An Investigation on Quadcopter Controller Designs with focus on practical implementation issues

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ABSTRACT
Aerial robots specifically quadrotors or quadcopters have recently seen a boom in research interest due to the far reaching potential applications being envisaged in almost every domain. This paper investigates the dynamics of the quadcopter and the challenges posed in its control. A review of the controller design strategies is presented with a brief discussion on the requirement of adaptive techniques for practical scenarios. An example of a non-linear geometric controller is also presented; with the simulation results for agile maneuvers discussed in detail. Moreover the requirements for robust state estimation and simultaneous localization and mapping are discussed with emphasis on multi sensor fusion for practical scenarios. Lastly with the recent focus now shifting towards multi-agent collaborative control strategies some recommendations have been included for future research.

KEYWORDS
Quadcopter control, non-linear system, geometric controller, back-stepping control

I. Introduction
Aerial robots specifically quad-rotors or quad-copters have recently seen a boom in research interest due to the far reaching potential applications being envisaged in almost every domain. The trend has been supported with steady advancement in component miniaturization along with improved performance specifications and lower costs of supporting technologies in the last decade. At the moment there is a huge trend in international market for more useful industrial applications. The movement is gaining support in form of various grant based competitions and industrial liaisons. Potential applications range from Agriculture, Infrastructure Inspection, Border Patrols, Photography, Construction, Film Production, Packages delivery and Traffic and security monitoring to many others.

Control of quadcopters is a difficult multi input/ multi output control task as the dynamics exhibits inherent instability, under actuation and strong axial coupling along with rapid response constraints. This in presence of parametric uncertainties and high agility requirements imposes more challenging control complexities. Another problem is control of quadcopters is state feedback in unknown environments, where there is a need for robust simultaneous localization and mapping (SLAM)

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algorithms. This too becomes a tricky task when the mission requires quadcopters to be deployed in diverse environments. In such scenarios a multi-sensor fusion approach is often suggested. Apart from this, the design dilemma facing the research fraternity is to keep a balance between the payload capabilities in terms of the on-board sensor suite, processing resources and the mission duration that is impeded with limited battery capacity.

In this aspect, the paper provides a glimpse on the design aspects and practices in published literature for control of quadcopters. Section II, provides an introduction on the general design and principle of operations of the quadcopter and the dynamics model of a generic quadrotor. Section III, provides the typical control schemes in use for quadcopter. Section IV, presents a brief discussion on the typical on-board navigation sensor suite and some important Sensor Fusion and Simultaneous Localisation and Mapping (SLAM) algorithms that may be required for autonomous field operations. Finally Section V, provides recommendations on the current research focus of collaborative control.

II. The Quad-rotor Dynamics

The operation of the quad-rotor is illustrated in Figure 1, where it can be observed that rotors 1 and 3 rotate in clockwise direction whereas the rotors 2 and 4 rotate in the opposite direction. The propellers are designed in such a way that all four propellers provide thrust in the same direction to overcome the gravitational force. In order to hover at a certain position, the propellers are rotated at a nominal speed and for upward movement in the z-axis by increasing the speeds of the all rotors. The roll movement (about X axis) is achieved by creating a parity between speeds of rotors 1 and 3. Similarly for pitch movement (about Y axis) using rotors 2 and 4. The yaw movement (about Z-axis) is achieved by increasing the speeds of one pair of rotors more from the other and employs the law of conservation of angular momentum. However there is no direct translation possible in the X and Y axis. In order to achieve this motion a roll-pitch maneuver has to be made which accelerates the quadcopter towards that direction. In order to stop the vehicle an opposite roll-pitch maneuver has to be made to decelerate the vehicle. In order to define the quadcopter dynamics an inertial frame $\{\vec{i}_1, \vec{i}_2, \vec{i}_3\}$ is defined for reference and a body fixed frame $\{\vec{b}_1, \vec{b}_2, \vec{b}_3\}$ such that its center of mass lies in the geometric center of the quadcopter, with the propeller thrust vector perpendicular to the $\vec{b}_1, \vec{b}_2$ plane as shown in Figure 2. The $\vec{b}_3$ vector is defined downward opposite to the thrust direction. We denote R as the rotation matrix from body frame to inertial frame.

$$b_i = Re_i$$
$$e_1 = [1;0;0], e_2 = [0;1;0], e_3 = [0;0;1] \qquad (1)$$

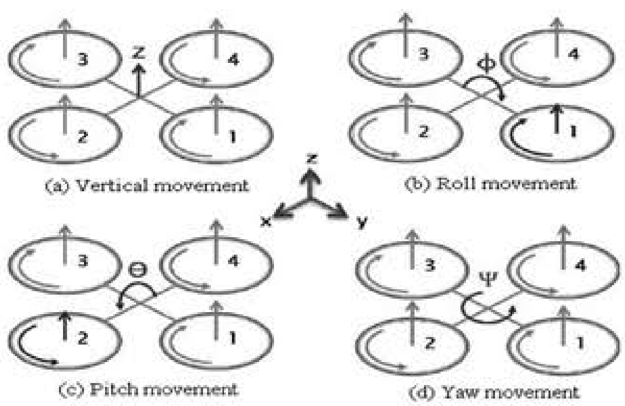

Figure 1: Quadcopter Vertical and Attitude Movements with Rotor Speeds

Now based on the definitions as in

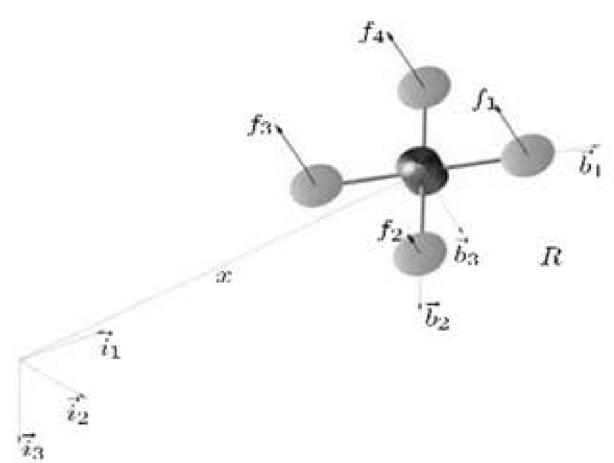

Figure 2: Quadcopter reference frames

The dynamics model based on f and M as input can be given as.

Table 1 and underlying assumptions the quadcopter model can be given as in (3).

- The quadcopter is considered rigid with homogenous density and geometric center aligned with the center of mass.
- Torque generated by each propeller is directly proportional to thrust, with propeller and rotor dynamics neglected.
- The thrust of each rotor is perfectly aligned with the $\vec{b}_3$ axis.
- Each Thrust vector can be independently controlled
- The torque of each propeller is considered as $\tau_i = (-1)^i c_{\tau f} f_i$ for a given constant $c_{\tau f}$.
- The Total thrust $f = \sum_{i=1}^{4} f_i$ is along the direction of $-\vec{b}_3$, or by definition (1), $-fRe_3 \in \mathbb{R}^3$ in the inertial frame and mapping the individual propeller thrust to combined force and moments as follows:

$$\begin{bmatrix} f \\ M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & -d & 0 & d \\ d & 0 & -d & 0 \\ -c_{\tau f} & c_{\tau f} & c_{\tau f} & c_{\tau f} \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \quad (2)$$

The dynamics model based on f and M as input can be given as.

$$\begin{gathered} \dot{x}(t) = v(t) \\ m\dot{v}(t) = -f(t)Re_3 + mg\boldsymbol{e_3} \\ \dot{R} = R\,S(\omega) \\ J\dot{\omega} = M - \omega \times J\omega \end{gathered} \quad (3)$$

Where $S(\omega)$ denotes the skew symmetric matrix.

Table 1: Quadcopter Dynamics Parameters Definition

$m \in \mathbb{R}$	The quadcopter mass
$J \in \mathbb{R}^{3\times3}$	The inertia tensor in body frame
$R \in SO(3)$	The Direction Cosine Matrix (DCM) from body frame to inertial frame belongs to the special orthogonal group.
$\omega \in \mathbb{R}^3$	Angular velocities in body frame
$x \in \mathbb{R}^3$	Coordinates if the center of mass in inertial frame
$v \in \mathbb{R}^3$	The translational velocities of the center of mass in inertial frame
$d \in \mathbb{R}$	Rotor moment arms from center of mass to rotor center in the $\vec{b}_1, \vec{b}_2$ plane
$f_i \in \mathbb{R}$	Thrust of i[th] vector
$\tau_i \in \mathbb{R}$	Torque of each rotor along $\vec{b}_3$ axis
$f \in \mathbb{R}$	Total Thrust
$M \in \mathbb{R}^3$	Total Moment in the body frame

III. Quadcopter Control

Robust control of quadcopters for precise agile maneuvering is a research pinnacle at the moment. The dynamics of a quadrotor exhibits under actuation as 6 outputs need to be controlled using 4 inputs. Moreover there exists strong coupling of the roll, pitch and yaw axis. Therefore it is a difficult multi-input/multi-output control problem especially with the inclusion of parameter uncertainties and nonlinearities. In this regard various methods have been published for quadrotor control, accounting for regulation and trajectory tracking. The under actuated nature of the system can be observed from the illustration of the dynamics into a rotational and translational subsystem as in Figure 3.

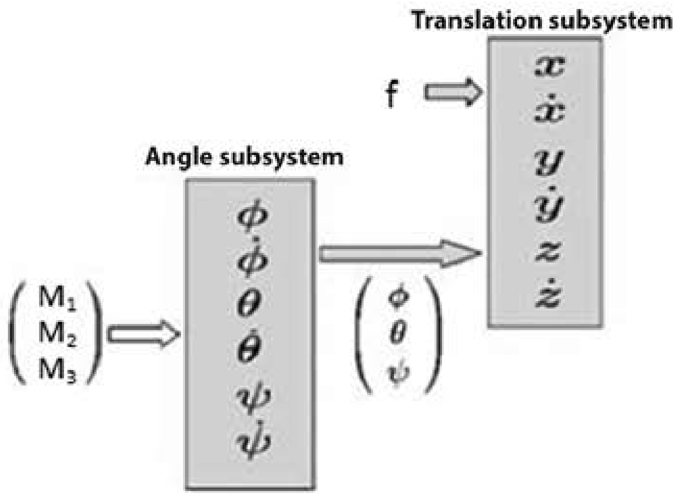

Figure 3: The Rotational and Translational Quadcopter Subsystems

I.A. Controller Designs

The objective is to find a controller or a control strategy that permits the convergence of the quadrotor states to a desirable state trajectory. Conventional linear control techniques such as PID, gain scheduled PID and LQR based control as proposed in [1, 2, 3, 4] permit only acceptable performance around the linearization/operating point. They are fruitful only for stabilization at the hover state and small angular & altitude tracking. Their performance suffers drastically in horizontal motion tracking and agile maneuvers. When considering precise agile maneuvering, a wider flight envelop is to be considered, which suggests the use of non-linear techniques. A common method for such under actuated systems is a Backstepping controller. As suggested by [5], a Backstepping controller can be formalized based on Lyapunov control theory; the architecture can be divided into 2 subsystems. The 1st subsystem represents the relationship of the horizontal position coordinates (x, y) with the roll and pitch angels and constitutes an un-actuated subsystem. The 2nd subsystem incorporates the dynamics of the yaw angle vertical position, representing a fully actuated subsystem. A similar backstepping controller is also presented in [6] using the same two subsystem approach.

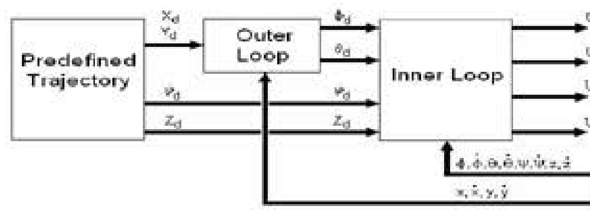

Figure 4: Typical Inner and Outer Loop Controller Architecture

The main idea here is that the quadcopter dynamics can be divided into fully actuated and under actuated sub-systems using a suitable co-ordinate transformation. Then other non-linear techniques such as sliding mode controllers [6, 7, 8] can be applied. The robust nature of sliding mode controller facilitates in overcoming parametric uncertainties and environmental disturbances. The ideal sliding mode control signum function is replaced with a continuous saturation function to avoid chattering. Moreover another promising feedback linearization technique, suggests Dynamics Inversion [9]; deconstructing the dynamics into an inner loop and an outer loop. Then insuring the stabilization of the internal dynamics (residual dynamics) guarantees the controllability of the overall system. However feedback linearization techniques are more sensitive to noise in the feedback.

The proposed controllers don't tend to work very well with large parameter and model uncertainties. There can be scenarios where the quadcopter has to pick up/deploy an arbitrary payload on the way or the environmental disturbances significantly change. In order to cater for such cases adaptive backstepping controllers [10,11] and in-direct adaptive least square methods [12] have been proposed. Moreover recently efficient Model Predictive Control like schemes [13] has demonstrated better performance in case of quadcopter model uncertainties. However there are significant processing challenges due to the fast response time requirements. There are 3 alternate rotation representations on which the controller design can be based. These include the set of 3 Euler angles (roll, pitch & yaw), the quaternion (which includes 4 parameters; a scaler and a 3D vector) and Rotation matrix (DCM with nine elements, on SO(3)). The Euler based approach has singularity issues whereas the quaternion has intuitive complexities in performing complex maneuvers, restricting the overall trajectory tracking problem when considering non-trivial trajectories. It has been shown that by employing geometric control techniques [14] for non-linear manifolds such as SO(3) better controllers can be designed for quadcopters

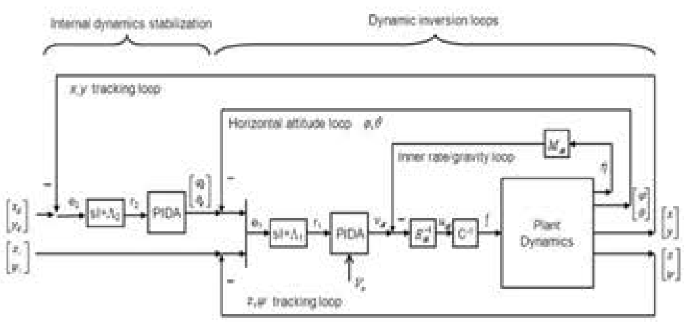

Figure 5: Dynamic Inversion based Controller Architecture [11]

I.B. Quadcopter Controller Example

The trajectory tracking geometric controller is presented as an example to demonstrate the benefits. The controller is developed on SE(3), using rotation matrix [14]. In classical mechanics the Special Euclidean group SE(3) is employed for representing the kinematics of a rigid body. Any rigid transformation in SE(3) can be divided into, a translation and a rigid rotation. Rotations can be alternatively expressed by quaternion, Euler angles or orthogonal rotation matrix (special orthogonal rotation matrix SO(3)). Directly using this SO(3) Nonlinear Lie group makes it avoid singularities and the physical interpretation is much more intuitive. The controller architecture is based on the conventional inner and outer loop methodology with an inner attitude tracking controller and an outer trajectory tracking controller.

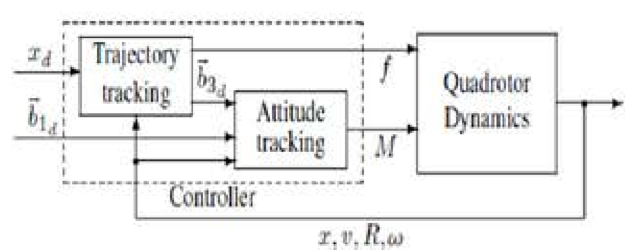

Figure 6: Trajectory Tracking and Attitude Tracking Controllers Architecture

The controller is designed to follow a desired trajectoryof the center of mass and the yaw angle (or the heading direction given by direction of $\vec{b}_1$ axis) of the vehicle as defined by the dynamics in previous section. If the desired trajectory is given by $x_d(t)$ and the desired direction is given by $\vec{b}_{1d}$ then the trajectory tracking errors for x, v, R and ω can be given as :

$$\begin{aligned} e_x(t) &= x(t) - x_d(t) \\ e_v(t) &= \dot{x}(t) - \dot{x}_d(t) \\ e_R &= \frac{1}{2}(R_d{}^T R - R^T R_d)^\vee \\ e_\omega &= \omega - R^T R_d \omega_d \end{aligned} \tag{4}$$

Where the desired attitude is given by

$$R_d = [\vec{b}_{2d} \times \vec{b}_{3d} \quad \vec{b}_{2d} \quad \vec{b}_{3d}] \in SO(3) \tag{5}$$

And

$$\vec{b}_{3d} = -\frac{-k_x e_x(t) - k_v e_v(t) - mge_3 + m\ddot{x}_d(t)}{\|-k_x e_x(t) - k_v e_v(t) - mge_3 + m\ddot{x}_d(t)\|} \tag{6}$$

Also it is assumed that:
$-k_x e_x(t) - k_v e_v(t) - mge_3 + m\ddot{x}_d(t) \neq 0$ and that $\vec{b}_{1d}$ is not collinear to $\vec{b}_{3d}$. Then

$$\vec{b}_{2d} = (\vec{b}_{3d} \times \vec{b}_{1d}) / \|b_{3d} \times \vec{b}_{1d}\| \tag{7}$$

If the following is also satisfied

$$\|-mge_3 + m\ddot{x}_d(t)\| < B \tag{8}$$

For a positive constant B. The control inputs can be given as

$$f = -\left(-k_x e_x(t) - k_v e_v(t) - mge_3 + m\ddot{x}_d(t)\right) \cdot Re_3 \quad (9)$$
$$M = -k_R e_R(t) - k_\omega e_\omega(t) + \omega \times J\omega - J(S(\omega)R^T R_d \omega_d - R^T R_d \dot{\omega}_d)$$

The three dimensional position command and one dimensional yaw angle (heading direction) are tracked using the four dimensional control inputs and it is guaranteed $x(t) \rightarrow x_d(t)$ and Proj[$\vec{b}_1] \rightarrow \mathrm{Proj}[\vec{b}_{1d}]$ as $t \rightarrow \infty$, where Proj denotes projection and is illustrated by Figure 7. Moreover the function for attitude error on SO(3) can be given as:

$$\Psi(R, R_d) = \frac{1}{2} tr[I - R_d{}^T R] \qquad (10)$$

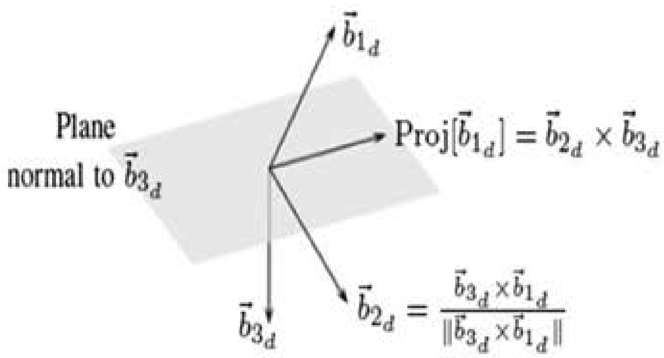

Figure 7: Illustration for Rd formalization

The attitude dynamics have been shown to be exponentially stable for initial attitude error less than 180°. In addition by choosing larger the region of attraction for larger angular velocities can be achieved. Since the translational tracking errors are dependent on the attitude tracking errors, it can be shown that for the stability of the complete dynamics the initial attitude errors should be less than 90°. Since the attitude tracking errors take a finite time to converge if the initial attitude errors are greater than 90° but less than 180°, the overall dynamics will therefore converge in finite time therefore the controller is said to have almost global exponential attractiveness. For simulation purposes following assumptions are taken as shown in Table 2.

Table 2: Assumptions taken for simulation

Inertia Tensor, J	[0.08 0 0;0 0.084 0;0 0 0.14] kgm²;
Mass, m	4.3 kg
Rotor moment arms, d	0.3 m
Propeller torque constant, $c_{\tau f}$	8×10^{-4} m
k_x	15m
k_v	5.5m
k_R	8.8
k_ω	2.5

Two trajectories are simulated for testing the controller. For the first one the controller is tasked to follow simple trajectory commands with an initial attitude error in yaw. The desired heading vector is defined such that the yaw angle is fixed at 0. Table 3 shown desired trajectory in which yaw angle is fixed.

Table 3: The desired trajectory and attitude with fixed yaw angle

Desired Trajectory
$x_d(t) = [0.5t, 0.4t, 0.6t] \;\; 0 < t \leq 12$
$x_d(t) = [0.5(12), 0.4(12), 0.6(12)] \;\; 12 < t \leq 20$
$\vec{b}_{1d}(t) = [1,0,0]$
Initial Conditions
$x(0) = [-2,-2,0]$, $v(0) = [0,0,0]$
$R(0) = [0,1,0;-1,0,0;0,0,1]$ i.e a 90° rotation about Yaw $\omega(0) = [0,0,0]$

Figure 8 illustrate the position tracking from which it is evident that even a large initial error of 2m in x and y coordinates is compensated within 6 seconds. Moreover as the trajectory is frozen at t=12 seconds, the quadcopter decelerates in under 4 seconds and stabilization errors are quickly reduced in the hovering condition. For the second example, the quadcopter is desired to hover from an initial upside down position. The quadcopter then tracks a circular yaw profile at a rate of π/4 radians/second. The desired trajectory and attitude is given in Table 4.

Table 4: The desired trajectory and attitude

Desired Trajectory
$x_d(t) = [0,0,3]$
$\vec{b}_{1d}(t)$ =[cos((pi/4)*t); sin((pi/4)*t); 0] $0 < t \leq 12$
Initial Conditions
$x(0) = [0,0,3]$, $v(0) = [0,0,0]$
$R(0) = [1,0,0; 0, -0.9995, -0.03141; 0,0.03141, -0.9995]$ $\omega(0) = [0,0,0]$ i.e a -178.2° rotation about Roll (upside down attitude)

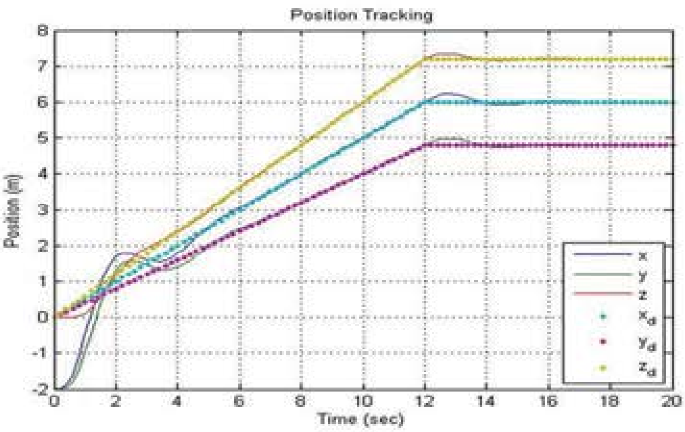

Figure 8: Case I, Position Tracking Trajectories

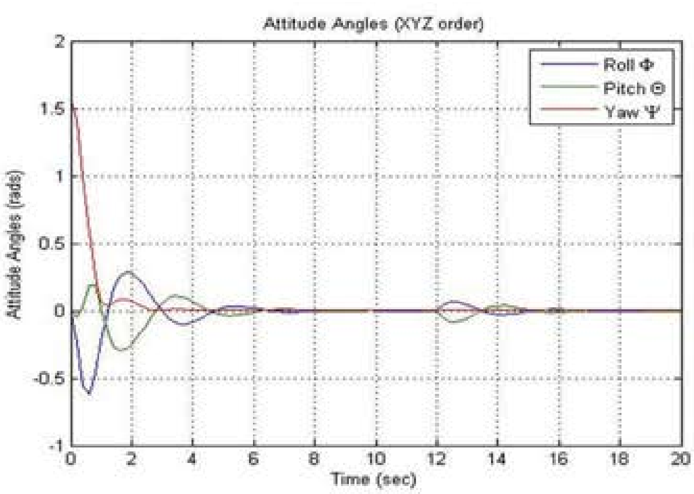

Figure 9: Case I, Attitude Angles Stabilization

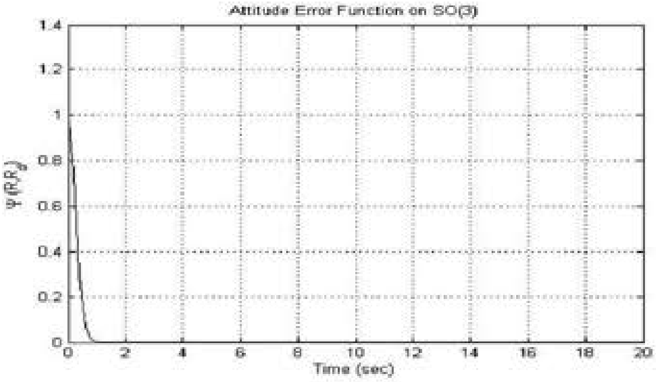

Figure 10: Case I, Attitude Error Function on SO(3)

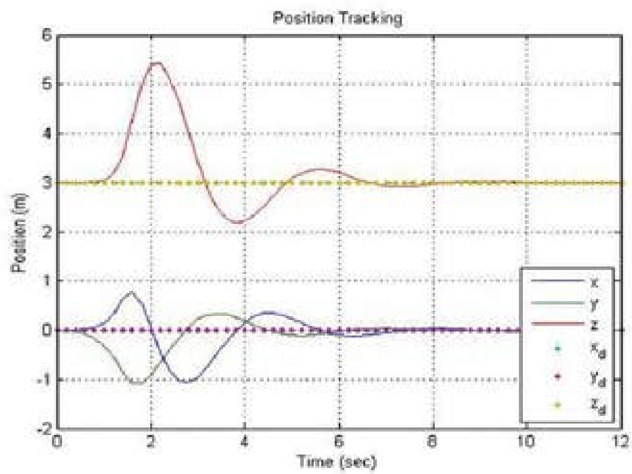

Figure 11: Case II, Position Stabilization

As shown in Figure 11, the position stabilization is achieved after the desired attitude profile is attained. Figure 12 illustrates that the quadcopter initially performs an attitude roll maneuver to attain nominal hover position and at the same moment starts tracking the desired heading profile.

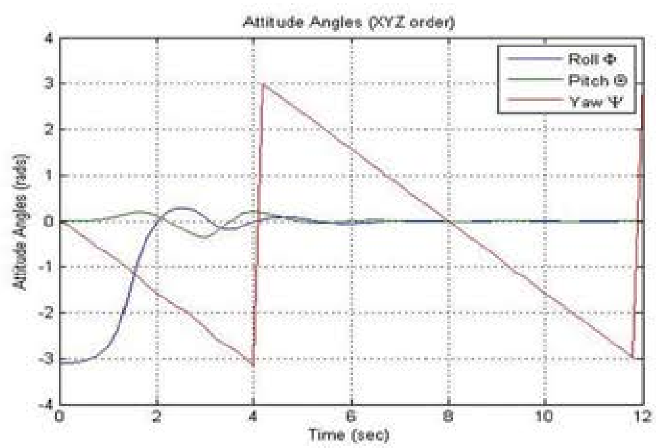

Figure 12: Case II, Attitude Angles Tracking

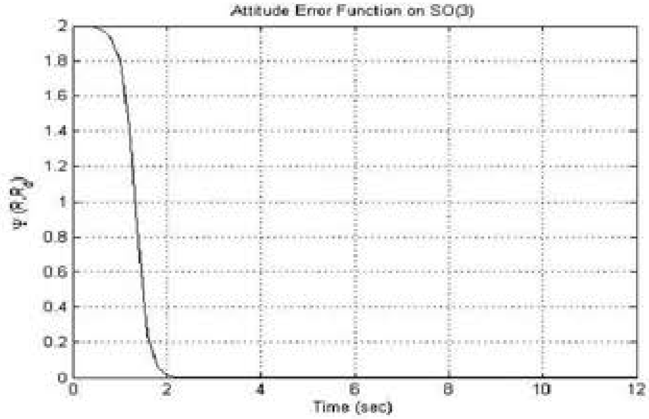

Figure 13: Case II, Attitude Error Function on SO(3)

IV. Quadcopter State Estimation

Robust state estimation is vital to autonomous flight particularly because of the inherently fast dynamics of quadcopters. Due to cost and lift constraints, most MAVs are outfitted with inexpensive proprioceptive sensors (e.g. MEMS IMUs) that are incapable for long term state estimation. Therefore exteroceptive sensors, such as GPS, cameras, and laser scanners, are usually fused with proprioceptive sensors to improve estimation accuracy.

When quadcopters need to be automated in an unknown or dynamic environment outside the lab environment, onboard robotic perception and robust state estimation constitutes the major hurdle. GPS outages are a challenging problem for autonomous navigation as inertial sensor based navigation have dead reckoning issues. In these conditions Simultaneous Localisation and Mapping is the ultimate choice for researches. There have been recent development for autonomous flight incorporating robust state estimation using laser scanners [15, 16], monocular [17, 18] and stereo cameras [19, 20], and RGB-D sensors [21]. However, all these methods rely on a solo exteroceptive sensor that is may be prone to malfunction under variant environment conditions; vision based techniques require adequate lighting and features, laser-based schemes demand structured environments, and GPS works in the open outdoors. This makes them error prone to changing environments. In such scenarios, fusion of all these measurements may yield increased estimator robustness and precision. One way is to handle this extra information as switching between sensor suites [22] or a more accurate way is to use them all together in a novel estimator such as in [23].

V. Future Recommendations

The recent focus has now shifted towards collaborative control of quadcopters. This is drawing considerable interest in research community due to the tremendous benefits of collaborative schemes for carrying out critical industrial operations that is tedious and often not possible with human operators. In this aspect a centralized cum decentralized topology offers more robustness; with a central planning phase before the beginning of the mission and decentralized on board controller taking care of safer reactive control maneuvers in order to ensure the mission is carried out with minimal information exchange with the central station. An important requirement is the ability of the aerial vehicles to autonomously avoid static and moving obstacles and at the same time maintain a minimum inter vehicle separation. Typical techniques involve collision cone (or velocity obstacle) based schemes, virtual potential field approach and randomly-exploring random-tress based methods.

Various collaborative schemes have been tested and demonstrated in controlled lab environments with reasonable assumptions and constraints. Nevertheless field operation of these techniques pose practical and theoretical challenges mainly in terms of state estimation and sensor fusion, motion planning and control, vehicle designs and inter systems communications. There is plenty of room for novel ideas for practical collaborative control techniques.

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