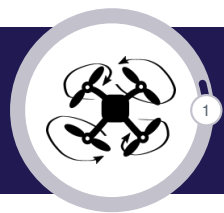


# Principles of Flight

## Lecture 2 | Principles of Flight



# Draft

Using its four propellers, how does the quadcopter 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

Lecture 2 | Principles of Flight



# Draft

# About Propellers

## Lecture 2 | Principles of Flight



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

# Draft



# About Propellers

## Lecture 2 | Principles of Flight

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

Draft



# About Propellers

## Lecture 2 | Principles of Flight

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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 rotation.
- ▶ 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)



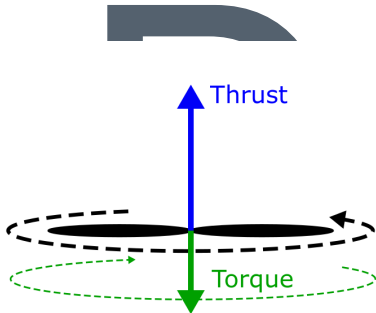
# About Propellers

## Lecture 2 | Principles of Flight

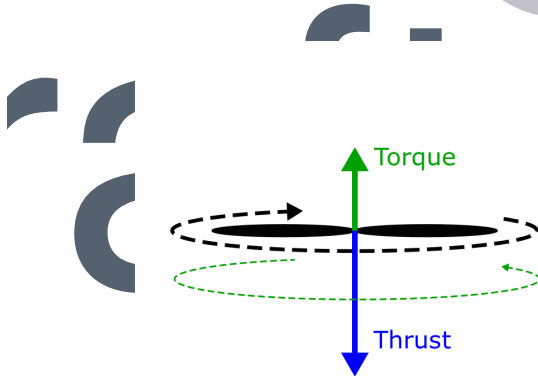
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- ▶ There are two types of propellers. Type 1, or right-handed propeller, produced thrust in the upward direction when rotating CCW. Type 2, or left-handed propeller, produces thrust in the upward direction when rotating CW. (CW and CCW defined as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

# Type 1 (CCW) Propellers

## Lecture 2 | Principles of Flight



Type 1 (CCW) Propeller turning CCW



Type 1 (CCW) Propeller turning CW



# Quadrotor Principles of Motion

## Lecture 2 | Principles of Flight

# Draft

- ▶ The quadrotor is an underactuated system
- ▶ There are 6 degrees of spatial freedom:
  - ▶ Translation DoF: up/down, forward/backwards, left/right
  - ▶ 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 ?

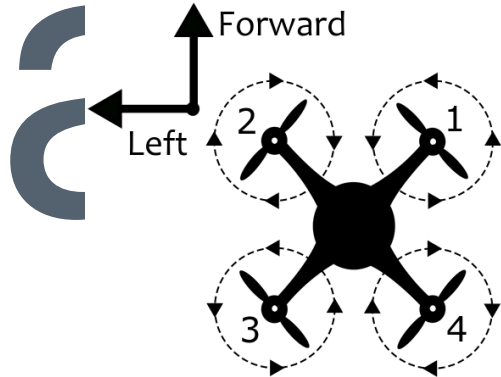
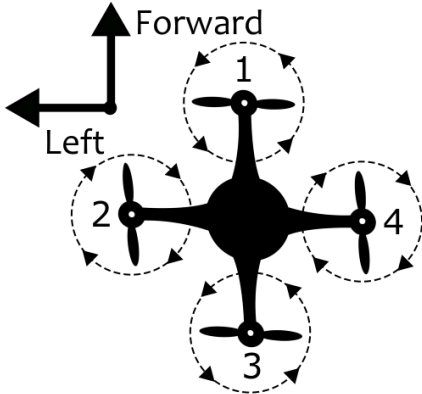


# Plus and Cross Configurations

## Lecture 2 | Principles of Flight



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



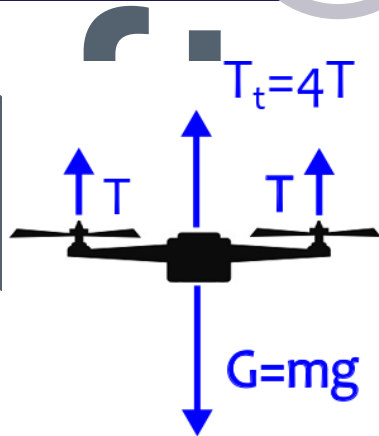


# Moving up and down

## Lecture 2 | Principles of Flight

# Drift

- ▶ 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 in the vertical direction 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

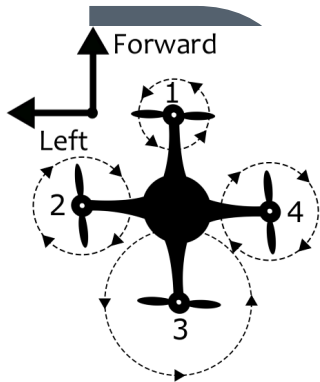
## Lecture 2 | Principles of Flight

# Draft

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

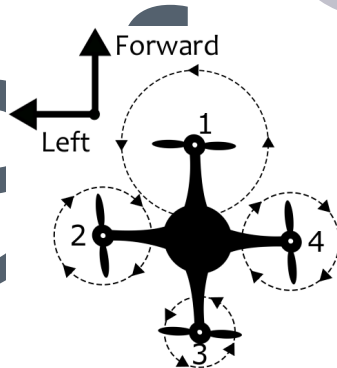
# Pitching | Tilting front and back

## Lecture 2 | Principles of Flight



Plus config: pitch forward

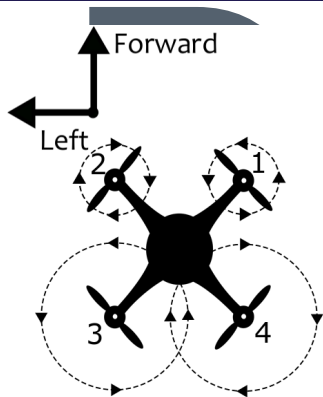
ra



Plus config: pitch backward

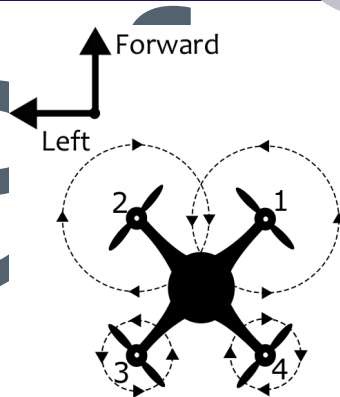
# Pitching | Tilting front and back

## Lecture 2 | Principles of Flight



Cross config: pitch forward

ra



Cross config: pitch backward



# Moving forward and backwards

## Lecture 2 | Principles of Flight

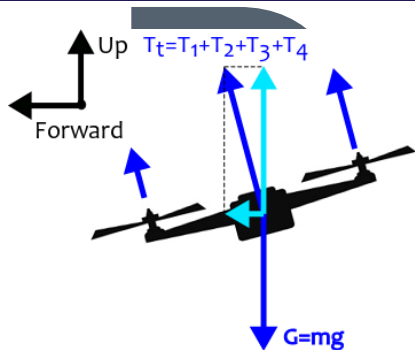
# Draft

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

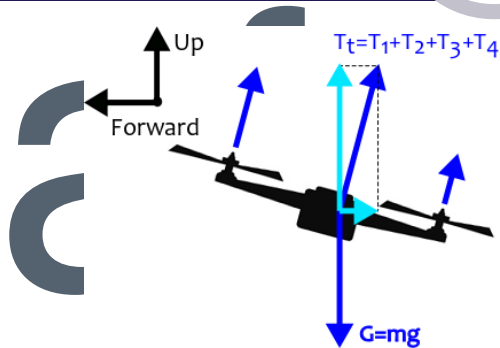


# Moving forward and backwards

## Lecture 2 | Principles of Flight



Forward Pitch and Acceleration



Backward pitch and Acceleration



# Rolling | Tilting sideways

## Lecture 2 | Principles of Flight

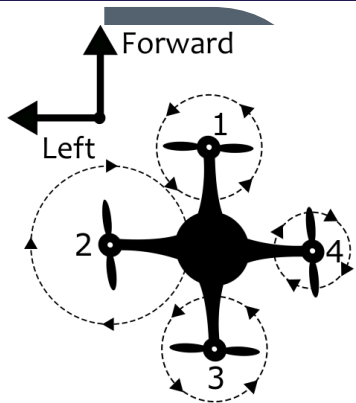
# Draft

- ▶ To roll i.e. rotate around the forward-backward axis, we must create an imbalance 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



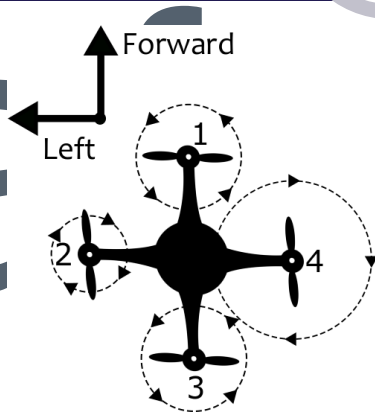
# Rolling | Tilting sideways

## Lecture 2 | Principles of Flight



Plus config: Roll right

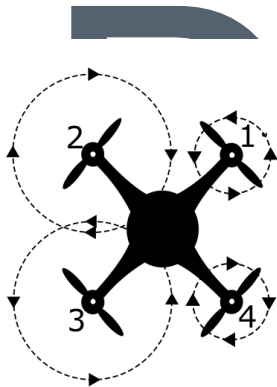
roll



Plus config: Roll Left

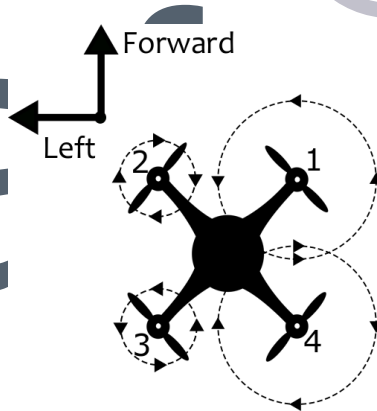
# Rolling | Tilting sideways

## Lecture 2 | Principles of Flight



Cross config: Roll right

roll



Cross config: Roll Left



# Moving left and right

## Lecture 2 | Principles of Flight

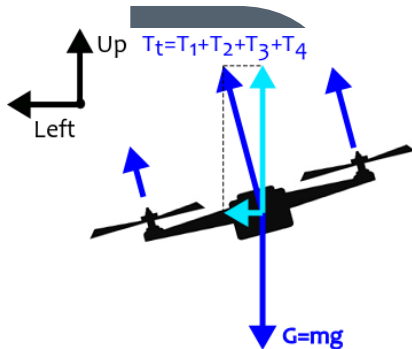
# Draft

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

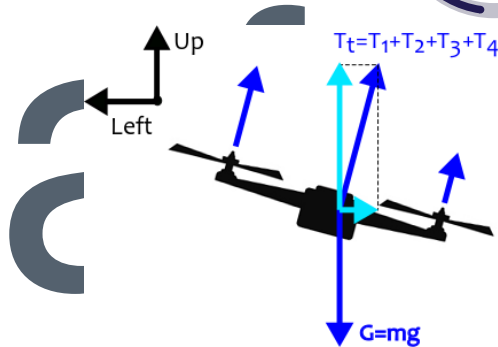


# Moving left and right

## Lecture 2 | Principles of Flight



Left Roll and Acceleration



Right Roll and Acceleration

# Yawing | Changing heading

Lecture 2 | Principles of Flight



# Draft

Yawing is rotation around the up-down direction.



# Heading stability

## Lecture 2 | Principles of Flight

# Draft

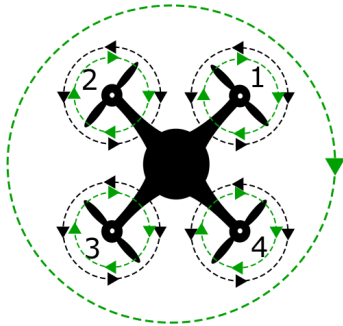
- ▶ Remember that rotating propellers are causing an opposite torque turning effect on the frame. If all propellers would be rotating in the same direction, the frame would rotate around the up/down axis in the opposite direction, it would be spinning in place.
- ▶ The quadrotor has two types of propellers,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

# Yawing | Changing heading

## Lecture 2 | Principles of Flight

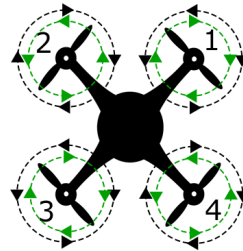


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All CCW propellers

re



Two CW and two CCW propellers



# Controlled Yawing

## Lecture 2 | Principles of Flight

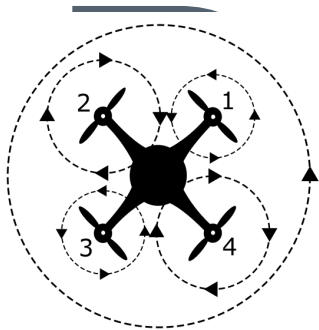
# Draft

- ▶ 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.



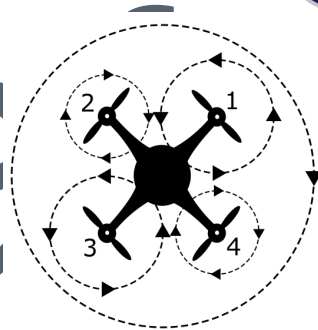
# Yawing | Changing heading

## Lecture 2 | Principles of Flight



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

ra



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



# Underactuated System

## Lecture 2 | Principles of Flight

# Draft

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

Onto the quiz !

