UAS Autopilot

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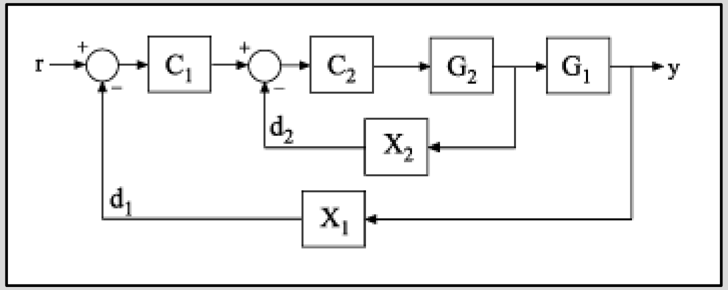
Outline

- Theory
  - Guidance
  - Navigation
  - Control
- Hardware
  - Setup
  - Testing
- Software
  - Choices
  - Use
  - Testing
- Integration



Northrop Grumman X-47B: Autonomous aerial refueling

Theory

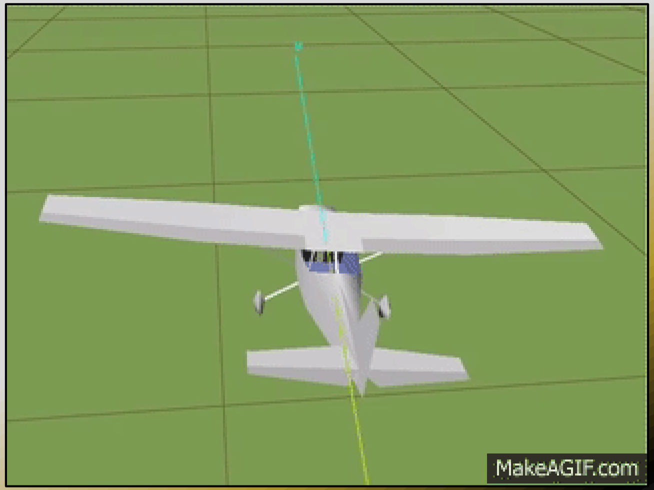
- Goal: Control full non-linear EOMs of your 6 DoF system (aircraft)
- How :
  - Identify behavior of your aircraft: Parameter Identification
  - Provide controller for each dynamic mode that doesn't behave how you want it to (Dutch roll, phugoid, etc.)
  - Provide controller for guidance/navigation
    - Navigation: Where you are
    - Guidance: Where you're going
  - Ground station software rolls all this into one package, with most of the work already done for you, though it is not necessarily all-encompassing

Theory – Parameter Identification

- Goal: Find stability derivatives
  - Relates the movement of a control surface, CG position shift, velocity, etc. to the reaction that the aircraft will have
  - Difficult to calculate by hand
- Predicted values – will need to coordinate values from several different sources
  - CFD
  - CAD
  - AVL
- Measured values
  - Flight tests: Accelerometers and airspeed are most common data
  - Wind tunnel: May be able to provide some data

Theory – Controllers

- Goal: Provide controller for each dynamic mode that doesn't behave how you want it to (Dutch roll, phugoid, etc.)
- Generally use linearized EOMs and successive loop closure to create controllers for each system
  - Define system inputs and outputs (e.g., elevator signal input, AoA output)
  - PID Control in Ground Station software
- Can implement additional filters



Theory – Navigation

- Goal: Know where you are
- Sources
  - GNSS (GPS, GLONASS, Galileo, BeiDou)
    - RTK for more precise positioning – requires extra hardware
  - Inertial (Based on accelerometers and/or gyros)
  - Magnetic Compass (Magnetometer)
  - Barometer
  - Sensor fusion – Uses all of the above, with Kalman filtering, to provide a better solution to the problem
    - Not trivial
    - Built in to ground control software/firmware

Theory – Guidance

- Goal: Get where you want to go
- Driven by cross-track error: How far to the left or right (or below/above) are you of your desired track?
  - Generally a controller gain set to define how “aggressively” you want to get to your desired track
  - May be limited by bank angle limit, airspeed, or other factors
  - How close is close enough?
    - Is it the same in all phases of your flight plan?

Hardware

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WARNING

None of us are equipped to deal with a severed finger (duct tape can only go so far). Please take steps to ensure that you stay safe when conducting bench, testbed, or production aircraft tests. Ideally, perform all tests *without* a propeller attached. Only attach a propeller once you are read to go fly.

Hardware

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- A hardware solution that will allow for easy integration and that will allow you to connect servos, ESCs, radio receiver, etc., is desirable
- Pixhawk is the cheapest
- Pixhawk 2 is newer, with better connectors
- Pixhawk 4 the newest, with same connector types as Pixhawk 2
- Some projects based on Raspberry Pi
- Additional “nice to have” (might be required, depending on mission design) components
  - External GPS
  - Pitot-static system

Hardware

- Pixhawk
  - Onboard IMU (accelerometers, gyros, barometer, magnetometer)
  - Lots of extra connectivity options
    - I2C
    - UART
    - CAN
    - ADC
    - …
- Telemetry/control radio is nice to have
- Each team already working?

Hardware – Setup

- Not going to describe each individual step here
  - Lots of tutorials available online
  - Not enough time
- Install Pixhawk unit as near to the CG as possible (arrow facing forward for all software defaults)
  - Forward-aft adjustment easiest
  - Vertical also important, but less variation
  - Foam or rubber to dampen vibrations

- Attach all electrical connections
  - Verify servo connections not reversed anywhere (very common)
  - Don’t stretch wires taut
  - Try to avoid a rat’s nest

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Hardware – Setup

- Use MAIN OUT for all connections if possible (this provides hardware failsafes)
- Mapping between servo channels and Mission Planner
  - Main Out 1 = Servo1
  - Main Out 2 = Servo2
  - …
  - Aux Out 1 = Servo9
  - Aux Out 2 = Servo10
  - …
- Do not use RCIN for anything other than PPM receiver connection

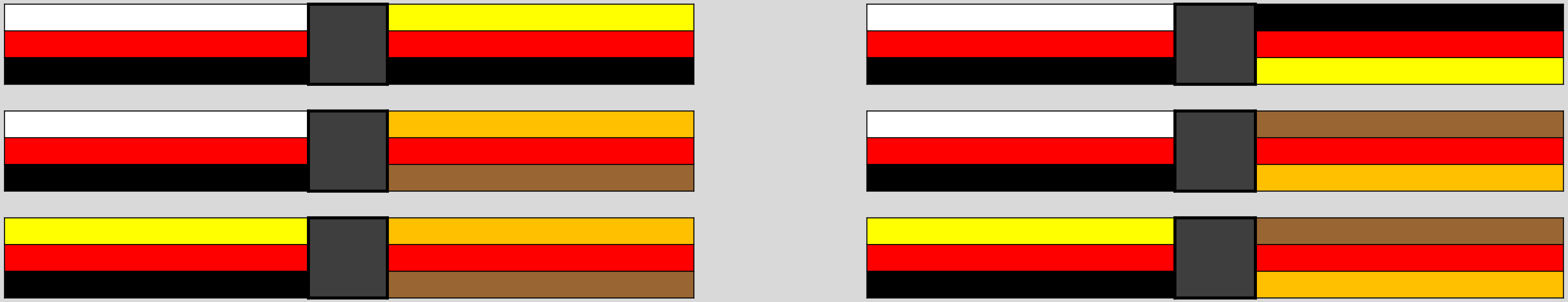
Hardware – Power

- Three main power consumers on a basic plane
  - Motor (a LOT of power)
  - Servos (some power)
  - Pixhawk (really not very much power)
- Other power consumers
  - Other on-board processors (GPUs, air quality sensor pack?)
  - Transmitters (video and telemetry)
- Power sources
  - Pixhawk power brick
    - Only powers "brains", NOT the servo rail
  - ESC's BEC, standalone BEC, or secondary battery
    - Needed to power servo rail
    - Operating voltage of BEC/battery must match servos

Hardware – Servo Wires

White/Yellow/Orange: PWM Signal   Red: +VDC   Black/Brown: -VDC

RIGHT   WRONG



- Easiest way to avoid issues is to standardize all servos and wires, but that takes some additional planning
- Custom-length servo wires take longer to integrate but probably will save some weight and space

Hardware – Testing

- Bench testing highly recommended before installation in airframe
  - Chances are your final aircraft will not be ready for integration before you get all of your autopilot components together
  - Pre-assemble/test as much of the system as possible
    - Include as much of the actual system you will use
      - Servo extensions
      - Cameras
      - Transmitters
    - A couple of pieces of wood or foam will work – it need not be complex
  - Allow access to Pixhawk and other components to check connections or current conditions
    - Much harder to dig around inside of a fuselage and trace wires

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Hardware – Testing

- Testbed aircraft
  - Use to test/practice…
    - Assembly/start-up steps
    - Ground station practice
    - Flight modes
    - Sensors (airspeed, cameras)
  - Can use to create or refine…
    - Stability models and tuning
    - Methods for data collection
  - Use a known stable design
    - Mitigate risk of using the autopilot the first time in your only aircraft

Software – Choices

- Lots of options, especially depending on platform; can use a tablet or desktop (laptop) based system
  - Mission Planner*
  - APM Planner 2
  - QGroundControl
  - UgCS
- No “right” answer; download one or all of them, they are all free
- Spend some time using each one
  - Steep learning curve for new users
  - Best way to learn it is to use it

*I’ll be using links to this software. QGC has analogs to most of the links I provide.

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Software – Uses

- Control
  - Mission Planning
    - Waypoints
    - Vertical (profile) planning
    - Point of interest (loiter, circle)
  - Component integration
    - Cameras
    - Sensors
  - Joystick (if you want)
- Telemetry
  - Real-time info on location, speed, ETA, etc.
  - Diagnostic/status info

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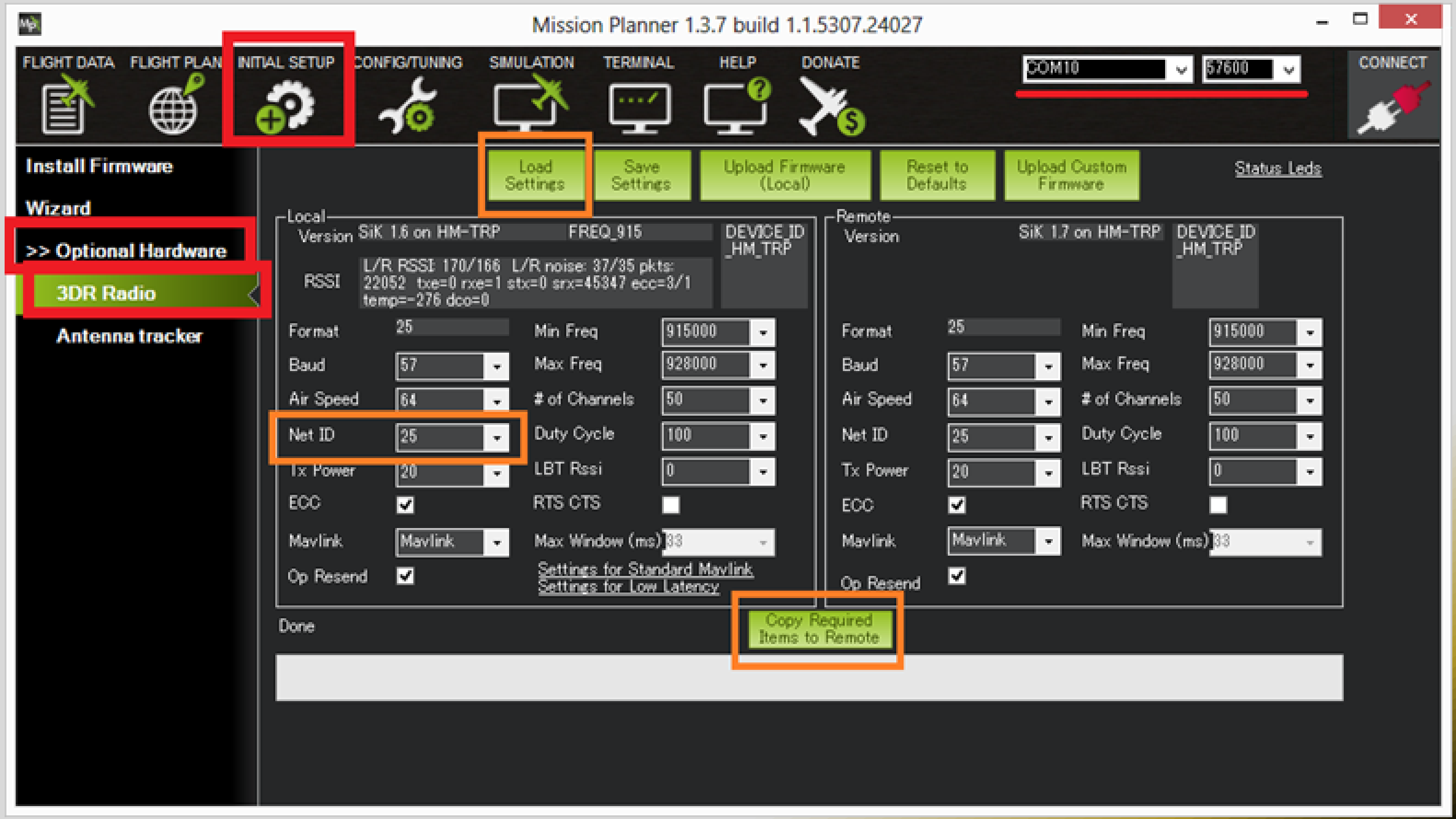
Software – Uses

- Telemetry channels
  - To prevent interference with other teams
- Steps
  1. Plug both radios in (one to GCS via USB, other to Pixhawk telem port)*
  2. Initial Setup → Optional Hardware → SiK Radio
  3. "Load Settings"
  4. Change Net ID
  5. Copy Req'd to Remote

*Alternate: Connect each to GCS via USB independently, then change Net ID



*Older version of Mission Planner shown

Software – Uses

- Mission Planner Setup
  - Units (make sure they match what you are designing in)
  - Telemetry rates
    - Higher rate = finer data, may lose some data over telemetry (depends on aircraft configuration, geography, etc.)
  - Log Path
    - To find telemetry logs after flight
  - Advanced mode
    - Enables full parameter list and tree

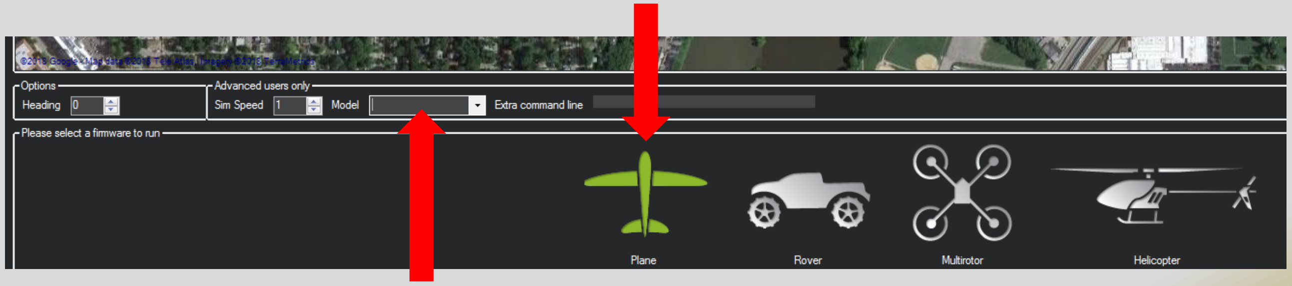
Software – Uses

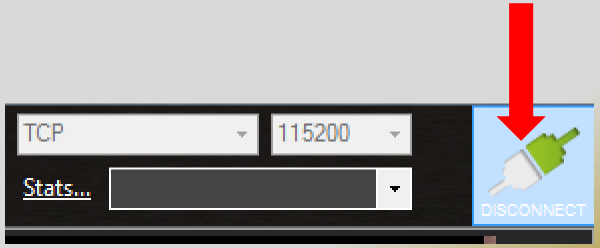
- Simulation
  - Standard "plane" uses default gain values to guess how your airplane will fly – you need to update the defaults to be able to simulate your airplane without it connected
  - With your real plane connected (via USB or telemetry), see how servos react, cameras point
  - Will not be perfect; fidelity is fairly low
  - Use to test out new mission profiles
  - Use to teach additional team members to operate your plane

> **Tip**
>
> Crashing simulated planes is a lot cheaper than crashing real ones!

Software – Uses

- Simulation
  - Click "Simulation"
  - Select Model
  - Click "Plane"
  - Will load SITL items
  - Initializes a simulated plane
  - Can interact just as if it was a real plane
    - Load waypoints
    - In-situ mission (takeoff, loiter, point camera, etc.)
    - Change parameters on-the-fly
  - Disconnect "TCP" to stop





Software – Uses

- A word on waypoint definition
  - Defined as a 3-Dimensional point
    - Latitude, Longitude, Altitude
  - Built-in Lat-Long “tolerance”
    - Radius (NOT diameter)
    - As soon as the aircraft is within radius, the next waypoint is sequenced
  - Be careful with altitude definition
    - Absolute = MSL
    - Terrain = AGL
    - Relative = Compared to Home point

Software – Testing

- Same pretense as hardware testing: Know what you're getting into and practice it
- Set up Pixhawk to be able to talk to your ground station
- Test out different modes in testbed
  - Use ground station and RC transmitter to change modes
- Understand what the software is doing; don't just assume it will do what you want it to
- Know how to set the failsafe and what to expect if it takes effect
- Always be ready to take control back from the autopilot
  - Know where the "Manual" or "Override" switch is and how to use it

Integration

- Probably the hardest part of all of this (in the build process), but the least material to talk about
  - All of the airplanes are different
  - All of the missions are different
  - Must relate specific performance of each given system to your KPIs and decide what needs done first
- This will take you longer than you think, unless you have specifically designed how to integrate each individual component (down to servo wires) into your airframe
  - Generally there is ample tape used in this process ☹

Integration

- Make sure you can access Pixhawk to plug components in
- Install components individually
    - Servos
    - ESC
    - Camera(s)
    - Pitot-static tube
    - Lidar/other rangefinder
    - GPS Antenna
    - Pixhawk unit (and associated accessories)
    - Radio transceivers

Integration

- Make sure everything works individually before plugging in to Pixhawk
  - Common to think the Pixhawk is malfunctioning, but there is actually a servo extension installed upside down in line
  - Use a servo tester
  - Ensure prop rotation direction is correct (also a common “Oops” moment, but sometimes fixable with ESC programming)
- Plug in all components to Pixhawk
  - Should already have wireless ground control connection made, right?
  - Take care with the tiny connectors (pins are easy to bend, plastic is brittle)
- Go through start-up process

Integration

- Go fly!

  NOTE: It is highly recommended to fly by hand initially, then switch modes to "Stabilize" to check that the system works

  - Arm the system
  - Launch and climb to a safe altitude
  - Engage "Stabilize" or "FBW" mode
  - Always be ready to remove control from the autopilot
  - Mission Planner includes an "Autotune" mode that is supposed to set some of the PID values automatically; trust but verify is a good principle here.
  - For the rest of the controller values, set them individually
    - May be able to get a good first guess from community-submitted values
    - Only use a similarly sized aircraft if its weight and configuration is also similar

Integration

- Flight Modes
  - Control specifics of what your aircraft is doing
    - Can pre-plan with "Auto"
      - Set up automated takeoff (even hand launching)
      - Follow waypoints
      - Loiter over a specific point for a specified amount of time
      - Drop a payload?
      - Return to launch
      - Automated landing
    - Can hand-fly with "Stabilize", "FBW", or "Cruise" (or "Manual", obviously)
    - Ad-hoc automated modes, "Loiter" and "Circle"
  - Lots of options available, and lots more you can add and customize

Integration

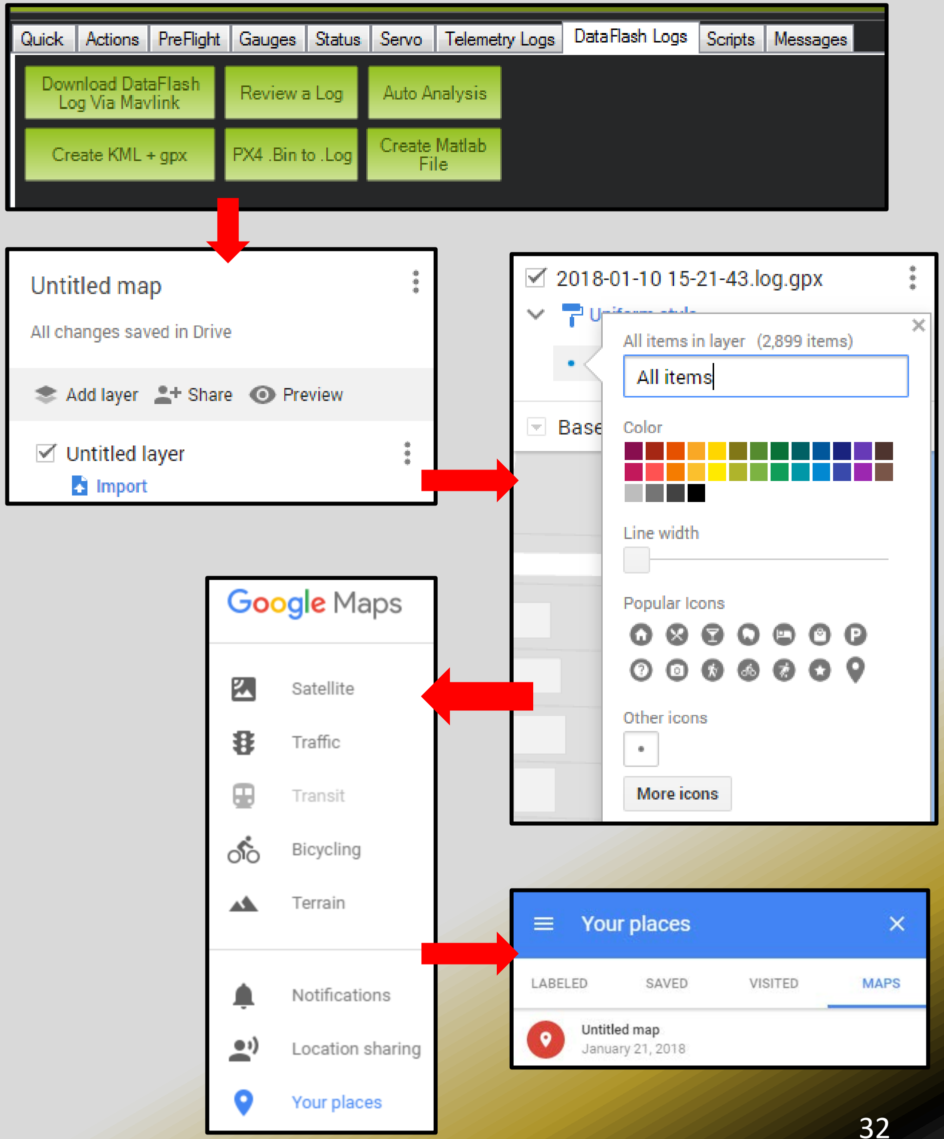
- Built-in safety
  - [Envelope protection]
    - Prevents stall, overspeed, or other undesirable conditions
    - “Free insurance”
    - Once again, trust but verify its operation
  - [Geo-fencing]
    - Keep your airplane IN a specific area (Flight box)
    - Keep your airplane OUT of a specific area (Airports, sporting events, etc.)
  - [Terrain following]
    - Might be useful in mountains or other adverse terrain
    - Might be less useful on the ocean

Integration

- Debrief
  - Use [data collected during flight]
    - Prove a parameter is met
      - Altitude during cruise
      - GPS location of payload drop
      - Flight time
      - Battery capacity (mAh) consumed
    - See if there are any improvements to be made
      - Change controller gains
      - Change climb-out angle
      - Change landing approach speed
  - Discuss what went right
  - Discuss anything that went poorly
    - Use data to analyze and correct for next flight

Integration

- Debrief
  - View 3D flightpath
    - Convert dataflash log to GPX
    - Upload GPX to google.com/mymaps
      - Under Untitled Layer → Import
    - Uniform Style → Whatever icon you want → Smallest Line Width
    - Save
    - Go to maps.google.com
    - Click on Your places → Maps
    - Select the map you generated
    - Click 3D View
  - This used to be a lot easier with Google Earth…



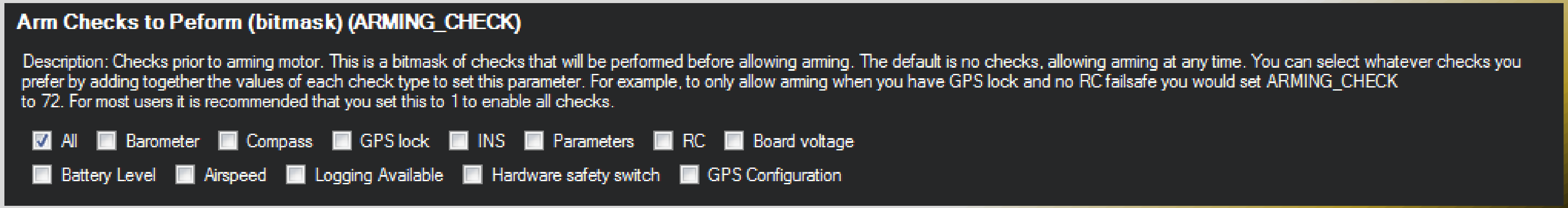
Integration

Integration

- Use your now fully-autopilot-enabled aircraft to carry out an extensive flight test program
- Then deliver vaccines, or look for lost hikers

Integration – Common Issues

- Can’t connect Mission Planner to Pixhawk over USB
  - Check COM port assignment in Windows Device Manager
- Can’t connect Mission Planner to Pixhawk over Radio
  - Check both radios have the same Net ID
- Servos won’t work
  - Check servo wires, make sure they are receiving power (5-6 VDC)
  - Check orientation of wires at Pixhawk and any connections
  - Check if channels enabled when A/C Unsafe and/or Not Armed
- Aircraft won’t arm
  - Investigate Arm Checks parameter – If you don’t have an airspeed sensor, but require one to arm, you will have issues



Homework for teams

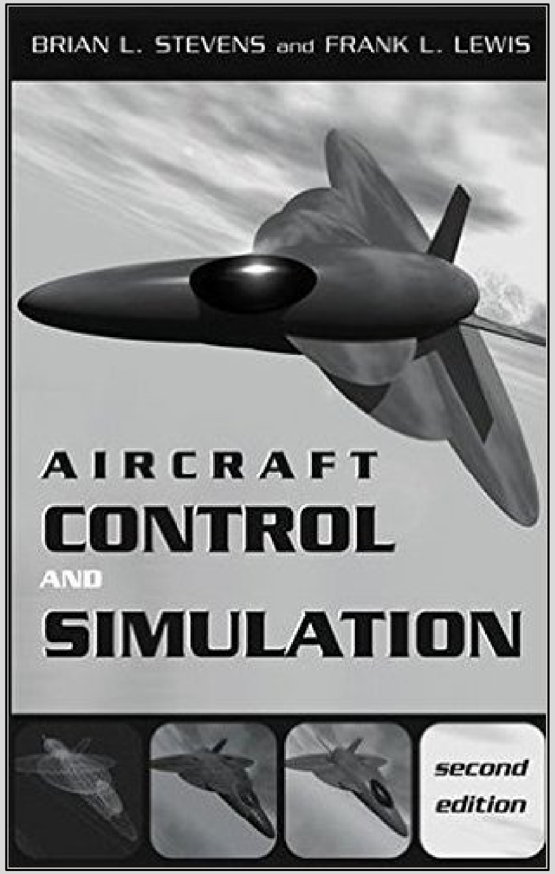
- Set your telemetry radio to the following channels

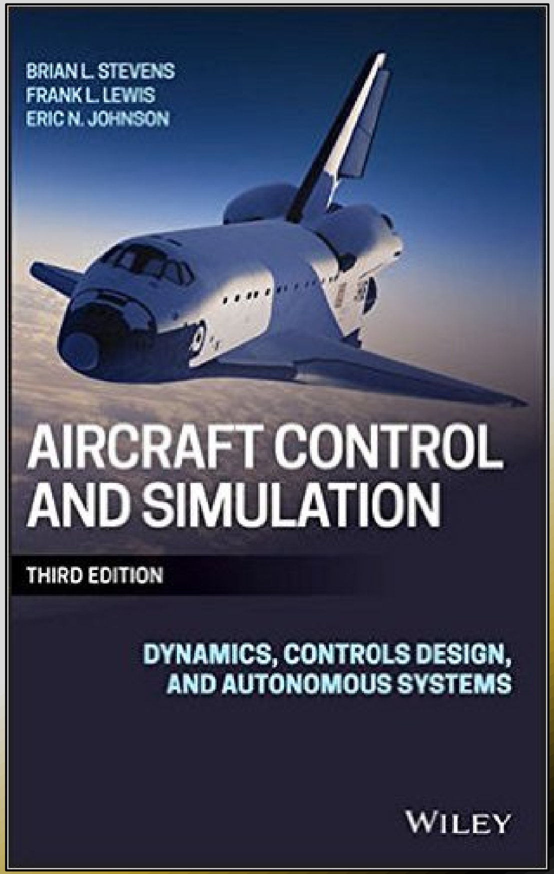
Team	Net ID
1 – HALO	10
2 – Flying Pharma	20
3 – STORM	30
4 – SAVIOUR	40
5 – Caladrius	50
6 – MARTI	88
7 – ARMOS	70

- What video frequencies are teams using?
  - Try to avoid interference from identical/adjacent/harmonic frequencies

Related reading

- Aircraft Control and Simulation, Brian Stevens/Frank Lewis/Eric Johnson (3rd Ed.)
  - 2nd Edition*
  - 3rd Edition (has a chapter on sUAS)
- APM: Plane





*I have this if anybody wants to borrow it

Questions?