Large electric radio-controlled model helicopters: An engineering perspective

George Coulouris

28 February 2010

Abstract

Radio-controlled model helicopters are rich in physics, electrical engineering, aerodynamics, control theory, and optimization with constraints. I will present a high level, top down overview of the various systems and how they interact. Some familiarity with RC, helicopter mechanics and basic physics and electronics is assumed. I have provided hyperlinks to relevant external articles when necessary.

Components and dependencies

- The battery supplies electrical power to the Electronic Speed Control (ESC) and Battery Eliminator Circuit (BEC)
- The ESC supplies electrical power to the motor
- The motor supplies mechanical power to the main and tail rotors
- The BEC supplies electrical power to the receiver (RX)
- The RX supplies electrical power and pilot's commands to swash servos and the gyro
- The swash servos control cyclic and collective pitch
- The gyro is connected to the tail rotor servo
- The tail rotor servo controls tail rotor pitch

Part I

Feedback control systems

Every helicopter has at least 5 feedback control mechanisms, so it's worthwhile to list them up front.

Gyro

The gyro is what people usually think of when it comes to feedback control systems on helicopters. The gyro modulates the tail rotor blade pitch to make the actual yaw rate (as measured by an angular rate sensor) match the yaw rate commanded by the pilot. In this sense, the gyro is an active component; the pilot specifies a desired outcome and the gyro takes care of the rest. As a result, the pilot's commands on the stick do not necessarily have an intuitive relationship with the deflection of the tail rotor servo.

A gyro in rate mode is a proportional controller. A a gyro in heading hold (HH) mode is a PID controller, that is, the sensed angular rates are integrated to find angular position. This is how it "knows" where the tail is.

If the gyro gain is too high, the tail will oscillate. If the gyro gain is too low, the tail will not hold well.

Governor

The governor is part of the ESC and is the second common feedback loop on a helicopter. The governor tries to maintain a constant motor RPM, analogous to how a car's cruise control tries to maintain a constant speed. Like the gyro, the governor is an active component; the pilot specifies an outcome (desired RPM), and the governor takes care of the rest. Similarly, the pilot is no longer in direct control of the throttle.

It's good to start by selecting a power system that achieves the desired headspeed at 80% throttle; the governor needs some headroom to allow for:

- the varying loads imposed by the pilot's commands
- lower voltage as the battery discharges

The governor often has its own gain setting. Note that the governor's control loop can interact with that of the tail gyro in undesirable ways, causing resonance and tail oscillation.

Flybar

The flybar operates as a rate damper for the cyclic; that is, if an external force tries to tilt the rotor disc, the flybar will produce negative feedback proportional to the external force. Flybarless systems achieve this same goal using 3-axis gyros and PID loops.

Servos

Servos are active components in the sense that the pilot specifies a desired outcome (a deflection, in degrees) and the servo takes care of the rest. Servos maintain the commanded deflection regardless of varying external mechanical loads.

When connected directly to the RX, as is the case for swash servos, there is an intuitive relationship between the pilot's commands on the sticks and the swashplate. This is no longer the case when flybarless stabilization systems are used, since gyros are again interposed between the pilot and the control surfaces.

Analog servos have proportional feedback and digital servos have PID control. Control signals are delivered from the RX by pulse width modulation (PWM).

Servo output is rotary, but for helicopter applications, we want linear output. For small deflections, motion is approximately linear (since $\sin(\theta) \approx \theta$), so nonlinearity is generally not a problem.

Servos of the correct size should be chosen; overkill wastes weight and power.

BEC

The BEC is a DC to DC switching regulator. It tries to maintain a constant output voltage despite varying electrical loads. 5-6V output voltages are common. The BEC must be able to supply sufficient current, otherwise brownouts can occur.

Part II

Other systems

Motor

- 3 phase brushless DC electric motor
- Motor constants, such as RPM per volt (KV) are usually published.
- Dyno data is hard to come by.

Overall, brushless motors are typically around 85-90% efficient. They are less efficient at very low loads and at very high loads.

ESC

The electronic speed controller:

- controls motor RPM by PWM
- is aware of the motor's phase (and, consequently, RPM) by back EMF
- is more efficient at high power levels than at low power levels

Battery

- XsYp: X cells in series, Y cells in parallel
- C rating: a measure of current in terms of the battery's capacity. e.g. a 30C 2200mAh pack can produce a maximum discharge rate of $30\times2.2 = 66$ amps
- lipos die if they go below 3V/cell; a rule of thumb to prevent overdischarging is to never take out more than 80% of the pack's rated capacity.
- lipos must not be charged past 4.2V/cell; get a good charger and practice safe charging habits.
- nominal voltage is 3.7V/cell.
- lipos should be stored at 50% state of charge (SOC)
- Battery choices are constrained by CG, desired flight time, and overall all-up weight (AUW).

Power system design

It takes a certain amount of power to deliver a desired headspeed. How does one pick the variables of the power system optimally?

- battery voltage × motor KV × pinion size ÷ main gear size = main rotor headspeed
- There typically aren't many choices for the main gear.
- Higher voltage systems are more efficient. Batteries have an internal resistance. $v = ir$ and $p = iv$, so $p = i^2r$, so, for a given amount of power, if you double the voltage and halve the current, the resistive losses drop by $\frac{1}{4}$. Less resistive loss = less heat in your battery = longer battery lifetimes.
- After the pack voltage is determined, a motor with the appropriate KV is chosen.
- Finally, the headspeed can be fine-tuned by selecting the pinion.

Part III

Radio operation

The transmitter (TX) can be viewed as a pipeline of mixes and transformations from pilot inputs to servo outputs. For example, the the vertical axis of the left stick drives the throttle and collective pitch according to the throttle and pitch curves. The desired cyclic and collective pitches are combined into swash servo deflections with cyclic/collective pitch mixing (CCPM). A more complete list includes:

- per-servo subtrim
- CCPM mixing
- swash mixes
- endpoint adjustment
- dual rates and exponential
- trim settings

There are switches for:

- normal/idle 1/idle 2; toggles in throttle and pitch curves for different flight regimes
- rate/HH mode; toggles the gain on the gyro
- dual rates/expo; generally used to soften control inputs for warmup flights
- throttle hold; turns motor on and off

Part IV

Mechanical considerations

Helicopters are filled with vibrations; everything must be secured.

- All metal-to-metal joints require loctite.
- Wires should be strapped down.
- Electronics should be velcroed down or strapped down with foam padding underneath.
- Antennas should be stress-relieved to reduce vibration to the extent that it is possible.

There are three recurring themes when setting up helicopter mechanics:

- Equal throws. You generally want the pitch ranges to be symmetric around zero.
- Linearity. If linkages are perpendicular throughout, you will maximize linearity.

- Resolution. The radio has a finite number of steps. Therefore, to maximize resolution, you want to connect linkage rods to the smallest radius on the servo output arm that maximizes travel, as opposed to, say, using the largest hole on the arm and then adjusting the endpoints in the radio.

For example, when setting up the head, one typically works from the bottom up, from the servos to the blade grips:

- collective at center stick
- swash servo arms at 90 degrees
- swashplate should be level
- washout mixer arms should be level
- flybar cage should be level
- Bell-Hiller mixing arms should be level
- blade grips should read zero pitch

There are further constraints that the swash should be centered properly and should not hit either the washout or the top bearing block. At mid stick, blade pitches must zero, and more importantly, must be equal to each other to ensure good blade tracking.

Similarly, when setting up the tail:

- Adjust linkage such that the helicopter is trimmed (i.e. tail does not drift) in rate mode
- Adjust gyro endpoints such that there is no binding
- Adjust gyro gain such that there is no oscillation
- Note that wire pushrods can flex and vibrate; carbon fiber rods are preferable

Part V

Electrical considerations

- Belt-driven tail rotors systems can behave like Van de Graaf generators; the resulting static discharge can interfere with the radio. Ensure that there is electrical continuity throughout.
- Carbon fiber frames are electrically conductive and often have sharp edges that can wear through insulation, leading to short circuits.

Part VI

Flight dynamics

Helicopter flying is an exercise in vectors. Collective pitch lets you change the sign and magnitude of the lift vector. Cyclic pitch lets you change the direction of the lift vector, and consequently, the pitch and roll rates and translational velocity. The tail rotor allows you to rotate around the z axis. In general, the rotors like air that is not turbulent.

- Ground effect; there is a cushion of air near the ground.
- Vortex ring state; you can get sucked in to your own downwash.
- Translational lift; the faster you fly, the more the rotor disc behaves like an airplane wing. This applies to the tail rotor as well; in fast forward flight (FFF), the tail will weathervane. If the gyro is in rate mode, you can fly banked turns with elevator and aileron, like an airplane.
- Phasing; on most rotorheads, there is a 90 degree lag due to gyroscopic precession.

For full-scale helicopters in forward flight, the advancing blade generates more lift than the retreating blade; this led to the introduction of flapping hinges. Blade flapping changes the location of the center of mass; conservation of angular momentum then causes the blade to accelerate or decelerate. This led to the development of lead-lag hinges. In contrast, model helicopters generally have relatively simple rotorheads with a teetering hinge; when one blade flaps up, the other flaps down, so the center of mass does not change, so the blades do not require flapping or lead-lag hinges.

- FAA Rotorcraft Flying Handbook