Development of Transition Control Methodology for a Quad Rotor-Biplane Micro Air Vehicle From Hover to Forward Flight

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1. Introduction

There is significant interest in the development of efficient and viable Micro Air Vehicles (MAVs) that can perform various tasks such as surveillance, targeting, natural disaster support, chemical agent detection etc., which are nominally hazardous or inconvenient for human involvement. For many of these tasks, aerial platforms are required that have the ability to hover as well as travel long distances quickly. Therefore, there is a need to combine the advantages of fixed and rotary wing designs into a hybrid MAV design. Researchers have looked at the development of certain hybrid concepts, such as tail-sitters, tilt-rotors and tilt-wing [1-5]. Tail-sitter configurations have been proposed and developed where the thrusting propeller produces downwash over control surfaces to enable transition from vertical to horizontal flight. To generate adequate aerodynamic control forces, these surfaces require high propwash velocities. This is not possible for a lightweight MAV design. Additionally, efficiency in the hover mode would deteriorate significantly at these high disk loadings. Scaling down conventional tilt-rotor vehicle designs would be prohibitive at small scales due to the mechanical complexities involved in providing cyclic pitch controls for both the rotors. In this paper, a quad rotor bi-plane configuration is proposed (Fig. 1). The various operating modes from hover to forward flight are schematically shown in Fig. 2. The advantages of this configuration are: (1) the maneuverability of a quad rotor is utilized in hover, (2) pitching moments to achieve transition is generated entirely by differential rotor thrust without the requirement of aerodynamic control surfaces.

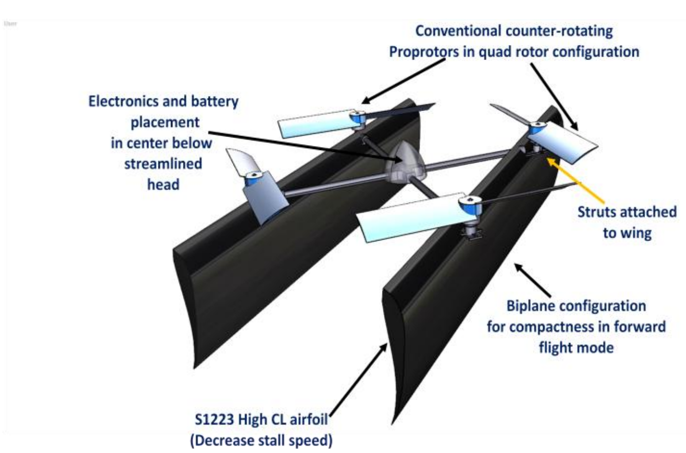

Fig. 1. Quad-rotor Biplane conceptual design

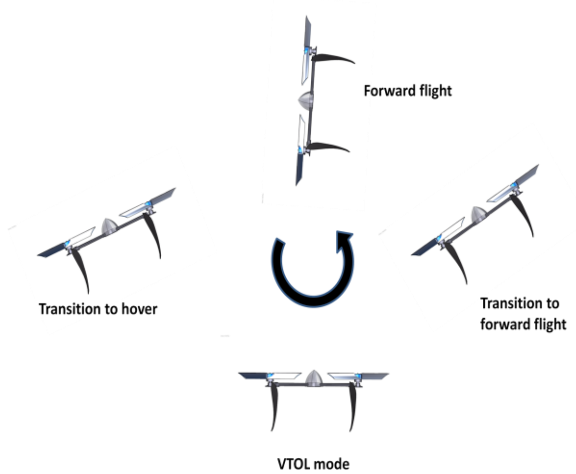

Fig. 2. Operating flight modes

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2. Approach

2.1 Vehicle Description

The assembled vehicle is shown in Fig. 3. It consists of counter-rotating proprotors arranged in a conventional quad rotor configuration. The wing is constructed from polyurethane foam and has a high lift S1223 airfoil in order to decrease stall speed. The gross weight of the vehicle is 236 grams. The wing span is 26 inches and the distance between the wings is 10.7 inches. For electronics, a micro robotic automation platform (UCB's GINA) is incorporated. It consists of a microcontroller, three gyros and accelerometers, and a radio transceiver that can enable onboard computation of vehicle attitude and implementation of appropriate attitude feedback controllers. Outer loop pilot control can be provided for translational positioning of the vehicle.

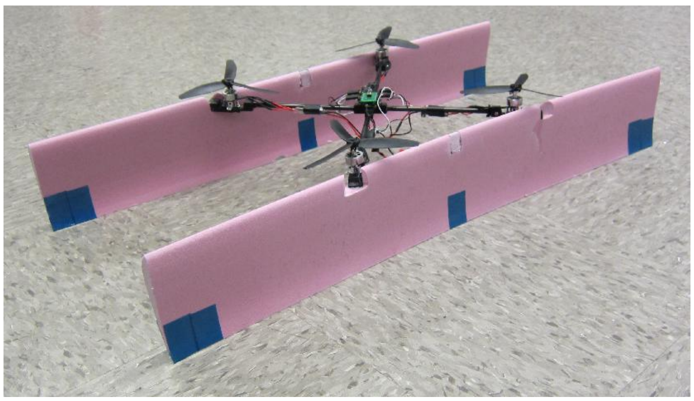

Fig. 3. Assembled vehicle

Fig. 4. Hover flight testing

2.2 Hover Flight Testing

Prior to developing methods to control the vehicle during transition, it was necessary to verify hover capability. Of particular interest was to see if the sideways force generated by the wings due to the rotor downwash would result in undesirable drifting of the vehicle. For this, the bare quad rotor was hover flight tested to ensure proper functioning of electronics following which the quad biplane was successfully hover tested as shown in Fig. 4. It was possible to negate the effect of the sideways force through careful trim of the vehicle.

2.3 Control Methodology and Simulation

Developing a control strategy for a vehicle that transitions between level hover with rotors and translational fixed-wing flight requires special considerations. Since the vehicle must pitch down by 90-degrees to effectively use its wings, quaternion attitude feedback is better suited for the on-board controller to avoid the singularity encountered when using Euler angles. The rotational rate kinematics will be

$$\dot{p}(t) = \left(\frac{1}{I_{xx}}\right)\left(q(t)r(t)\left(I_{yy} - I_{zz}\right) + q(t)\textstyle\sum\Omega J_r + lbU_1(t)\right) \tag{1}$$

$$\dot{q}(t) = \left(\frac{1}{I_{yy}}\right)\left(p(t)r(t)(I_{zz} - I_{xx}) - p(t)\textstyle\sum\Omega J_r + lbU_2(t)\right)$$

$$\dot{r}(t) = \left(\frac{1}{I_{zz}}\right)\left(p(t)q(t)\left(I_{xx} - I_{yy}\right) + dU_3(t)\right)$$

with b as a thrust coefficient, d a torque coefficient, $\sum\Omega$ the sum of rotor rotational velocities, and U_i the motor inputs [6]. The corresponding equation for the quaternion attitude dynamics is

$$\underline{\dot{\gamma}}(t) = \left(\frac{1}{2}\right)\begin{bmatrix} 0 & -p(t) & -q(t) & -r(t) \\ p(t) & 0 & r(t) & -q(t) \\ q(t) & -r(t) & 0 & p(t) \\ r(t) & q(t) & -p(t) & 0 \end{bmatrix}\underline{\gamma}(t) \tag{2}$$

where $\underline{\gamma}^T(t) = [\gamma_0(t) \quad \gamma_1(t) \quad \gamma_2(t) \quad \gamma_3(t)]$ is a quaternion vector, and $p(t)$, $q(t)$, and $r(t)$ are the body rates [6]. For preliminary tests, the aerodynamic contributions of the wings are neglected. The system described by the above equations is controlled by giving a desired quaternion. In hover, the quaternion is $\underline{\gamma_{d0}}^T = [1 \quad 0 \quad 0 \quad 0]$, and in translational flight the desired quaternion becomes $\underline{\gamma_{d1}}^T(t) = [0.7071 \quad 0 \quad 0.7071 \quad 0]$ for 90-degrees pitch required for forward flight. According to Yuan [7], an effective means of quaternion feedback can be achieved using the control law

$$\underline{U}(t) = J^+\big(\underline{\dot{\omega}}(t) - K_\omega\big(\underline{\omega}(t) - \underline{\omega}_d\big) - K_e\underline{e}_0(t)\big) \tag{3}$$

where J^+ is the pseudo-inverse of the Jacobian of Equation (1) with respect to $\underline{U}^T(t) = [U_1(t) \quad U_2(t) \quad U_3(t)]$, $\underline{\omega}^T(t) = [p(t) \quad q(t) \quad r(t)]$, and K_ω and K_e are the rate and attitude gains, respectively. The vector $\underline{e}_0$ corresponds to the error between the desired and actual attitude quaternions, which is expressed as

$$\underline{e}_0(t) = 2\partial\eta(t)\partial\underline{\nu}(t) \tag{4}$$

where, given that $\underline{\gamma}(t) = \big(\eta(t), \underline{\nu}(t)\big)$ and $\underline{\gamma}_d = (\eta_d, \underline{\nu}_d)$,

$$\begin{aligned} \partial\eta(t) &= \eta_d\eta(t) + \underline{\nu}_d^T\underline{\nu}(t) \\ \partial\underline{\nu}(t) &= \eta_d\underline{\nu}(t) - \eta(t)\underline{\nu}_d - \underline{\nu}_d \times \underline{\nu}(t) \end{aligned} \tag{5}$$

With a quaternion feedback control law established, a simulation can be set up and used to determine if the equations are feasible when used on a quadrotor.

The simulation is based on a desktop demonstrator designed to test the control law and gains before implementation on the full-scale vehicle. The test apparatus can be fixed to only rotate in pitch or yaw, and so preliminary simulations have been designed to help in tuning the desktop demonstrator. Keeping this in mind, modified variants of Eqs. 1 and 2 with fixed rotations are used for the plant dynamics, and Eq. 3 is implemented as the control law. For simulation with free pitch rotation only, the demonstrator is given an initial desired quaternion for level hover, which then changes to the quaternion for translational flight after five seconds. During each of these periods, a control impulse is given to simulate a disturbance and ensure that the system remains stable. As seen in Fig. 5, the vehicle remains stable while in hover, switches orientation, and then recovers from the second impulse. These results suggest that, even though the vehicle has changed its orientation by 90-degrees, the control law applies to both attitudes. In actual implementation, however, the gains K_ω and K_e would have to be changed to account for the introduction of the wing aerodynamics in forward flight. In the future, this will be tested in simulation using gain scheduling. In the mean time, however, the simulation demonstrates the efficacy of the control law in Eq. 3

In order to demonstrate transition control in pitch, a bench top demonstrator was used comprising of two rotors as shown in Fig. 6. In this experiment, the controller from Eq. 3 would try to stabilize the system at various desired pitch angles, from 0 to 90 degrees. Figure 7 shows the results of the control experiment. The system was satisfactorily stabilized at various pitch angles. It can also be seen that the disturbance rejection of the system is satisfactory.

3. Future Work for Full Paper

Hover flight testing was successfully demonstrated. Simulation and single axis bench top experiments suggest that the proposed controller can be implemented for transition control. Future tasks that build upon the work so far are:

1) Implement controller on vehicle unconstrained only in pitch and perform wind tunnel trim at various angles of attack
2) Investigate gain scheduling between roll and yaw as vehicle transitions from hover to forward flight
3) Implement controller on vehicle and perform transition flight tests.

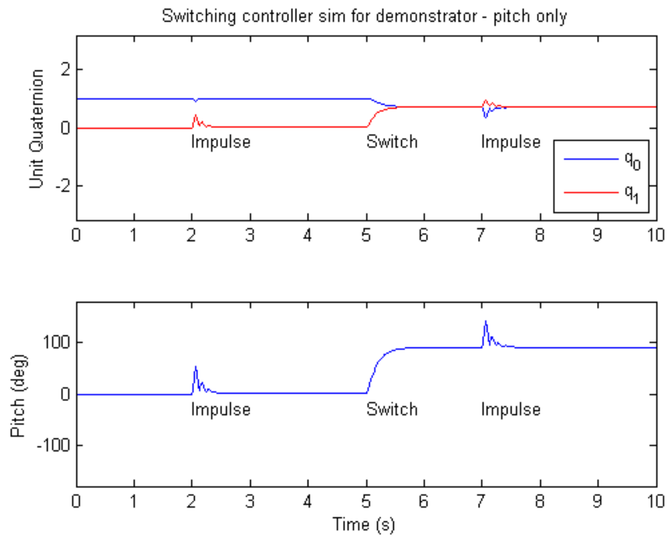

Fig. 5: Simulation results of demonstrator undergoing change in desired quaternion with disturbances.

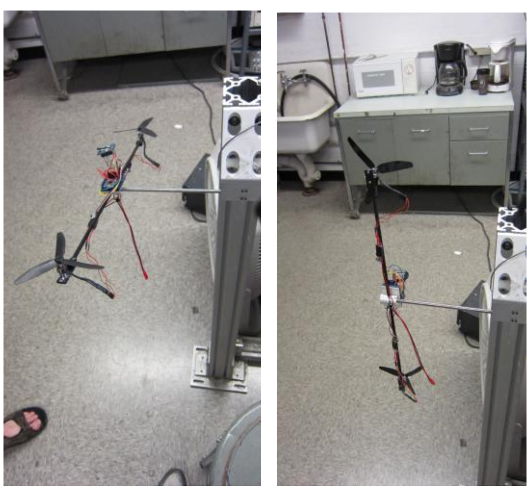

Fig. 6. Bench top demonstrator, free to rotate in pitch

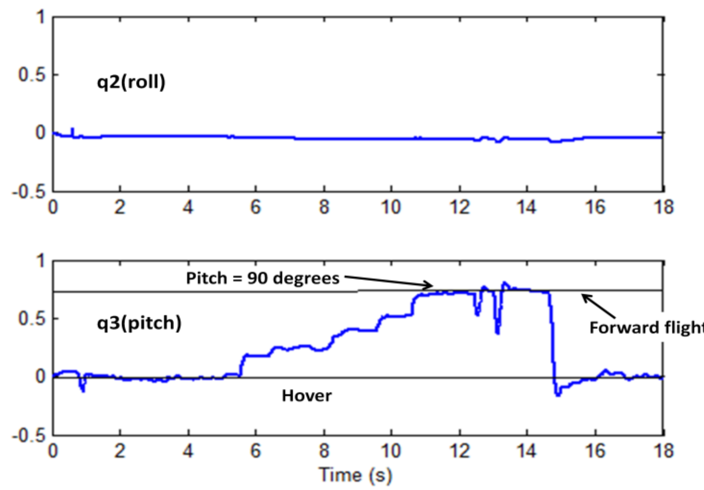

Fig. 7. Bench top results of demonstrator undergoing change in desired quaternion, q3 with disturbances

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