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Inertial Navigation Attitude Solution for Quadrotor Flying Robots

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Abstract: Quadrotor flying robots, valued for their VTOL capability, agility, and compact design, underpin diverse missions like aerial photography, delivery, and search-and-rescue. Stable flight hinges on precise attitude estimation—tracking roll, pitch, and yaw—where inertial navigation systems (INS), relying on inertial measurement units (IMUs) with gyroscopes and accelerometers, play a central role. Yet, raw IMU data faces critical limitations: gyroscopes drift over time due to bias/noise, while accelerometers conflate linear motion with gravity, degrading accuracy during dynamic maneuvers or prolonged operation. Thus, robust inertial attitude solutions are pivotal for quadrotor autonomy.

Keywords: Inertial Navigation System (INS); Quadrotor; Attitude Estimation; Sensor Fusion; IMU; Kalman Filter; Complementary Filtering; Dynamic Disturbances; Visual-Inertial Odometry (VIO)

1. THE FLIGHT PRINCIPLE OF A QUADCOPTER FLYING ROBOT

The unique "X"-shaped structural form of the quad-rotor flying robot allows it to easily complete flight tasks such as aerial hovering. All its air movement methods are composed of the most basic six air movement states. The following describes the body structure of the quadrotor flying robot and its six most basic states of air motion, respectively.

1.1 Structural form of quadcopter flying robot

Power for the quadrotor flying robot is provided by four separate motors, each with a propeller on board.Two propellers in the diagonal direction are called a set of counter-propellers, the two blades within one set of counter-propellers rotate in the same direction, and the blades of the two sets of counter-propellers rotate in opposite directions. So when the vehicle is in balanced flight, both the gyro effect and the aerodynamic torque effect are cancelled out[1].The flying robot controls four motors as well asThe force output by the corresponding propeller blade is used to stabilize the aerial attitude of the flying robot and realize its flight action in the airBody structure of a quadrotor flying robotAs shown in FIG 1Shown.

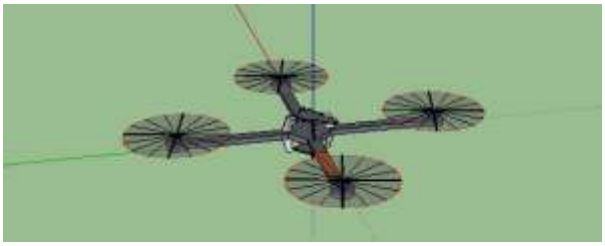

Figure. 1 Quadrotor flying robot body structure

1.2 The basic spatial motion state of the quadcopter flying robot

Quadrotor flying robots share in space6degrees of freedom (respectively along)3A "coordinate axis" performs translation and rotation actions), this6The control of each degree of freedom can be achieved by adjusting the speed of different motors[2]. Thus its basic state of motion comprisesVertical movement,Pitchmotion,Rollmotion,Yawmotion,Anteroposterior,LateralmovementCommon6 Plant. Such asDiagram2, order Motor1Andmotor3Rotatecounterclockwise,SimultaneousMotor2And motor4Make "clockwise rotation"It satisfies the same direction of rotation of the counter-paddle and the same direction of rotation of the two pairs of counter-paddles[3]. AndPrescribed alongXAxis positiveThe "movement" is called forwardSport,Use arrows to indicate the motor speed changes of the four rotors.Right6This "basic movement" analysis is as follows:

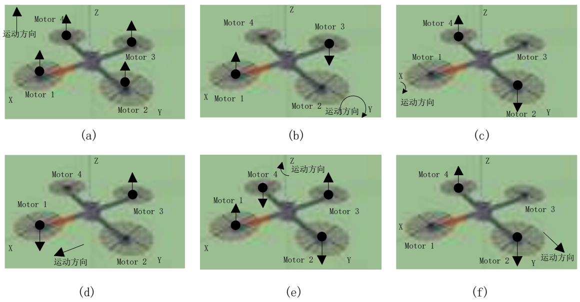

Figure. 2 Six basic states of motion of a quadrotor flying robot

(1)vertical motion:It can be considered as a translational motion along the Z-axis.As shown in FIG 2(a), Because the steering of the two pairs of motors is opposite, it can be used to balance the anti-torque of the two pairs of motors to the fuselage.When the output power of the four motors is increased simultaneouslyWhen, the motor drives the propeller RPMBigSuch that the total pulling force increases, when the total pulling forceGreater than the gravity of the entire quadrotor flying robot itselfWhen, quadcopter flight Robots Then "rise vertically from the ground "Contrary,When Simultaneously reducing the output power of the four motors Time, quadcopter flightThe robot will descend vertically until Balanced State landing on the ground, achievedAlongZ-axis translationSport[4]. When No Outbound perturbation Presence And In FourLifting force generated by the rotor,The sum is equal to that of the quadrotor flying robot itselfHeavyWhen "force" is reached, the aircraft can Keep AirHover state.How Four rotors guaranteedThe speed increases and decreases simultaneously Yes Control quadrotor flying robotKey to vertical movement.

(2) Pitch motion: It can be considered as a rotational motion around the Y-axis. 2 (b), when the rotational speed of the motor 1 is increased, the rotational speed of the motor 3 is decreased, and the rotational speed of the motor 2 and the motor 4 is kept unchanged (in order to ensure that the overall torque of the quadrotor flying robot and the change in the total pulling force of the rising force are not caused by the change in the rotational speed of the rotor 1 and the motor 3, it is assumed that the magnitude of the change in the rotational speed of the motor 1 and the motor 3 is equal) As the lift of the rotor 1 increases, the lift of the rotor 3 decreases, and the resulting unbalanced moment rotates the quadrotor flying robot body about the Y-axis. On the contrary, when the rotational speed of the motor 1 is reduced and the rotational speed of the motor 3 is increased (again, assuming that the magnitude of the rotational speed change of the motor 1 and the motor 3 is equal), the resulting unbalanced moment rotates the quadrotor flying robot body in the opposite direction about the Y-axis, and finally achieves the pitching motion of the quadrotor flying robot.

(3) Rolling motion: It can be considered as rotational motion around the X-axis. 2 (c), the principle of pitching motion is the same, while changing the rotational speed of the motor 2 and the motor 4, while keeping the rotational speed of the motor 1 and the motor 3 unchanged, so that the quadrotor flying robot body can be rotated around the X-axis (forward and reverse), and the rolling motion of the quadrotor flying robot can be realized.

(4) Front and rear motion: It can be considered as translational motion along the X-axis. To achieve the fore-and-aft motion of the quadrotor flying robot on the horizontal plane, an X-axis force must be applied to the quadrotor flying robot on the horizontal plane. 2 (d), the rotational speed of the motor 3 is increased so that the pulling force is increased, and the rotational speed of the motor 1 is decreased accordingly so that the pulling force is decreased. The flying robot first undergoes a certain degree of tilting so that the upward pulling force of the rotor creates a horizontal component, so that the forward movement of the flying robot can be achieved. On the contrary, by increasing the rotational speed of the motor 1 so that the pulling force increases, and correspondingly decreasing the rotational speed of the motor 3 so that the pulling force decreases, the backward motion of the flying robot can be realized. In addition, when performing pitching motion or tumbling motion, the flying robot will also produce motion in the horizontal direction of the X or Y axis.

(5) Yaw motion: It can be considered as rotational motion around the Z axis. The yawing motion of the quadrotor flying robot is achieved with the aid of the torsional moment generated by the rotor. During turning, the rotor of the flying robot forms an anti-torque opposite to the direction of forward turning due to the action of air resistance. The magnitude of the counter-torque moment is related to the rotational speed of the four motors. When the rotational speeds of the four motors are the same, the counter-torque moments generated by the four rotors balance each other, and the four-rotor flying robot body hovers in the air; when the rotational speeds of the four motors are not exactly the same, Unbalanced torsional moments can cause adjustments in the air attitude of quadrotor flying robots. As shown in FIG 2(e), when the rotation speed of motor 1 and motor 3 increases and the rotation speed of motor 2 and motor 4 decreases, the anti-torque moment of rotor 1 and rotor 3 on the fuselage is greater than the anti-torque moment of rotor 2 and rotor 4, and the fuselage Rotate around the Z-axis under the action of excess anti-torque torque Realizing yaw motion for a quadrotor flying robot. Its turning direction is opposite to the steering of the motor 1 and the motor 3.

(6) Tendency motion: It can be considered as translational motion along the Y-axis. 2 (f), correspondingly changing the rotational speed of the motor 2 and the motor 4 in the same principle as the forward and backward motion enables the quadrotor flying robot body to advance or retreat (forward and reverse) in the direction of the Y-axis, thereby achieving the propensity motion of the quadrotor flying robot.

2. ATTITUDE CALCULATION PRINCIPLE OF INERTIAL NAVIGATION METHOD OF QUAD-ROTOR FLYING ROBOT

As one of the important purposes of attitude measurement of quadrotor flying robots, navigation occupies an important place in the flying robot control system. According to the adopted navigation theory and navigation device, navigation can be divided into radio navigation, Doppler radar navigation inertial navigation,satellite positioning navigation, astronom navigation, map matching navigation and other modes. At present, inertial navigation, since it does not need to rely on external conditions such as light, magnetism, and terrain, can be applied around the clock without any constraints and become an irreplaceable autonomous means of navigation for any other navigation method. Almost all advanced combined navigation methods are based on inertial navigation .Inertial navigation is divided according to the navigation mechanism, which can be divided into platform inertial navigation and Czech-linked inertial navigation. Platform"Inertial navigation" establishes a real physical entity platform and uses electromechanical control and other means to simulate the navigation coordinate system. Its disadvantages are that the structure is relatively complex and bulky; Jielian inertial navigation uses the angular motion and linear motion information of the carrier obtained by the sensor to solve the problem. Navigation is realized through calculation, which is characterized by relying on algorithms to establish navigation coordinate system information and omitting the physical entity platform Therefore, it has the advantages of simple structure, small size, light weight, low cost, good reliability and easy maintenance .

2.1 Inertial navigation coordinate system and common parameters

In inertial navigation, theRightThe study of attitude control must introduce a corresponding coordinate system in order to proceed, and for different research objects and specific task requirements, it is very important to correctly select different coordinate systems .CarrierThe attitude parameters are determined by the interrelation ships between these different coordinate systems. Commonly used in inertial navigation There are the following six coordinate systems, which are defined as:

(1) Geocentric inertial coordinate system (subscript is i),

A geocentric inertial coordinate system is a fixed coordinate system in which the origin is defined at the center of the Earth, but does not itself participate in the rotation of the Earth. Normally, we choose The axis points along the Earth's axis in the direction of the geographic North Pole, while , The axis is defined in the equatorial plane of the Earth, The axis points to the equinoxes defined by astronomy, and the three coordinate axes form the geocentric inertial coordinate system by the right hand . This coordinate system is often used as a reference datum for inertial measurement units to measure aircraft, and is referred to simply as an inertial coordinate system.

(2) Earth coordinate system (subscript is e),

The Earth coordinate system refers to a coordinate system fixed to the surface plane, which is inertial with respect to the center of the earth At the Earth's rotational angular velocity Rotating, the origin of the earth's coordinate system coincides with the geocentric inertial coordinate system Axis to Earth's axis of rotation Axis coincides, The axis points to the Earth's time zone boundary, and the three coordinate axes form the Earth's coordinate system according to the right hand method .

(3) Geographic coordinate system (subscript is g),

The geographical coordinate system, also known as the northeastern celestial coordinate system, is a coordinate system commonly used on aircraft to describe the spatial coordinate situation of the aircraft. The origin of the geographical coordinate system is located at the center of the aircraft, The axis points due east, The axis points skyward, with gravity Opposite direction. The three coordinate axes form a geographical coordinate system by the right hand .

(4) Body coordinate system (subscript is b),

The airframe coordinate system refers to the coordinate system fixed to the airframe, which is mostly used for determining the air flight attitude of an aircraft. The origin of the airframe coordinate system is different from that of the northeastern celestial coordinate system, and is defined at the center of gravity of the aircraft The axis direction points to the positive direction of the horizontal axis on the right side of the longitudinal axis direction of the aircraft The axis is perpendicular to the plane of the body and points towards the vertical axis of the carrier. The three coordinate axes form the body's coordinate system according to the right hand method .

(5) Platform coordinate system(Subscript is n),

Platform coordinate systems refer to reproducing navigation coordinate systems with inertial navigation systems (mainly gyroscopes) The coordinate system used. Its coordinate origin Equivalent to the origin of the body coordinate system, it is the center of gravity of the aircraft Axis with The axes are likewise defined in the same way as the navigation coordinate system. The reason why the platform coordinate system is defined for error correction in the inertial navigation system is that for the platform inertial navigation system, it is the error angle between the gyroscope and the physical platform, and the error of this angle due to manufacturing process and the like can be eliminated by the conversion matrix between the platform coordinate system and the navigation coordinate system. For the JetLink inertial navigation system, it refers to the angle of error between the MEMS device sensors (mainly digital gyroscopes, accelerometers) and the mathematical horizontal plane defined by the JetLink inertial navigation system, which is implemented by the direction cosine matrix defined in the software algorithm, and there is no real physical device corresponding to it But the calibration of its errors can also be compensated by the transformation matrix in this platform coordinate system.

2.2 JieLian inertial navigation

The mathematical operations in "JieLian inertial navigation" are mainly the conversion operations of several parameters in different coordinate systems. These parameters are very important for the JieLian inertial navigation system. Here, the relevant parameter information involved in the mathematical operations of the JieLian inertial navigation system is introduced.

(1)Attitude angle, the attitude angle that describes the aerial attitude of a flying robot usually refers to the following three angles: (heading), carrier heading angle. The angle of rotation of the carrier with respect to the Z-axis of the body’s coordinate system; (pitch), carrier pitch. The angle of rotation of the carrier with respect to the Y-axis of the body’s coordinate system; (roll), carrier roll angle. Angle of rotation of the carrier with respect to the X-axis of the body coordinate system.

(2)Angular velocity

Angular velocity is used as Similar symbol representation, then the meaning of b is the projection of this angular velocity in the b-coordinate system (body coordinate system), and the meaning of nb is the angular velocity of the b-coordinate system (body coordinate system) turning relative to the n-coordinate system (navigation coordinate system).

(3)Coordinate System Transformation Matrix

The coordinate system conversion matrix is used as A similar symbol representation, then it is a transition matrix from the n-coordinate system (navigation coordinate system) to the b-coordinate system (body coordinate system).

(4)Earth's rotational angular velocity

The angular velocity of the Earth's rotation is the angular velocity of the Earth's rotation around the Earth's axis, with Representation.Its value .

3. CONCLUSION

In summary, the inertial navigation attitude solution serves as a cornerstone for the stable and autonomous operation of quadrotor flying robots. By leveraging inertial measurement units (IMUs) and integrating advanced estimation algorithms, these systems overcome the inherent limitations of raw IMU data—gyroscopic drift and accelerometer noise—to deliver accurate, real-time orientation estimates critical for flight control. Traditional methods like complementary filtering laid the groundwork by balancing short-term gyroscope precision with long-term accelerometer/magnetometer corrections, while modern Kalman filter variants (EKF, UKF) and nonlinear optimization techniques (e.g., gradient descent on attitude quaternions) have enhanced robustness in dynamic environments, mitigating errors from high-acceleration maneuvers or wind disturbances.

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