Adaptive Optimal Control - Assisted EKF For Quadcopter Trajectory Tracking Control

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Abstract

Precise control of UAV (Unmanned Aerial Vehicle) requires the accurate determination of vehicle orientation. Attitude and heading reference systems (AHRS) are popularly used for vehicle orientation determination. In these systems, Euler angle estimation is more appropriate than quaternion estimation because the accelerometer measurement and magnetometer measurement are separated. Furthermore, the accelerometer and magnetometer measurements have independent effects on the tilt and heading angles. An Euler based attitude estimation system that uses two-stage Extended Kalman Filtering is proposed. To avoid singularity of Euler angle, a new heading estimation parameter is introduced and a filter mode switching algorithm is proposed. In literature it is shown that estimation based on two-stage EKF are better than those obtained from quaternion algorithm based on magnetometer disturbance. Further-more, the results indicated that the proposed algorithm was immune to the singularity problem.

Dynamic Model of the Quadcopter

Derivation of dynamic model of a quadcopter is the central part of the high-level control implementation.

The complete dynamics of the vehicle is described below:

$$\dot{x} = u$$

$$\dot{u} = (C_\phi S_\theta C_\psi + S_\phi S_\psi)\frac{1}{m}U_1$$

$$\dot{y} = v$$

$$\dot{v} = (C_\phi C_\theta S_\psi - S_\phi C_\psi)\frac{1}{m}U_1$$

$$\dot{z} = w$$

$$\dot{w} = -g + (C_\phi C_\theta)\frac{1}{m}U_1$$

$$\dot{\phi} = p$$

$$\dot{p} = qr\left[\frac{I_{yy} - I_{zz}}{I_{xx}}\right] + \frac{J_r}{I_{xx}}q\Omega_d + \frac{l}{I_{xx}}U_2$$

$$\dot{\theta} = q$$

$$\dot{q} = pr\left[\frac{I_{zz} - I_{xx}}{I_{yy}}\right] - \frac{J_r}{I_{yy}}p\Omega_d + \frac{l}{I_{yy}}U_3$$

$$\dot{\psi} = r$$

$$\dot{r} = qp\left[\frac{I_{xx} - I_{yy}}{I_{zz}}\right] + \frac{1}{I_{zz}}U_4$$

$$\Omega_d = -\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4$$

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} b & b & b & b \\ 0 & -b & 0 & b \\ -b & 0 & b & b \\ d & -d & d & -d \end{bmatrix} \begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \\ \Omega_4^2 \end{bmatrix}$$

where m is the mass of the vehicle [kg], Ω_d is seen in roll and pitch dynamics, U_1, U_2, U_3 and U_4 are the control inputs and Ω_i is the angular speed of the i-th rotor [rad/sec].

Image for Real System

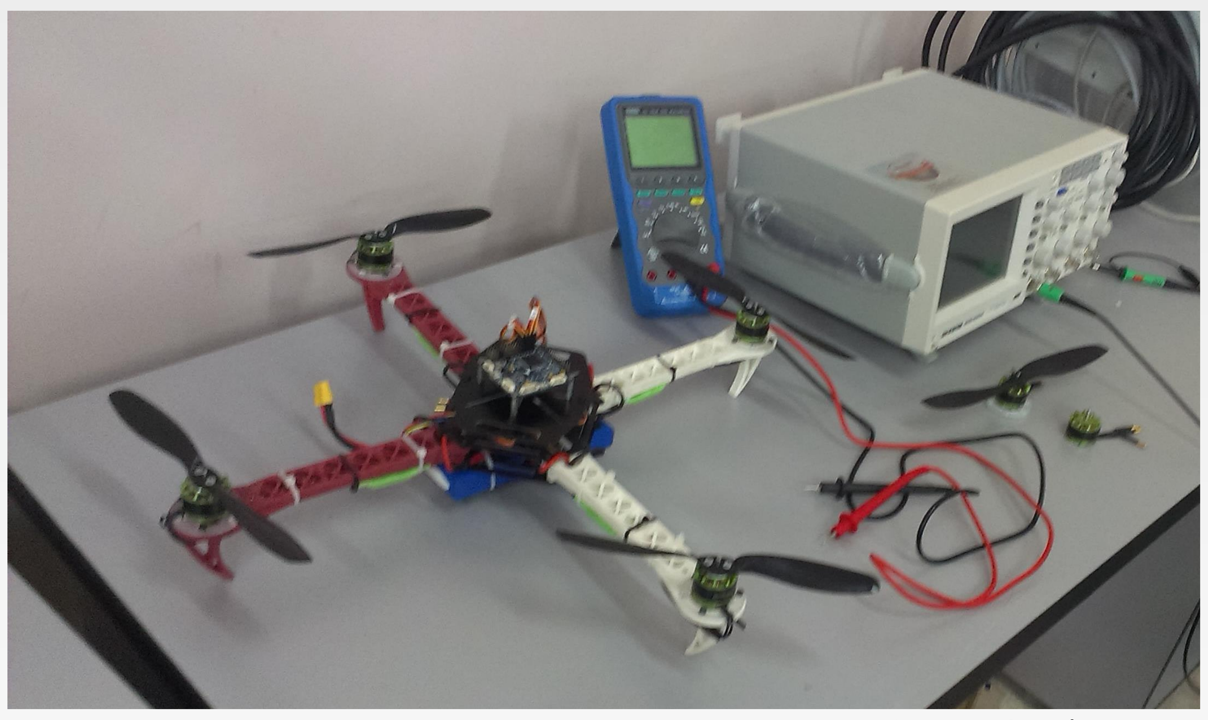

Figure 1 Quadcopter

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The main objectives of this project involve:

- Obtaining Euler Angles from Gyroscope, Accelerometer and Magnetometer and Altitude from Altimeter.
- Modeling and Simulation of Quadcopter System Using Advanced C++.
- Quadcopter Navigation and Control.

Introduction

Quadcopters have continually gained popularity among small rotary wing (UAVs). They are widely chosen as platforms for control design experiments, because of their low cost, agile dynamics and of course the ever-increasing performance of Micro Electro-Mechanical Systems (MEMS).

The research community has taken particular interest in UAVs, because of the emergence of a large number of potential civil. UAVs are important when it comes to situations that require unmanned operations such as performing tasks in dangerous and inaccessible environments that could put human lives at risk.

The aerodynamics of the quadcopter rotor is one of the most interesting and challenging problems facing Aerodynamicists. Understanding the detailed prediction of rotor loads, performance, vibration and acoustics, which also interacts with the fuselage, is an important aspect of the study.

Quadcopter Aerodynamics

Any air-breathing propulsion system, an engine-propeller combination, an engine-rotor combination, or a motor-rotor combination (like the quadcopter), derives its net thrust by adding momentum to a volume of air. Therefore, the production of thrust in helicopters is based solely on the action of the propeller. As the propeller rotates, it causes the air around it to accelerate from one side to the other, which results in the development of thrust in the opposite direction of the flow.

The rotor blades of the quadcopter are responsible for three basic functions:

1. The generation of a vertical lifting force (thrust) in opposition to the aircraft weight.
2. The generation of a horizontal propulsive force for forward flight and sideways flight.
3. A means of generating forces and moments to control the attitude and altitude of the helicopter.

Full Control Diagram

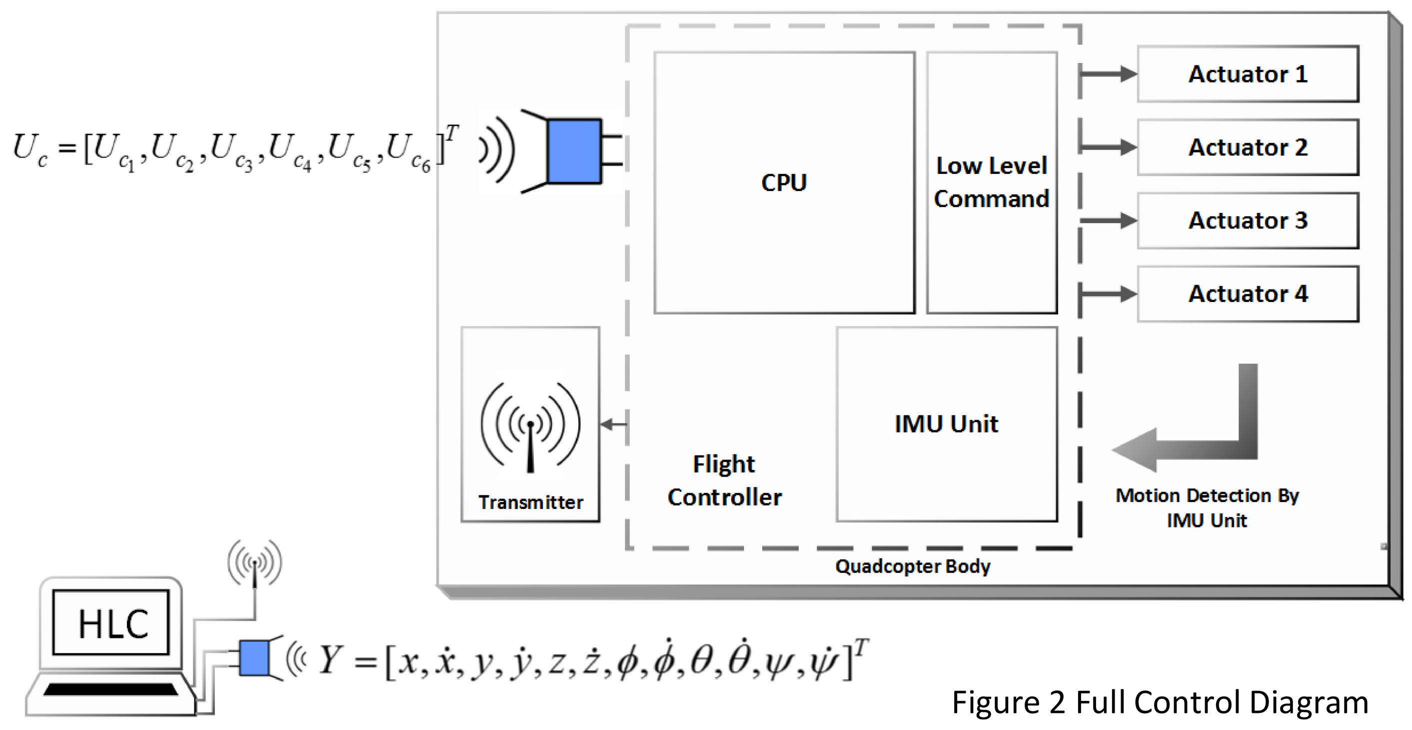

Figure 2 Full Control Diagram

BLDC Outrunner Motors

Most motors on quadcopters are outrunners. In outrunner motors, the rotating part is on the outside. Because of this layout this type of motors can generate much more torque. High torque is required for quadcopter, since it balances by changing the revolutions of the motor. The higher the torque the faster the ability to change the speed of propellers. High torque also means no need for a gearbox, and save a lot of mass.

Figure 3 BLDC Outrunner Motor

Conclusion

In this study the SK450 Quadcopter will be used for the implementation. Nonlinear state equations have been linearized around the hovering state conditions. Observation of Euler angles and throttle is calculated using raw values which been retrieved from the IMU Unit. Testing quadcopter's attitude in open-loop is accomplished stating that the behavior of the system is unstable. Modeling of the nonlinear equations using advanced C++.

Work is carrying on as follows:

- Building a high level control system for Quadcopter Posture Control.
- Investigating an Intelligent Collision avoidance procedure.
- Investigating for (UAV) responses for outdoor applications.

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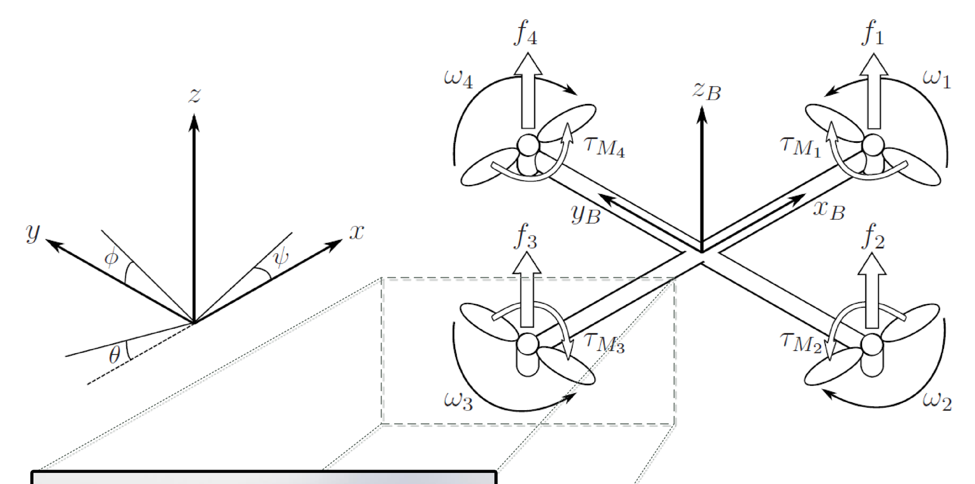
Quadcopter basic concepts

The quadcopter is a helicopter with four rotors mounted at each end of its cross-frame. It does not require complex mechanical control linkages for rotor actuation; instead, it relies on its fixed-pitch rotors and uses a variation in motor speed for control of the vehicle. In most cases, each propeller is directly connected to a brushless DC motor. These considerations show that the structure is rigid and control of the vehicle is achieved by slightly changing the rotor speeds because of the high sensitivity of the vehicle to rotor speed changes.

As the rotors spin, they produce lift forces and reaction torques. Normally, the reaction torque tends to make helicopter spin out of control. On the quadcopter, two of the rotors rotate counter-clockwise, while the other two rotate clockwise such that their reactions cancel each other.



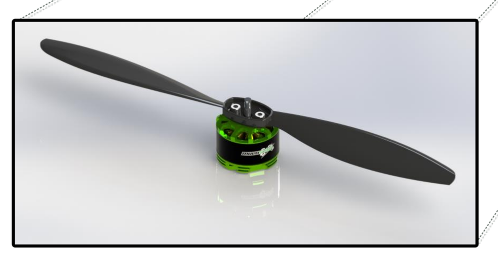


Figure 4 The inertial and body frames of a quadcopter

There are four basic commands, which allow the helicopter to reach a certain attitude and altitude.

a) Throttle

This command is provided by simultaneously increasing (or decreasing) all propeller speeds by the same amount and at the same rate. This generates a collective vertical force from the four propellers, with respect to the body-fixed frame. In consequence, the quadcopter is raised or lowered to a certain altitude.

b) Roll

The roll command is provided by simultaneously increasing (or decreasing) the left propeller speed and by decreasing (or increasing) the right propeller speed at the same rate. It creates a torque with respect to the x-axis and this makes the quadcopter to tilt about the same axis, thereby creating a roll angle. The total vertical thrust is maintained as in hovering, thus this command leads only to a roll angular acceleration.

c) Pitch

The pitch and roll commands are very similar. It is provided by simultaneously increasing (or decreasing) the rear propeller speed and by decreasing (or increasing) the front propeller speed at the same rate. This creates a torque with respect to the y-axis, which makes the quadcopter to tilt about the same axis, thereby creating a pitch angle (known as a nose-up or nose-down in a conventional aircraft). Again, there is no loss in the total vertical thrust; hence, this command leads only to a pitch angular acceleration.

d) Yaw

This command is provided by simultaneously increasing (or decreasing) the front-rear propellers' speed and by decreasing (or increasing) that of the left-right duo. This creates a torque imbalance with respect to the z-axis, which makes the quadcopter turn about the same axis. The yaw movement is generated because of the fact that the left-right propellers rotate clockwise while the front-rear pair rotates counter clockwise. Hence, when the total torque is unbalanced, the helicopter turns on itself around z. As obtained in the other movements, the total vertical thrust is still maintained as in hovering; hence, this command leads only to a yaw angular acceleration.

The goal of the quadcopter stabilization is to find those values of the actuators' commands which maintain the quadcopter in a certain position required in the task. This process is also known as inverse kinematics and inverse dynamics.

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