A self-rotating, single-actuated UAV with extended sensor field of view for autonomous navigation

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Outline

1 Introduction

2 Results

3 Discussion

4 Materials and Methods

Major problem

The abilities of self-localization, environment mapping, and obstacle avoidance are important to UAV. These abilities are usually based on the environmental observation provided by visual sensors on board the UAV, passive (e.g., RGB camera and thermal camera) or active [e.g., light detection and ranging (LiDAR) and infrared depth camera]. But the small field of view (FoV) of these sensors severely limits the UAV’s perception capability and task efficiency.

Methods for extending sensor FoVs on UAVs

Methods:

1. Use a sensor with a large FoV, such as a fisheye camera, catadioptric camera, and 360° LiDAR
2. Use multiple sensors, such as cameras, stereo cameras, fisheye cameras, or LiDARs

Disadvantage:

1. distortions, low resolution
2. additional sensor cost and processing time, more power consumption

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3. Use the self-rotation that the UAV is already capable of

Disadvantage:

1. distortions, low resolution
2. additional sensor cost and processing time, more power consumption
3. UAV design and control, high-rate rotation causes severe motion blurs and rapid FoV change

Contributions

The researchers propose an autonomous, single-actuated, and self-rotating UAV with extended sensor FoVs called PULSAR:

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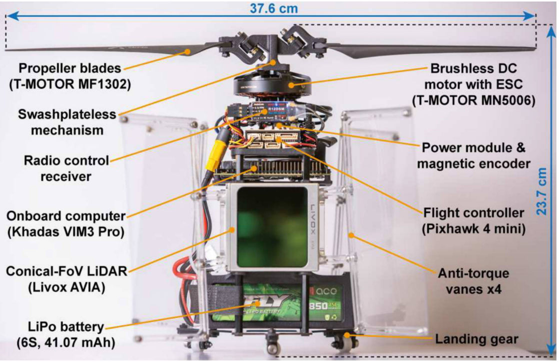
Outline

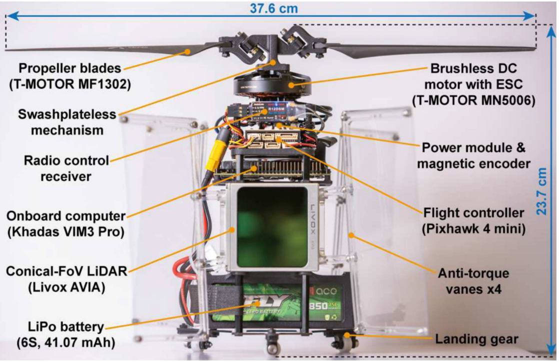
UAV system overview

- Overall weight: 1.23 kg
- Maximum thrust: 25.45 N
- Thrust-to-weight ratio : 2.1
- Diameter: 37.6 cm
- Height: 23.7cm



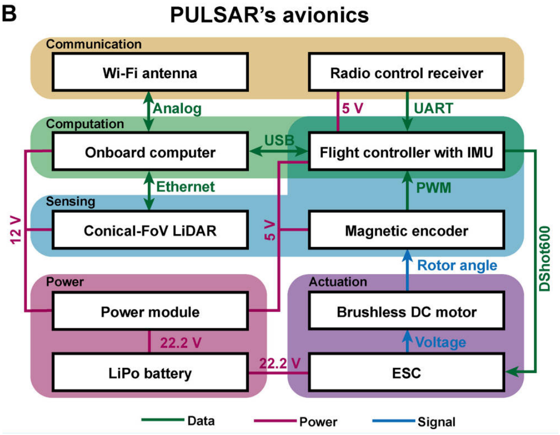
Mechanical design

- A flight control module at the top (i.e., propeller, motor, and flight controller)
- A 3D LiDAR sensor with an onboard computer in the middle
- A battery chassis and landing gears at the bottom.



Avionics

- A six-cell 41.07-Wh (1850-mAh) battery
- An onboard computer: Khadas VIM3 Pro with an ARM processor
- A flight controller: Pixhawk 4 Mini
- Livox AVIA LiDAR
- A magnetic encoder: AS5600
- T-MOTOR MN5006 KV450
- A common electronic speed controller (ESC) of the model CYCLONE 45A



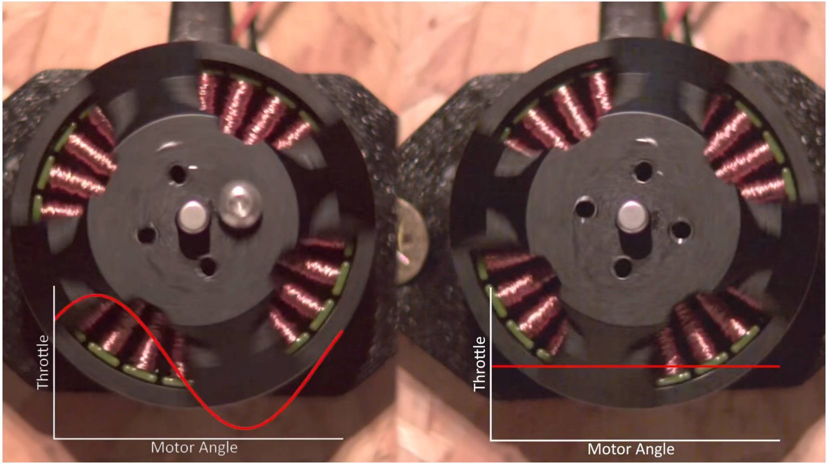
Swashplateless mechanism

Definition

A swashplate is a mechanical device that translates input via the helicopter flight controls into motion of the main rotor blades. Because the main rotor blades are spinning, the swashplate is used to transmit three of the pilot’s commands from the non-rotating fuselage to the rotating rotor hub and main blades.

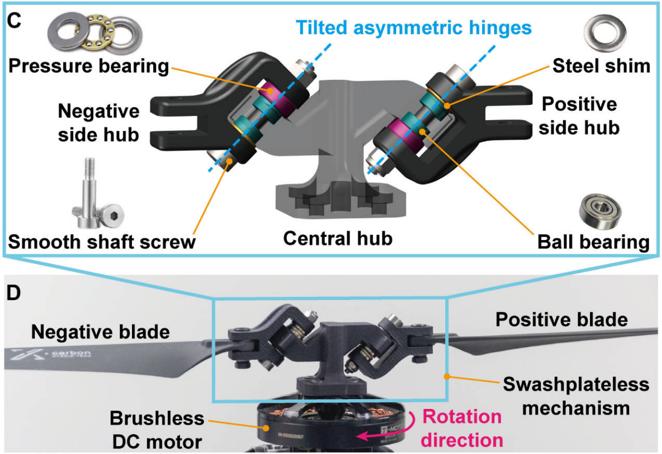
According to the aforementioned definition, unmanned aerial vehicles such as helicopters, which rely solely on a single rotor to generate lift, typically require the utilization of a swashplate mechanism in order to achieve controllability.

Swashplateless mechanism



The motor speed can be manipulated as desired, and the lift can be deduced from the average rotational speed of the motor.

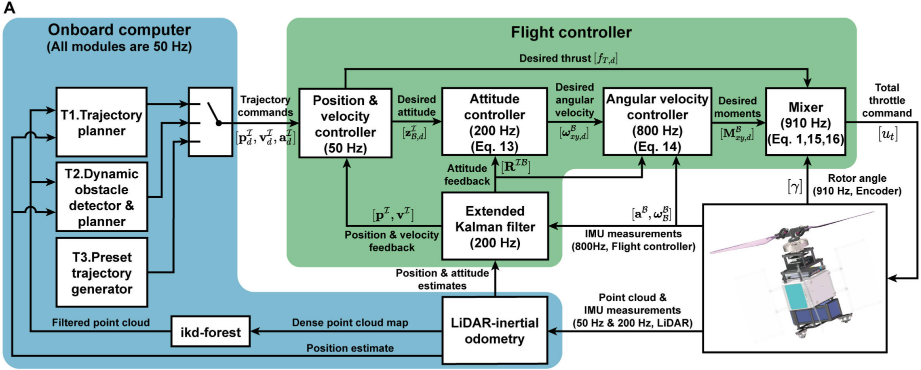
Swashplateless mechanism



The specially designed swashplateless structure in this paper reduces the energy consumption caused by friction.

Experimental validation

A



Onboard computer
(All modules are 50 Hz)

T1.Trajectory planner

T2.Dynamic obstacle detector & planner

T3.Preset trajectory generator

Trajectory commands
$[\mathbf{p}_d^{\mathcal{I}}, \mathbf{v}_d^{\mathcal{I}}, \mathbf{a}_d^{\mathcal{I}}]$

Filtered point cloud

ikd-forest

Dense point cloud map

Position estimate

LiDAR-inertial odometry

Flight controller

Desired thrust $[f_{T,d}]$

Position & velocity controller (50 Hz)

Desired attitude
$[\mathbf{z}_{\mathcal{B},d}^{\mathcal{I}}]$

Attitude controller (200 Hz) (Eq. 13)

Desired angular velocity
$[\boldsymbol{\omega}_{xy,d}^{\mathcal{B}}]$

Angular velocity controller (800 Hz) (Eq. 14)

Desired moments
$[\mathbf{M}_{xy,d}^{\mathcal{B}}]$

Mixer (910 Hz) (Eq. 1,15,16)

Total throttle command
$[u_t]$

Attitude feedback
$[\mathbf{R}^{\mathcal{IB}}]$

$[\mathbf{p}^{\mathcal{I}}, \mathbf{v}^{\mathcal{I}}]$
Position & velocity feedback

Extended Kalman filter (200 Hz)

$[\mathbf{a}^{\mathcal{B}}, \boldsymbol{\omega}_{\mathcal{B}}^{\mathcal{B}}]$
IMU measurements (800Hz, Flight controller)

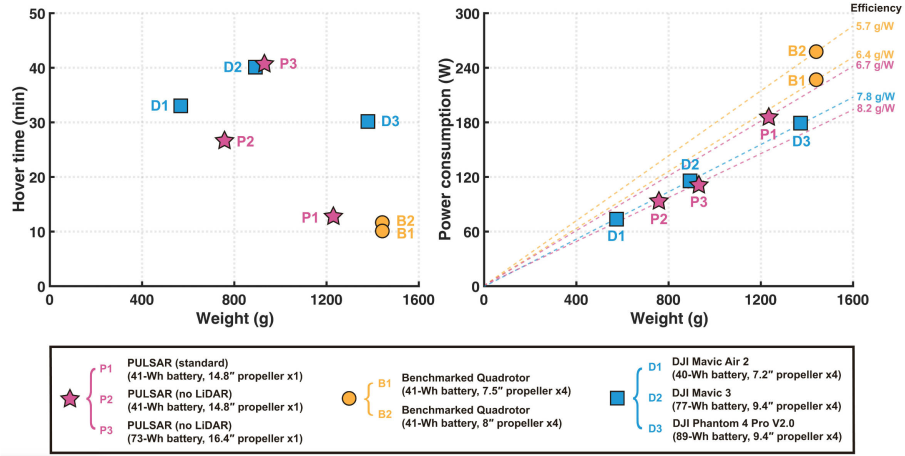
$[\gamma]$
Rotor angle (910 Hz, Encoder)

Position & attitude estimates

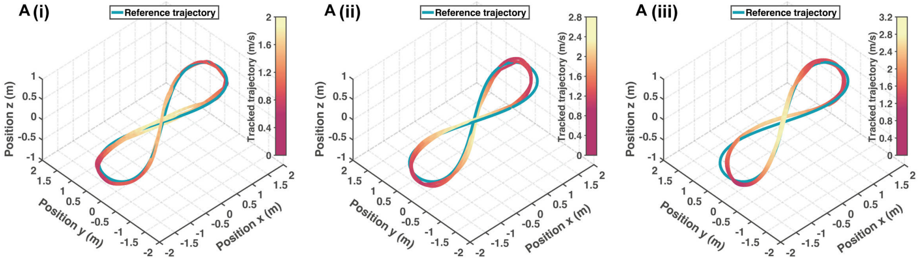
Point cloud & IMU measurements (50 Hz & 200 Hz, LiDAR)

Here lies the framework of this UAV. In all experiments, PULSAR used the same LiDAR-inertial odometry and trajectory-tracking controller to estimate its full state and track the trajectory commands.

Flight efficiency

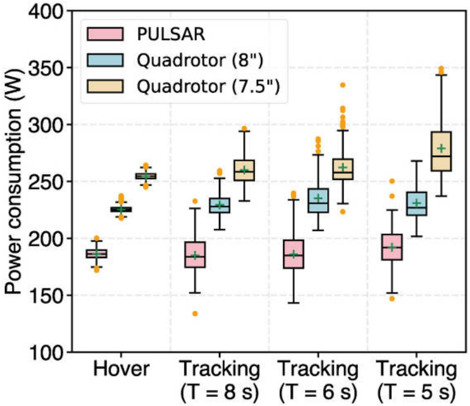


Trajectory tracking in indoor environment



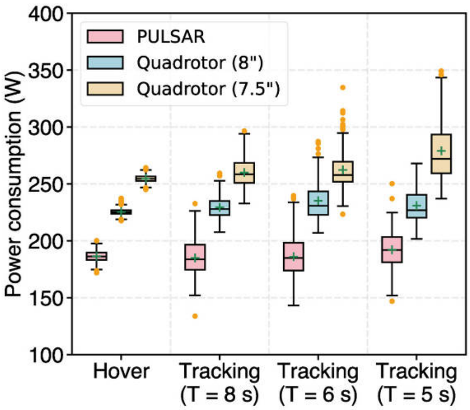
The trajectory under tracking is a figure "8" path with different periods, T. The green line represents the reference trajectory, whereas the line colored by velocity represents the actual flight path. Each trajectory is tracked for five cycles, where the middle three are displayed for better visualization of the speed. A(i), A(ii), and A(iii) are the trajectories with period T of 8, 6, and 5 s, respectively.

Trajectory tracking in indoor environment



Power consumption during hover and trajectory tracking.

Trajectory tracking in indoor environment



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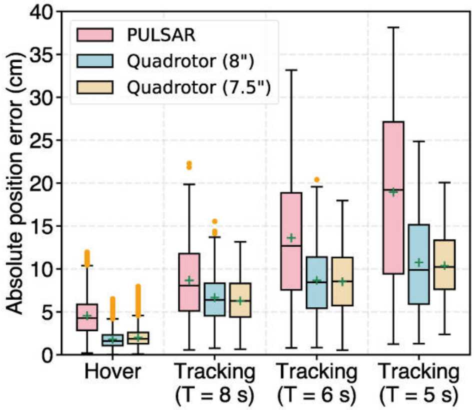
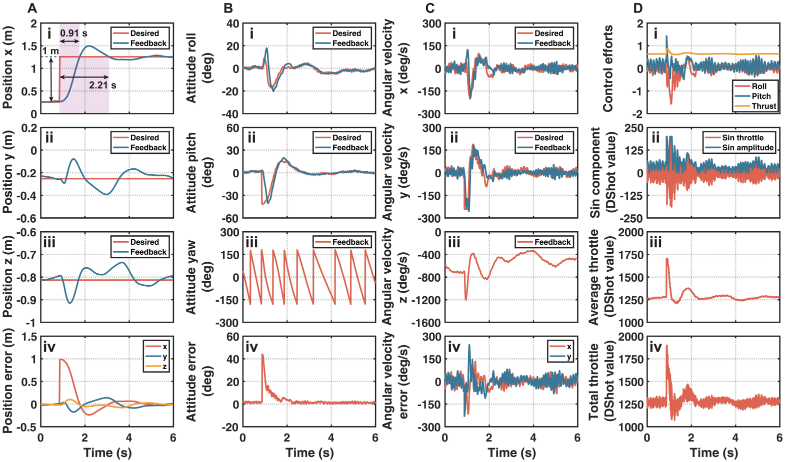


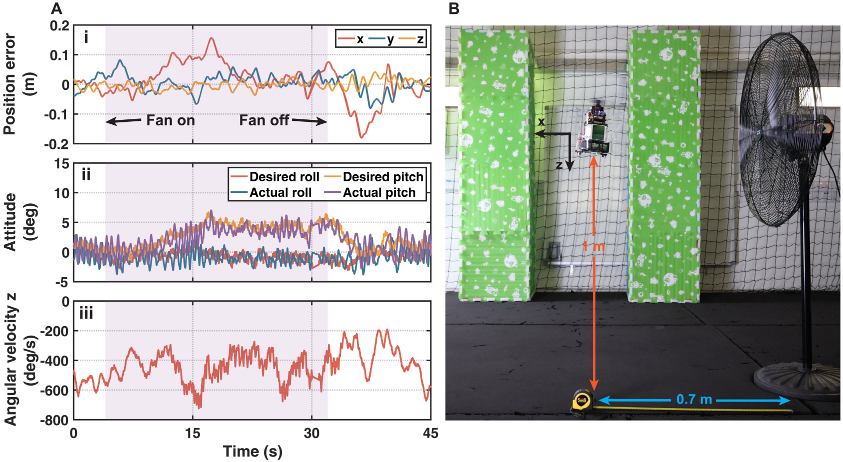
Absolute position error of hover and trajectory tracking.

Response to position commands



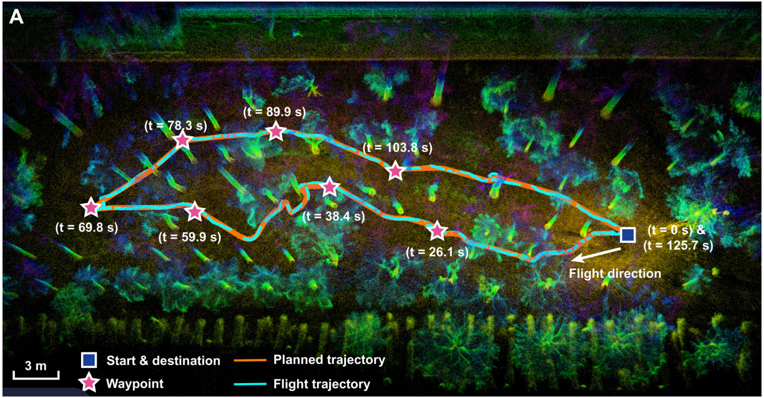
Response of PULSAR to a step position command in the x direction.

Robustness to external disturbances



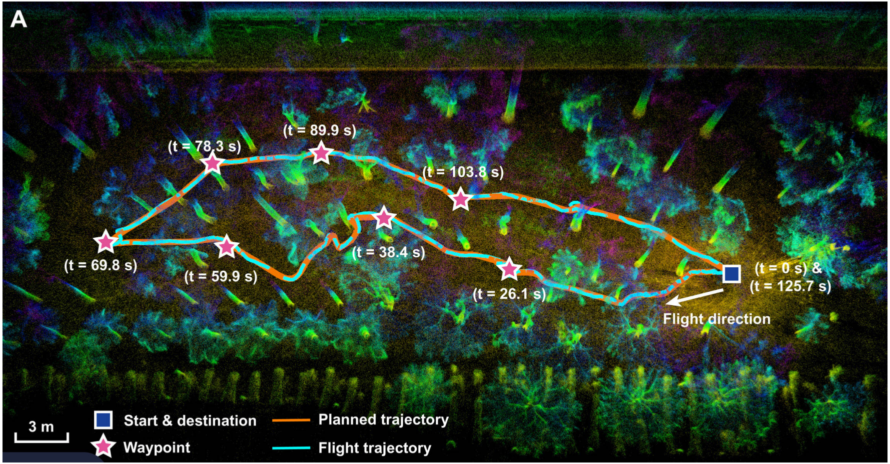
Wind disturbance rejection.

Autonomous navigation in unknown, GNSS-denied environments



To verify the full autonomous navigation ability of PULSAR, the researchers performed a waypoint navigation experiment in a wooded environment of 54m by 26m.

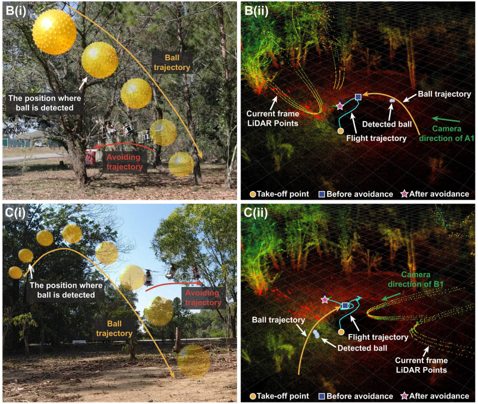
2 Results



A 3D point cloud map of the environment was obtained during the flight. Benefiting from the extended FoV of PULSAR, the built map had points uniformly distributed in all horizontal directions, instead of all lying within the small conical sensor FoV, leading to a more efficient exploration of the environment.

Avoidance of dynamic obstacles from different directions

Dynamic ball avoidance with PULSAR. The ball was thrown from two orthogonal directions whose avoiding processes are shown in (B) and (C), respectively.



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Energy efficiency

Definition

According to the momentum theory, a UAV has its ideal hover efficiency:

$$\mu = \frac{\sqrt{2\rho A}}{\sqrt{mg}}(g/W)$$

where m, A, ρ, and g are total mass, total propeller disk area, air density, and the gravity acceleration, respectively.

PULSAR has a greater energy efficiency when compared with the benchmarked quadrotors. For a quadrotor that preserves the same total disk area and weight as PULSAR, it should have the same power consumption and efficiency. However, four small propellers often have around 5.79 to 13.61 % lower efficiency than one big propeller. And rotor-to-rotor interactions and rotor-to-body interactions will cause a further efficiency drop.

3 Discussion

- Mapping efficiency
  - By employing solid angles, the enhancement of the actual field of view (FOV) of PULSAR was quantified
- Agility
  - PULSAR has a thrust-to-weight ratio (2.1) that is lower than those two benchmarked quadrotors: thrust-to-weight ratio of up to 2.7 (7.5-inch propellers) and 3.5 (8-inch propellers), but still achieved a good level of agility
- Scalability
  - The scalability of PULSAR along with its symmetric geometry allows for carrying various payloads of different weights as required by the task
- Potential applications
  - Environment surveying, search and rescue, disaster relief, terrain mapping, and automatic 3D reconstruction

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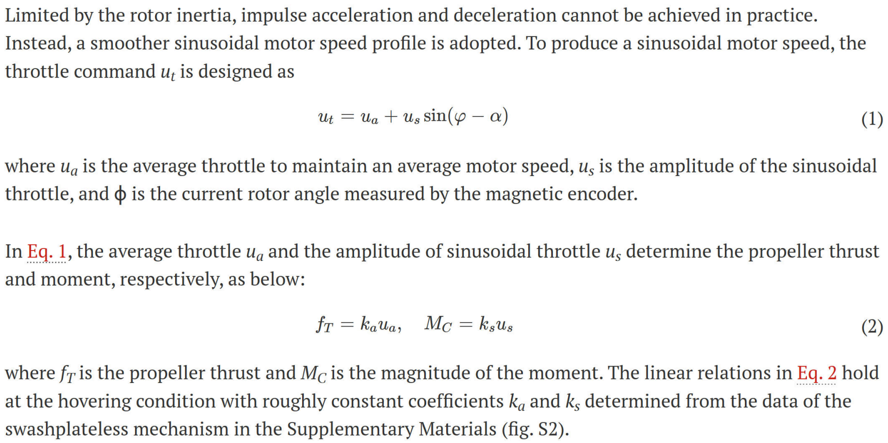
Working principle of the swashplateless mechanism



Limited by the rotor inertia, impulse acceleration and deceleration cannot be achieved in practice. Instead, a smoother sinusoidal motor speed profile is adopted. To produce a sinusoidal motor speed, the throttle command u_t is designed as

$$u_t = u_a + u_s \sin(\varphi - \alpha) \tag{1}$$

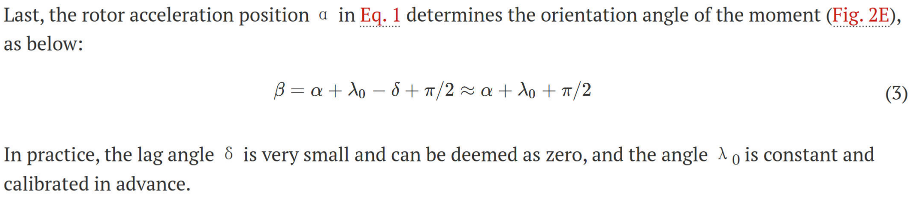
where u_a is the average throttle to maintain an average motor speed, u_s is the amplitude of the sinusoidal throttle, and ϕ is the current rotor angle measured by the magnetic encoder.

In Eq. 1, the average throttle u_a and the amplitude of sinusoidal throttle u_s determine the propeller thrust and moment, respectively, as below:

$$f_T = k_a u_a, \quad M_C = k_s u_s \tag{2}$$

where f_T is the propeller thrust and M_C is the magnitude of the moment. The linear relations in Eq. 2 hold at the hovering condition with roughly constant coefficients k_a and k_s determined from the data of the swashplateless mechanism in the Supplementary Materials (fig. S2).

4 Materials and Methods



Last, the rotor acceleration position α in Eq. 1 determines the orientation angle of the moment (Fig. 2E), as below:

$$\beta = \alpha + \lambda_0 - \delta + \pi/2 \approx \alpha + \lambda_0 + \pi/2 \quad (3)$$

In practice, the lag angle δ is very small and can be deemed as zero, and the angle λ_0 is constant and calibrated in advance.

Other materials

- Dynamic modeling
- Trajectory tracking control
  - outer-loop position controller: proportional controller
  - inner-loop velocity controller: PID controller
- Mixer for driving swashplateless mechanism
  - The computed desired thrust and desired moment are used to generate the total motor throttle command
- Software framework overview
  - ROS Noetic running in Ubuntu 20.04, C++, PX4 V1.11.2, MAVROS

Other materials

- LiDAR-inertial odometry
    - FAST-LIO2
- Incremental k-dimensional forest
- Trajectory generation and autonomous flight
    - kinodynamic A*
- Dynamic obstacle avoidance
    - A target point is generated such that its distance to the UAV is shorter than the nearest static points in the map and that it lies in a direction orthogonal to the object’s incoming direction

5 Acknowledgement

Thank you !

Q & A