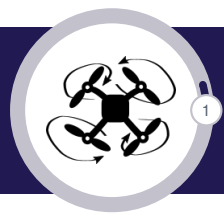


Principles of Flight



Using its four propellers, how does the quadrotor fly through the space? How does it move up and down, left and right, forward and backward, and is there more to it?

About Propellers



About Propellers



- ▶ A spinning propeller creates thrust, a force that is perpendicular on the propeller's rotation plane.

About Propellers

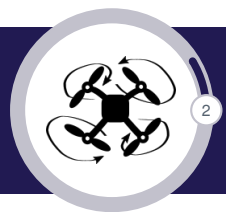


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- ▶ Besides the thrust force, a spinning propeller produces a turning effect (or torque) on the quadrotor frame. This is in the opposite direction to the propeller's rotation.

About Propellers



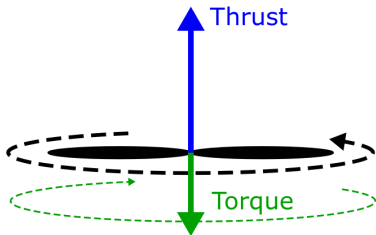
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- ▶ There are two types of propellers. Type 1, or right-handed propeller, produced thrust in the upward direction when rotating CCW. Type 2, or left-handed propeller, produces thrust in the upward direction when rotating CW. (CW and CCW defined as seen from above)



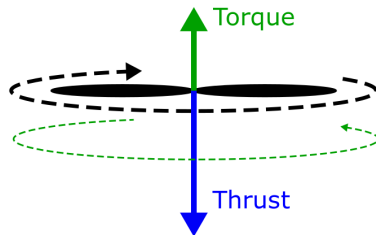
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- ▶ A quadrotor has two Type 1 and two Type 2 propellers.

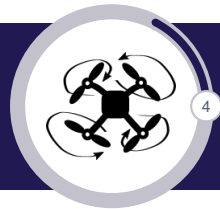
Type 1 (CCW) Propellers



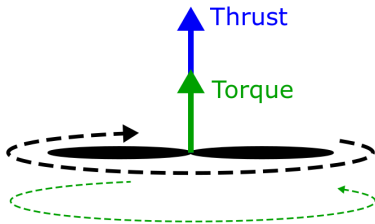
Type 1 (CCW) Propeller turning CCW



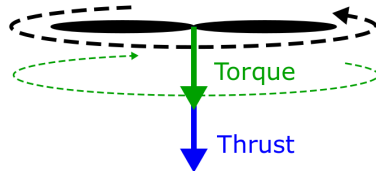
Type 1 (CCW) Propeller turning CW



Type 2 (CW) Propellers



Type 2 (CW) Propeller turning CW



Type 2 (CW) Propeller turning CCW

Quadrotor Principles of Motion

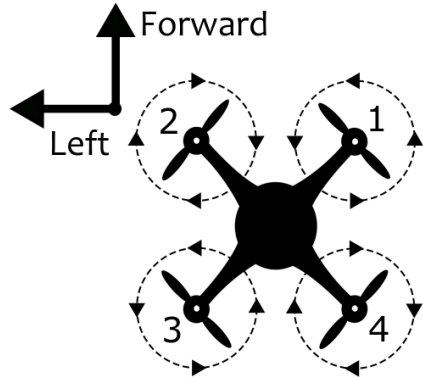
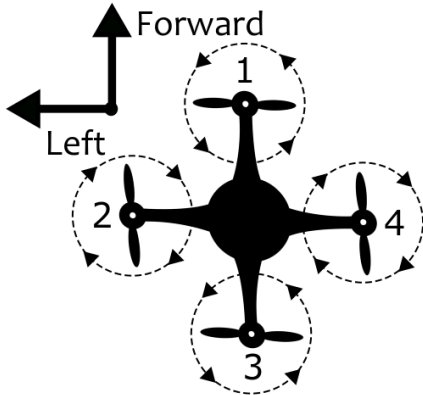


- ▶ The quadrotor is an underactuated system
- ▶ There are 6 degrees of spatial freedom:
 - ▶ 3 translational DoFs: up/down, forward/backwards, left/right
 - ▶ 3 rotational DoF: heading, pitch and roll
- ▶ Only 4 command that we send to the motors
- ▶ How does the quadrotor system, with its four (4) actuators, navigate the six (6) degrees of freedom of the 3D space ?

Plus and Cross Configurations



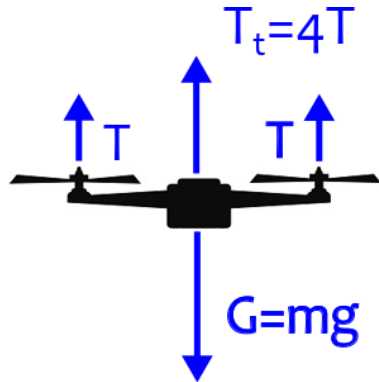
What is forward and backward, what is left and right?





Moving up and down

- ▶ Let's assume that the frame of the quadrotor is perfectly level with the ground, by giving equal commands to the motors.
- ▶ The overall thrust is in the vertical direction and can compensate for the gravity to generate a movement up.
- ▶ If the overall thrust is less than the force of gravity, then the quadrotor will move down.

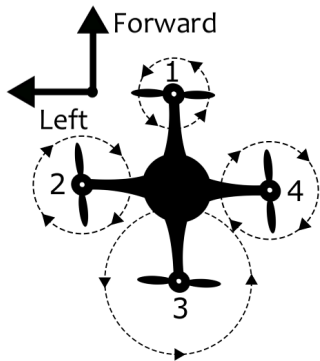




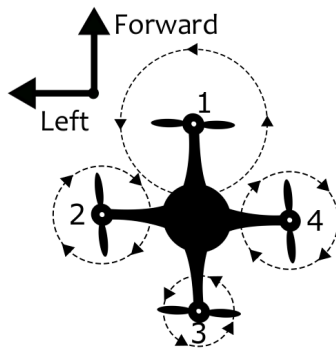
Pitching | Tilting front and back

- ▶ To pitch, i.e. rotate around the left-right axis, we must create an unbalance in the forward-side and backward-side forces.
- ▶ Pitching forwards is done by decreasing the force in the forward side and/or increasing in the backward side
- ▶ Pitching backwards is done by decreasing the force in the backward side and/or increasing in the forward side

Pitching | Tilting front and back



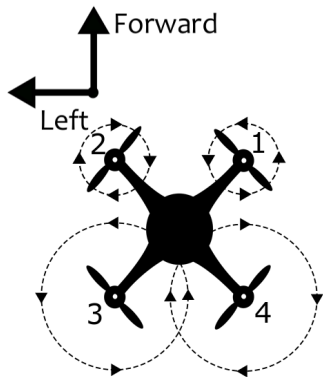
Plus config: pitch forward



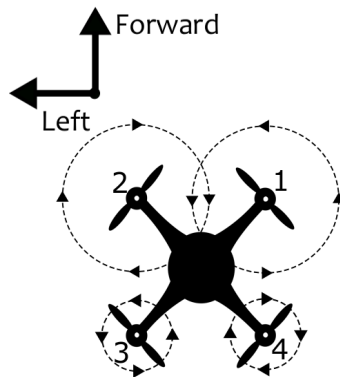
Plus config: pitch backward

Pitching | Tilting front and back

Lecture 2 | Principles of Flight



Cross config: pitch forward



Cross config: pitch backward

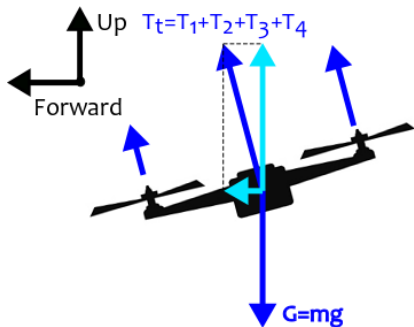
Moving forward and backwards



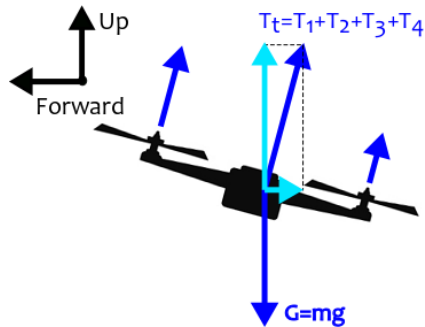
- ▶ The pitching rotation is coupled with translation on the forward/backward direction.
- ▶ When the quadrotor is pitching forward/backward it will also move forward/backward.



Moving forward and backwards



Forward Pitch and Acceleration



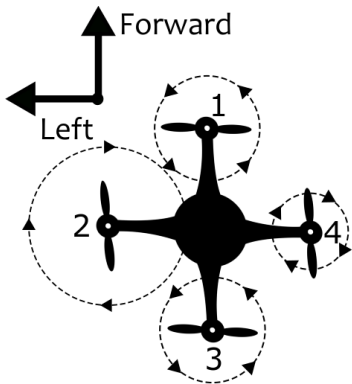
Backward pitch and Acceleration



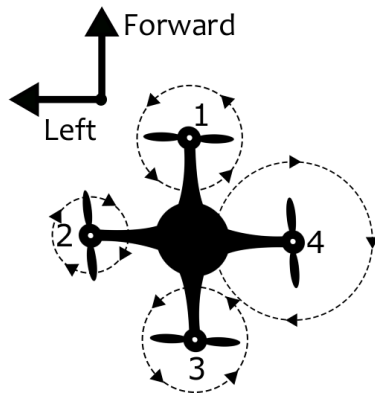
Rolling | Tilting sideways

- ▶ To roll, i.e. rotate around the forward-backward axis, we must create an unbalance in the left-side and right-side forces.
- ▶ Rolling right is done by decreasing the force in the right side and/or increasing in the left side
- ▶ Rolling left is done by decreasing the force in the left side and/or increasing in the right side

Rolling | Tilting sideways

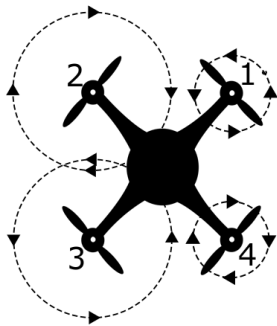


Plus config: Roll right

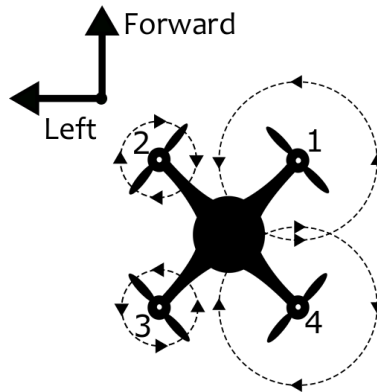


Plus config: Roll Left

Rolling | Tilting sideways



Cross config: Roll right



Cross config: Roll Left

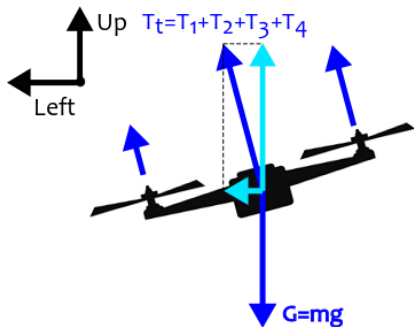
Moving left and right



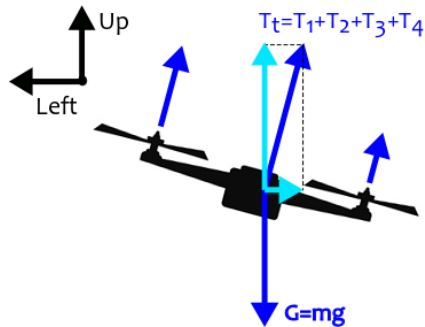
- ▶ The rolling rotation is coupled with translation on the left/right direction.
- ▶ When the quadrotor is rolling left/right it will also move left/right.



Moving left and right



Left Roll and Acceleration



Right Roll and Acceleration

Yawing | Changing heading



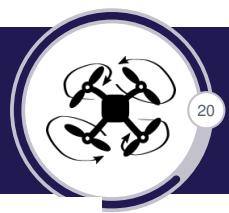
Yawing is rotation around around the up/down direction.

Heading stability

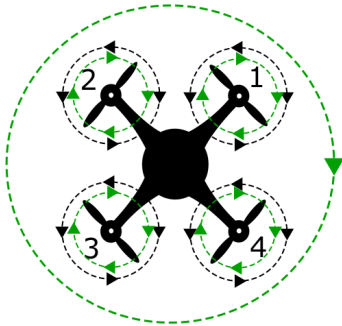


- ▶ Remember that rotating propellers are causing an opposite torque/turning effect on the frame. If all propellers would be rotating in the same direction, the frame would rotate around its up/down axis in the opposite direction, it would be spinning in place.
- ▶ The quadrotor has two types of propellers, such that they rotate in opposite direction in pairs, and the reaction effect is canceled.

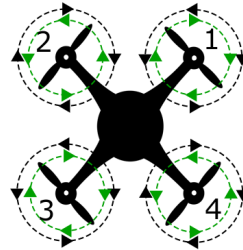
Yawing | Changing heading



20



All CCW propellers



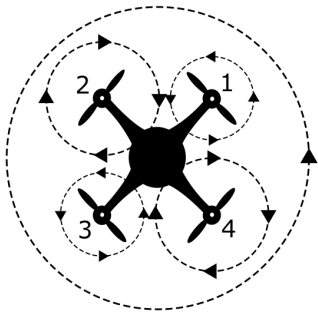
Two CW and two CCW propellers

Controlled Yawing

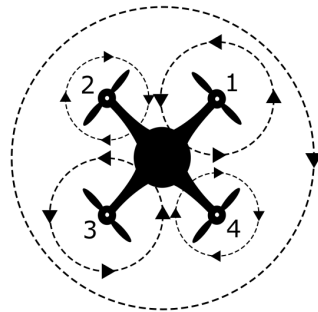


- ▶ To create a controlled CCW yawing rotation, the input is increased on the pair of CW propellers, and decreased on the CCW pair.
- ▶ To create a controlled CW yawing rotation, the input is increased on the pair of CCW propellers, and decreased on the CW pair.

Yawing | Changing heading



Yawing/Heading to the left (CCW as seen from the top)



Yawing/Heading to the right (CW as seen from the top)



Underactuated System

In summary:

- ▶ Pitching and forward/backward motion are coupled
- ▶ Rolling and left/right motion are coupled
- ▶ Up and down motion is independent
- ▶ Yawing (changing of heading) is independent