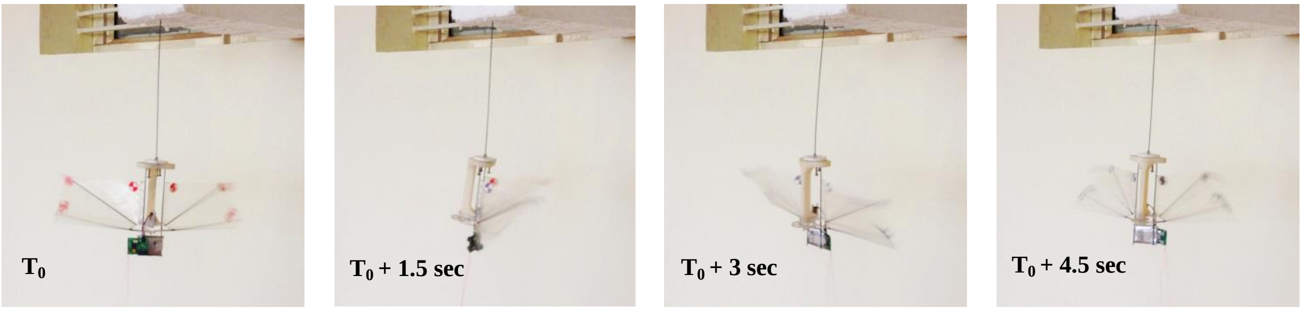


Figure 5 Roll test: Configuration III

### *D. Integrated TVC mechanism*

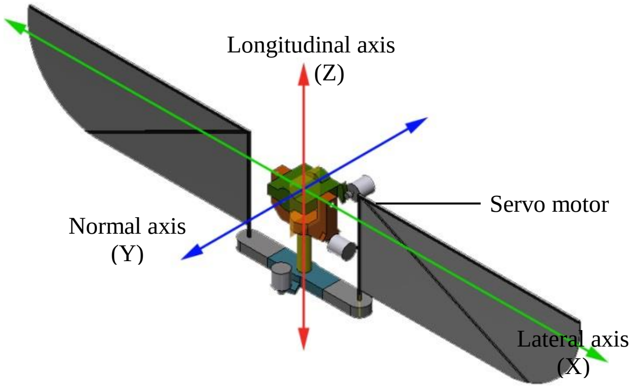


**Figure 6 Integrated thrust vector control mechanism**

Each of the pitch, roll and yaw setup consist of a servomechanism that are completely independent of each other. All three of them can be combined in operation to produce a diversity of forces and moments to execute complex maneuvers. Fig.6 depicts the integrated TVC mechanism with each of the three control modules functioning as an independent unit. The pitch, roll and yaw control modules are represented in orange, blue and green respectively. The proposed mechanism is not conditional about the nature of the flapping mechanism as long as it presents separate starboard and port wing root chords' trailing ends that can be manipulated mechanically by the mechanism.

## VI. AUTONOMOUS STABILIZATION

As the operation of the individual modules do not influence each other, each of them namely pitching moment, rolling moment and yawing moment, along with the motor RPM can be considered as a dimension of the system that is used to describe the movement of the MAV in the three dimensional space, over a period of time. This is analogous to the case of quadrotors where each of the motor RPM can be specified over a period of time to describe any complex maneuver.

$$\vec{P}_1 = f(\vec{P}, R_1, R_2, R_3, R_4, t) \qquad (1)$$

Similarly, in case of the flapping wing MAV,

$$\vec{P}_1 = f(\vec{P}, \vec{t}_P, \vec{t}_R, \vec{t}_Y, R, t) \qquad (2)$$

where $\vec{P}$ is the initial position vector of the vehicle, $\vec{P}_1$ is the subsequent position vector, $R$ is the RPM of the motor, $t$ is the time taken, $\vec{t}_P, \vec{t}_R, \vec{t}_Y$ are the torque vectors of the pitch, roll and yaw servos respectively.

Autonomous stabilization has been achieved in quadrotors by way of routing the input from an on-board Inertial Measurement Unit (IMU) to a flight control chip that continuously monitors the pose of the vehicle via IMU data and autonomously dispatches commands to the motors to change their RPM and maintain a fixed position in space [6]. Exploitation of this technology makes it possible to script missions enabling the quadrotors to be completely autonomous for carrying out a predefined task [7].

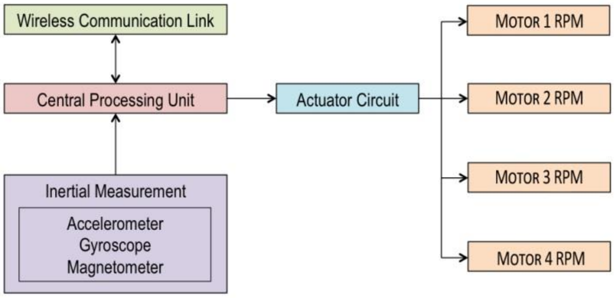


**Figure 7 Schematic of a quadrotor**

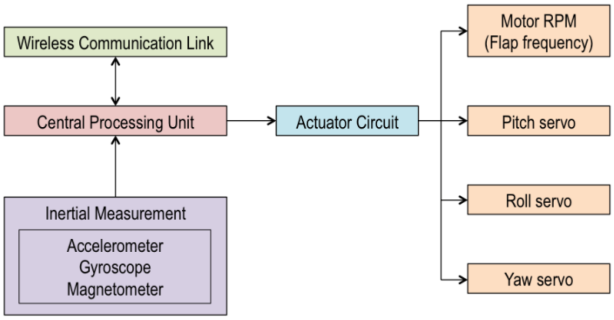


**Figure 8 Schematic of the conceived self-stabilizing FWMAV**

Similarly, it is possible to use the data from an on-board IMU mounted on the MAV and autonomously stabilize i.e. hover the flapping wing vehicle in three dimensional space by dynamically altering the motor RPM, torque vector of the pitch, roll and yaw servos. Like in quadrotors, missions can also be executed by following pre-fed control commands into the MAV's flight control chip or by dynamic scripting by use of positional aids such as Global Positioning system or Simultaneous Localization and Mapping [6].

## VII. CONCLUDING REMARKS

After validating the control hypothesis of modifying the rood chord morphology to gain directional control over the MAV, the next logical step was to consider the time taken by the MAV to transverse between a positive maximum of pitch, roll or yaw to its negative maximum. From the experimentation, it was also observed that that the MAV could turn over from front to back side in 4.5 seconds from the application of maximum roll. Focusing on reducing this turn-around time would lead to significant improvements in agility as this quantity can be taken as an empirical indicator of agility.

The thrust vector control system has eliminated the need of an empennage in FWMAVs by bringing the directional motion manipulation under its control envelope. Absence of a tail unit could mark the beginning of a new class of flapping wing vehicles that are faster, perform better in outdoor environments. Independence in terms of the form factor of the MAV, nature of the flapping mechanism is a positive improvement in the control mechanism development efforts as this system can be applied in a majority of the flapping wing systems to bring about progress leaps in both performance and morphology. Any flapping wing mechanism capable of generating more thrust than its body weight can be modified to hover with the help of auto stabilization.

Autonomous stabilization in flapping wing vehicles is one of the high thrust areas, as this will take FWMAVs to the next phase, where they are autonomy-ready. With the work presented in this paper and more streamlined activity in specific areas like flight dynamics and miniature circuitry, it is possible to come to some important conclusions about the autonomous stabilization of flapping wing systems. This is key to the survival of the FWMAVs in gusty environments and achieving this very goal would take them from confined and indoor operation to outdoor and urban settings.

## ACKNOWLEDGMENTS

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