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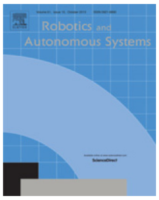

Comparison of various quaternion-based control methods applied to quadrotor with disturbance observer and position estimator

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HIGHLIGHTS

- Several attitude controllers using quaternion were designed to control quadrotor.
- Several position controllers were designed to control quadrotor.
- The disturbance observer and the state-space estimator were designed.
- The comparison of performance of combinations of controllers was carried out.
- The external disturbance was applied in the verification process.

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ABSTRACT

The aim of this article is to design and verify various control techniques for a quadrotor using a quaternion representation of the attitude. All attitude controllers use a quaternion error to compute control signals that are calculated from an actual quaternion and a desired quaternion obtained from a position controller. Attitude and position control laws are computed using a PD, LQR and backstepping control technique.

All combinations of controllers will be verified by simulation. We add noise, apply an actuator restriction and use a different sampling period for position and attitude feedback signals to get the simulation closer to real conditions.

Moreover, external disturbances were implemented into the simulation; hence a disturbance observer along with a position estimator will be designed to improve the performance of the presented controllers.

The performance of all combinations of controllers was evaluated using various quality indicators, such as the integral of absolute errors and total thrust, settling times and also maximum overshoots when external disturbance was applied. Some of the controllers exhibit very similar behaviour, so we chose the three best controllers for each scenario used in the simulation.

1. Introduction

In the last decades interest in Unmanned Aerial Vehicles (UAVs), also called drones, has increased. This group of vehicles consists of various flying platforms such as airships, fixed-wing or Vertical Take-Off and Landing (VTOL) vehicles. In the article we will focus on a quadrotor, which belongs to VTOL UAVs.

The main advantage of VTOL UAVs over fixed-wing UAVs is the ability to hover, allowing them to operate in a small and cluttered environment [1,2].

Comparing a multirotor to a helicopter other advantages can be identified such as greater trust-weight ratio and better manoeuvrability. The various numbers of rotors provide the possibility to use smaller blades instead of one large blade to produce a particular thrust. This leads to less structural and dynamical problems and in the case of an accident, the resulting injury is usually less heavy when compared to a helicopter [1,3,4].

Multirotors are normally controlled by changing the angular speed of rotors, so there is no need for a swashplate which simplifies not only the mechanics but also the maintenance of the system [3–5].

Multirotors can also continue in flight after an actuator failure occurrence when equipped with a failsafe controller. Although the failsafe controller is more straightforward to design for multirotors with 6 or 8 rotors, some controllers were also designed to manage an actuator failure of a quadrotor. Examples of failsafe controllers for a quadrotor can be found in the following works: [6–8].

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Multirotors have become very popular and their usage has spread over all fields of life. Some demanded tasks can be complicated and require the control algorithms to be faster, more efficient and reliable also under windy, uncertain and changing conditions. A disturbance observer (DO) is usually designed to compensate such uncertainties.

Various controllers based on classic or modern control theory were designed. The non-linear or linear model of a quadrotor is used depending on the chosen method.

The linear model of a quadrotor is achieved by linearization of the non-linear model around a hover operating point. Controllers using the linearized model generally perform well around a hover point. When the vehicle goes away from the linearized point, the performance may worsen. Furthermore, the input saturation can cause control failure when large rapid manoeuvres are required [4,5,9,10].

The use of a quaternion instead of Euler angles to describe the dynamics and to design controllers for a quadrotor is becoming very popular nowadays. A feedback signal in the form of a quaternion can be used to design linear and also non-linear attitude and position controllers.

The main advantages of linear controllers are simplicity and ease of implementation to a real platform. The disadvantage of this approach is the use of the linearized model of the quadrotor during the process of designing a controller. Commonly used linear controllers are a Linear Quadratic regulator (LQR) and a Proportional Derivative (PD) controller.

In [10] a cascade attitude controller was proposed. Both an inner and an outer control loop were formed by proportional controllers. The angular velocity and the quaternion were used as feedback signals. From this combination an attitude P2-controller arose. However, the final control law of the P2-controller corresponds to the standard PD controller designed in [3] and [11].

A scheduling LQR controller in [12] was tuned for two different situations; when a quadrotor is far from the reference and when the quadrotor is already tracking.

Another group of control units consists of a wide variety of non-linear controllers. The serious disadvantage of these controllers is the complexity that prevents the wide adoption of nonlinear controllers in real applications.

Among non-linear methods, the backstepping control technique based on the Lyapunov function is widely adopted due to its systematic design and a physically intuitive approach. The proposed control law is based on the compensation of non-linear forces or torques depending on whether an attitude or position controller is being designed. Applying Lyapunov stability analysis proves that the closed-loop system is asymptotically stable. This approach was used to stabilize the quadrotor in [4,5,9,13–15].

A backstepping-based inverse optimal attitude controller (BIOAC) was derived in [4] taking into account the input saturation. In [9] command filters are used to avoid a difficult analytic computation of required command derivatives in each step. The double-integral observer was developed in [13] to design a control law based on the Lyapunov function to track a reference trajectory. A decoupling attitude parametrization was presented in [14]. It allows the design of an independent and straightforward position heading tracking control using the backstepping control technique.

Some works try to overcome uncertainties (e.g. sensor noise, parametric uncertainties, and external disturbance) by designing adaptive controllers.

In another recent work [16], a flight controller based on a Neural Network model has been presented for stabilization and trajectory control.

The problem of disturbance rejection of the attitude subsystem of a quadrotor was addressed in [2]. An acceleration based disturbance observer was applied to a quaternion-based integral sliding mode attitude controller. This combination shows a significant improvement of the performance in position control as well as the compensation of large external forces.

Authors in [17] made a review of control techniques used to control a quadrotor pointing out their advantages and disadvantages.

Despite the interest in quadrotor control techniques, no one, as far as we know, has compared various types of linear and non-linear attitude and position controllers with the use of a disturbance observer. Most studies have only focused on the comparison of attitude controllers or of position controllers using the same attitude controller. Only a few works implemented a disturbance observer. Moreover, the position and linear velocity estimator is designed due to the different sampling periods of the feedback signals and the control loop, and the noise corruption of the feedback signals. This paper also calls into question an assumption that nonlinear controllers exhibit better performance when the external disturbance is present or the implementation of the disturbance observer to linear controllers is sufficient.

The article is structured as follows: firstly a model of the quadrotor dynamics will be derived using a quaternion representation of the attitude. Secondly, various attitude and position controllers will be designed using a quaternion-based feedback. Since the sampling of position is 10 times slower than the control loop period, a state space estimator is developed to predict and filter the actual position. Creating a disturbance observer to identify an attitude and position disturbance is important when a flying platform can operate in an environment, where constant wind and wind gusts can occur. Finally, a performance comparison of the designed controllers is followed by the conclusion.

2. Model of the quadrotor

This section focuses on the derivation of the mathematical model of the quadrotor using a quaternion representation. Before a short introduction to the quaternion algebra, advantages of this approach will be outlined.

Even though Euler angles are widely used to represent attitude, this representation suffers from several drawbacks. The most serious problem associated with the use of Euler angles is a "gimbal lock". The "gimbal lock" occurs when two of the rotational axes align and lock together. It implies the loss of one degree of freedom in a three-dimensional space. Another, but not less serious one is a high computational expense caused by the evaluation of quite a large number of trigonometric functions, such as sine and cosine [10].

An alternative representation of the attitude is the use of the Direction Cosine Matrix (DCM) or the quaternion. The DCM solves the singularity problem, but it is still very computationally expensive. Quaternions are free of singularities and are computationally more efficient in comparison with Euler angles or the DCM [3,10,18].

2.1. Quaternion algebra

This section is dedicated to build a mathematical background of the quaternion algebra. This knowledge will be exploited when deriving the mathematical model of the quadrotor and designing attitude and position controllers.

A quaternion defines a single rotation α around an axis $\mathbf{r}$. The notation of the rotation is given as a hyper complex number of rank 4 composed of the scalar $q_0 \in \Re$ and the vector $\mathbf{q_{13}} \in \Re^3$. The quaternion formulation is given by the following equation,