A Novel Helicopter Flight Control:
Attitude Command Velocity Hold

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Flight Theory

Flight has been a phenomenon that has intrigued even the most famous philosophers. Today, society has mastered the technique with different aircraft like airplanes, helicopters, and drones. These vehicles utilize the natural laws and physics to lift off the ground and accelerate. Specifically, a helicopter uses its main and tail rotors to accelerate off the ground and move in 3-dimensional space. To see how the rotors accomplish this, it is necessary to first look into how the aircraft generates lift.

Gravity holds the helicopter down to earth. Gravity exerts a force $F = M \cdot g$, where acceleration, $g$, is 9.8 meters per second squared, directed toward the center of the Earth. This force is proportional to the mass of the helicopter and load. To counteract this force, we need a force that is greater than the force of gravity and working in the opposite direction. This is where the main rotor comes in. The main rotor, when spinning, generates a lift greater than the force of gravity. However, there are some complications with this. If a helicopter only has a single rotor spinning in one direction, the torque generated by this rotor will cause the body of the helicopter to spin in the opposite direction. There are multiple ways to solve this issue. Most helicopters include a small tail rotor to counteract the torque produced by the main rotor. Some helicopters, like the CH-47F, have dual rotors that spin in opposite directions, effectively producing a net torque of zero. A more compact version of dual rotors is coaxial rotor produced by the Russian Kamov helicopter design bureau, where the two main rotors share the same axis of rotation. This can be seen in Lockheed Martin’s S-97 Raider.

Another complication is what happens when the helicopter is in the air. There are different ways the helicopter can move, forward or backward (positive and negative x-direction), left or right (positive and negative y-direction), and up or down (positive and negative z-direction. For going up and down it is simple. The pilot should be able to control the force produced by the main rotor to move up and down. More force from the main rotor will result in the helicopter moving up and a lower amount of force will result in the opposite.

The other two movements are based on the pitch and roll of the helicopter and the main rotor. Pitch and Roll are the rotational configuration of the helicopter based on a specific axis. If the head of the helicopter faces towards the positive x-direction, the pitch would be rotation of the y-axis and the roll would be the rotation around the x-axis. To simplify this, the pitch would signify the lowering and raising of the helicopter’s head. While the roll would signify the raising and lowering of the helicopter’s sides. This is very important in moving in a certain direction as it changes the angle of the force generated from the main rotor. For example, rotating the pitch of the helicopter would make it accessible to move in the positive and negative x-direction. Rotating the head downward changes the direction of the force that the main rotor creates to go slightly forward. That means that force not only has a z-direction, but also creates a force in the x-direction as well. To rotate the head down or up like this, the rotation on the y-axis of the main rotor is changed since the force coming off is parallel to the plane of the wings. The same concept applies to move right and left, however the axis of rotation is changed for the x-axis. To move the helicopter right and left, the main rotor must change its roll, which is changing its rotation on the x-axis.
Currently, the helicopter that has been described can move in all 6 directions. It can move left, right, up, down, forward, backward, and everything in between. However, no one wants to travel or should be traveling backwards to go from one place to another. The complication here is how to turn the helicopter such that the head of the helicopter faces the negative x-direction. This is where the rotation on the z-direction, or the Yaw, comes into play. To rotate in the z-direction, a rotational force needs to be created in the xy-plane. Coincidentally, one of the problems of the main rotor finishes the last area of movement. The torque that was created by the main rotor in the direction of rotation, can be used to rotate around the z-axis. Since the tail cancels out the torque by creating a force in the opposite direction of it, we can lessen that force slightly to rotate around that z-direction and turn the body of the helicopter 180 degrees. And if that force is greater than the torque, then the helicopter can turn 180 degrees in the opposite direction.

Inner and Outer Loop Control

Inner Loop Control

The inner loop stabilizes the dynamics of the helicopter associated with its angular velocities and Euler angles. The inner loop is governed by sensors which monitor the internal conditions of the helicopter using the IMU (Inertial Measurement Unit) to control outputs such as roll, pitch, yaw attitudes rates and accelerations. Some important flight control inputs are known as the cyclic stick, the collective lever, the anti-torque pedals and throttle.

Outer Loop Control

The outer loop controls the position of the unmanned system. It deals with the external conditions of the helicopter with functions such as airspeed, altitude and navigational information. Traditionally the outer loop controls are made out of PID or even proportional control laws. PID controllers allow us to change the actual command references and a transform to modify a command force.

Autopilot

An autopilot can be capable of many very time intensive tasks, helping the pilot focus on the overall status of the aircraft and flight. Autopilot is created through computer software; it is able to control the current position as well as the flight control system to guide the aircraft. The use of an autopilot helps automate the process of guiding and controlling the aircraft. Autopilots are used for maintaining an altitude, climbing or descending to an assigned altitude, turning to and maintaining an assigned heading, intercepting a course, guiding the aircraft between waypoints that make up a route programmed into an FMS, and flying a precision or non-precision approach.
Engineers vs Pilots:

Here are some important flight modes compared from an engineer and pilot point of view of how they work.

*Table 1: Flight modes of the PX4 flight stack: Engineer and Pilot perspective*

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<tr>
<th>Flight modes:</th>
<th>Engineers:</th>
<th>Pilots:</th>
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<tbody>
<tr>
<td><strong>Position mode</strong></td>
<td>The roll and pitch sticks control speed over ground in the left, right, forward and back direction, while the throttle controls speed of ascent and descent.</td>
<td>An easy to fly RC mode (safest manual mode for new fliers because the vehicle will stop when the sticks are centered)</td>
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<td><strong>Altitude mode</strong></td>
<td>The roll and pitch sticks control vehicle movement in the left-right, forward-backward direction while the yaw stick controls the rate of rotation over the horizontal speed and once again the throttle controls speed of ascent and descent.</td>
<td>Relatively easy to fly RC mode (safest non GPS manual mode, it is able to stabilize the vehicle when the sticks are released.</td>
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<td><strong>Stabilized mode</strong></td>
<td>The roll, pitch and throttle all do the same commands however when the sticks are released they return into a deadzone. The helicopter will level out and stop once the roll and pitch sticks are centered. The vehicle will maintain a hover as long as no other external forces are hitting it.</td>
<td>Stabilized mode stabilizes the multicopter when the RC control sticks are centered. To manually move/fly the vehicle you move the sticks outside of the center</td>
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**Inputs**

- **Cyclic** - determines air speed primarily, vertical speed secondarily (the cyclic stick controls the main rotor in order to change the helicopter’s direction moving it forward, back, up and down.)
- **Collective** - determines vertical speed primarily, air speed secondarily (the collective changes the pitch angle of all the main rotor blades collectively meaning when the collective input is made all the blades are changing equally causing the helicopter to increase and decrease the lift from the rotor.)
- **Yaw Pedals** - determines angle of aircraft parallel to the horizontal.
- **Throttle** – the throttle controls the power of the engine which is connected to the rotor by a transmission.
- **Inertial Measurement Unit (IMU)** deals with the position, velocity, acceleration.
  - Accelerometer - acceleration
  - Barometer - pressure, altitude (Baralt)
- Magnetometer - compass
- Gyroscope - position relative to horizontal
- GPS
  - External combined GPS/compass module
- Air speed sensor - Knots Indicated AirSpeed (KIAS)
- Air data computer
- Tachometer - measures rotational speed, can detect stalling

Outputs
- Yaw - pivot around main rotor
- Pitch - nose down and up motion
- Roll - side to side motion
- Electrohydraulic Servo Valve (EHSV) - the electrical operated valve that controls how the hydraulic fluid is sent to an actuator, providing precise control of position, velocity, pressure and force with good post movement damping.
- Swash plate - the device that translates input through the helicopter flight control to motion of the main rotor blades.
- Rotor head - joins the blades to the shaft, cyclic and collective mechanics.

Control Theory

In control theory, the **plant** is the system whose behavior we are trying to control. The goal of a control system is to be able to provide a setpoint that we want the system to maintain and have the plant’s output successfully remain at that setpoint. One way to achieve this is through a feedback control loop. In a feedback control system, the output of the plant is fed back (via a sensor) to the input along with the **setpoint** or **reference** output. The difference between the setpoint and the plant output is then fed into a **controller** which uses this error to produce an appropriate output that then becomes the input of the plant. The goal of a control system is to minimize this error while also keeping the system robust, i.e. resilient to disturbances and noise. Disturbances are aspects of the environment that can affect the output of the system, such as wind and friction. Noise is any random signal that is picked up by a sensor that may cause the sensor output to differ from the sensor input, i.e. the “real” value of a certain signal. The sensitivity of the system to noise and disturbances must be minimized, which can be attained through modification of the gains. Gains are any multiplicative factor applied to a certain signal.

In more sophisticated systems, there may be multiple inputs and multiple outputs, These are known as MIMO systems. A helicopter or drone is one such system. In these systems, different sensors “close the loop”, i.e. feedback, on different outputs.
Current PX4 Flight Modes

**Position:**
- Description: When sticks are centered, the aircraft (drone) hovers at a fixed GPS position and altitude.
- Sensors required: GPS, barometer (baralt), gyroscope

**Altitude:**
- Description: When sticks are centered, the aircraft maintains a fixed altitude but its x,y position might change due to wind.
- Sensors required: barometer (baralt), gyroscope

**Stabilized:**
- Description: Centered sticks only keep the vehicle level, but position is not stabilized.
- Sensors required: gyroscope

Attitude Command Velocity Hold

**High Level Design**

The pilot uses the control sticks to change the attitude of the aircraft. When the sticks are centered, the aircraft should move at a constant horizontal velocity determined by the velocity at the time the sticks were engaged. As such, the sticks should have a decently large dead zone. The autopilot uses this reference velocity to control the output velocity of the aircraft. The output velocity is fed to the autopilot via GPS, air data, and/or ground reference speed (where possible). This is the outer loop of control. The inner loop of control feeds back velocity and position data to keep the aircraft stable at all times.

**Sensors**

The inner control loop is used to keep the aircraft stable.
- **Inner Loop Control Sensors** -
  - IMU
    - Accelerometer - acceleration
    - Barometer - pressure, altitude (Baralt)
    - Magnetometer - compass
    - Gyroscope - position relative to horizontal

The outer control loop is used as the desired output for the ACVH controller.
- **Outer Loop Control Sensors** -
  - Navigation - GPS/compass module
- Radar - radar altimeter measures the altitude above the terrain beneath the aircraft timing how long it takes a beam of radio waves to travel all the way to ground and back.
- Reference to ground speed, or indicated air speed

Control Loop

![Control Loop Diagram](image)

**Figure 1: High-level overview of ACVH flight mode**

**Motivation**

From a pilot’s perspective, this flight mode is useful for operation in wide open spaces and over large distances. It allows the pilot to not have to constantly engage the pitch and roll sticks and throttle, only when he/she wants to change the direction or slow down. It is not a flight mode suitable for intricate maneuvering in tight areas. It is quite similar to the PX4 Position flight mode, in that it maintains a fixed altitude. However, instead of maintaining a fixed GPS position as in Position flight mode, ACVH will maintain a fixed velocity.
Reference

(1) https://link.springer.com/chapter/10.1007/978-0-85729-635-1_7
(2) https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/advanced_aviationics_handbook/media/aah_ch04.pdf
(3) https://link.springer.com/chapter/10.1007/978-0-85729-635-1_8
(4) https://www.rotorandwing.com/2013/06/01/automatic-flight-control-systems/
(6) https://docs.px4.io/master/en/flight_modes/#key_position_fixed