Internet of Things: Integrating Projects - Drones

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Drones, part 1, what are drones, how do they work, how do you spot them

- Taxonomy of drones
- Anatomy of a drone
    - Propulsion
    - Radios
    - GPS
    - Cameras
    - Altimeter
    - Accelerometer and gyro-compass
    - Firmware
    - Control
- Detecting and identifying a drone

The Drone (DJI Phantom)

- Weight: 3.4 kg.
- Control
  - Maximum pitch: 300 degrees.
  - Maximum yaw: 150 degrees.
  - Maximum roll: 35 degrees.
  - Ascent rate: 5 m/s, descent rate: 4m/s.
- Speed (no wind): 10 – 22 m/s.
- Battery life (TB47D): 22min (no payload), 20 mins (500g), 13 min (1 kg).
- Range: 2km, ceiling: 3000 meters

Picture: Wikipedia

Camera

- 1” CMOS, Effective Pixels: 20 million
- FOV: about 77°
- 35 mm Format Equivalent: 28 mm
- Aperture: f/2.8–f/11
- Video: 100-6400
- Photo: 100-3200 (auto)
- Electronic Shutter: 8–1/8000s
- Interval (JPEG: 2/3/5/7/10/15/20/30/60s RAW:5/7/10/15/20/30/60s)

Radios

- Controller frequencies:
  - 900MHz
  - 5.8GHz (802.11)
  - 2.4GHZ
- Modulation: OFDM (see 802.11 standard)

Sensors

- Drone CPU: Myriad 2 VPU (vision processor), quad-core, 4-Plus-1 ARM, low-power NVIDIA Kepler-based processor, 16 GB eMMC 4.51 storage.
- IMU (gyroscope and accelerometer): similar to MPU-6050 (I2C and SPI)
  - MEMS 3-axis gyroscope (Coriolis effect) – drift of up to .5 degrees/sec
  - 3-axis accelerometer - errors around 1%
- Compass
  - 3-Axis Digital Compass IC HMC5883L
  - 1° to 2° compass heading accuracy
- Barometric altimeter
  - MS5803-14BA
  - 20 mbar accuracy
- GPS (including oscillating denial and deception)
  - LS20033-2R/MediaTek MT3337
  - Serial protocol

Gyroscope Stability

Grade	Stability (deg/hr)
Commercial	>30
Industrial	1-30
Tactical	.1-30
Navigational	.1-1
Strategic	.01

Detection

- Best early detection
  - 2 km (X-band radar, optical, acoustic)
  - Can be reduced by shielding, anti-stealth, quieting
- Need to act quickly
  - 10-20 m/s flight speed, 100 second response window

Drones, part 2, how to drive unmanned aircraft

- Navigation
  - Trajectories around earth
  - Spherical geometry: distance, bearing
- Control
  - Thrust and lift: parameters of “heavier than air” vehicles
  - Attitude: roll, pitch and yaw
- Mission planning
  - Waypoints
  - Endurance
  - Stealth

Navigation

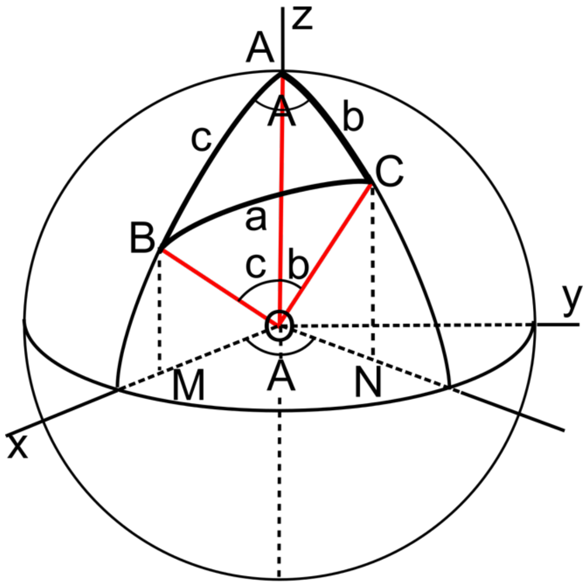
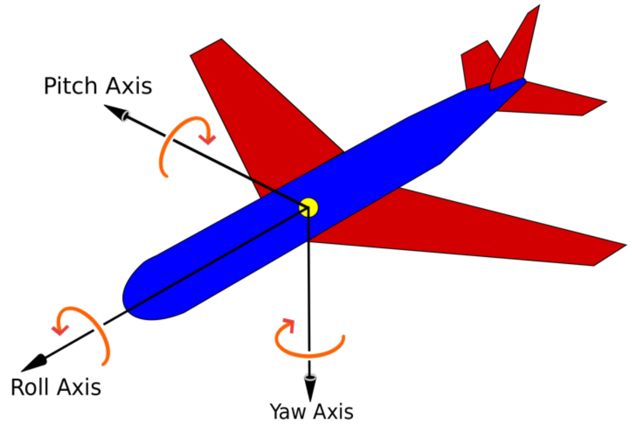


Diagram: Wikipedia

- Spherical triangles
  - $\cos(a) = \sin(b)\sin(c)\cos(A) + \cos(b)\cos(c)$
  - $\frac{\sin(a)}{\sin(A)} = \frac{\sin(b)}{\sin(B)}$. $R_{Earth} = 6378km$.
- Example: What is the distance (over the shortest path --- the great circle) between Boston and San Francisco?
  - $\lambda_{Boston} = 42.35$, $\phi_{Boston} = -71.05$, $\lambda_{SF} = 37.45$, $\phi_{SF} = -122.33$
  - $A = \phi_{Boston} - \phi_{SF} = 51.28, \mathrm{b} = 90 - \lambda_{Boston} = 47.65, \mathrm{c} = 90 - \lambda_{SF} = 52.55$
  - $\cos(a) = \cos(47.65)\cos(52.55)\cos(51.27) + \sin(47.65)\sin(52.55) = .842944$
  - $a = 39.05$
  - $D_{Boston-SF} = \frac{39.05}{360} 2\pi R_{Earth} = 4346.59km = 2700.85\, miles$
- What is the bearing (from true north) of the flight path (C)?
  - $\frac{\sin(51.28)}{\sin(39.05)} = \frac{\sin(52.55)}{\sin(C)}$, $\mathrm{C} = 39.67$

Introduction to aeronautics

Diagram: Wikipedia



- Boeing 737
  - Engines: CFM56-7BE 28,400 lb (126.3 kN)
  - Maximum Takeoff Weight: 174,200 lb (79,010 kg)
  - Wing area: 125 m²
- $F_{lift} = \frac{1}{2}\rho C_L v^2 A$
- Let's calculate takeoff speed, runway distance and takeoff time. C_L can be as big as 2.3 but we will use 1.5 in our calculation. $\rho = 1.2\frac{kg}{m^3}$, although this can vary with temperature and humidity. We'll ignore drag by derating C_L.
- $v = \sqrt{\frac{2mg}{1.5\rho A}}$, $v = 58.2\frac{m}{s}$ $(140mph)$
- $ma = F_{thrust}$, $a = \frac{250kN}{75kg} = 3.3\ \frac{m}{sec^2}$. $t_{takeoff} = \frac{58.2}{3.3} = 17.6\ sec$ (Assuming full thrust).
- $d_{runway} = \frac{1}{2}at_{takeoff}{}^2$. In our case, d_{runway} = 513m (about 1700 ft).
- Note these are approximate; many factors can affect result including actual weight, actual thrust applied, and actual air density.

Waypoints and drone navigation

- Same roll, pitch and yaw angles used to describe flight.
- Drone accelerated by tipping rotors down a little.
- Usually, we navigate to intermediate “waypoint.”
- Total journey consists of sequence of waypoints (like 737, listen to air traffic control).
- Given current location (say latitude and longitude) and next waypoint (latitude and longitude), we calculate bearing and use the compass. Head that way.
- We could also use the camera for navigation if the terrain is familiar.

Drones, part 3, critical RF dependencies

- GPS fundamentals
- RF effects
- Jamming drone control and data channels

GPS

- Four satellites needed. Each satellite transmits (x_i, y_i, z_i, s_i). s_i is the satellite time when the signal is transmitted,(x_i, y_i, z_i) is satellite position and t_i is the time according to the receiver clock. b is the receiver clock bias.
- Equations are $\sqrt{{x_i}^2 + {y_i}^2 + {z_i}^2} = d_i$ and $d_i = (t_i - b - s_i)c$. Solve for (x, y, z, b).
- If you have more than 4 sighted satellites, use least squares approximation to get the best solution.
- The GPS signal oscillates at the fundamental clock frequency of 10.23 Mhz. This signal is separately multiplied in frequency by the integers 154 and 120, to create the L1 and L2 carrier signals.
  - L1 (1575.42 MHz): Coarse-acquisition (C/A) and encrypted precision (P(Y)) codes, plus the L1 civilian (L1C) and military (M) codes.
  - L2 (1227.60 MHz): P(Y) code, plus the L2C and military codes.

GPS

- The satellite constellation is designed to have at least 4 satellites in view anytime for any location. Information is encoded using phase modulation. The binary digits 0 and 1 are represented by multiplying the electrical signals by either +1 or −1, which is equivalent to leaving the signal unchanged, or flipping the phase of the signal by 180.
- There are three types of code on the carrier signals: the C/A code, the P code, and the navigation code.
    - The C/A ("coarse acquisition") code is on L1 channel and repeats every 1 ms at a rate of 1.023 Mbps. The C/A code contains is the time according to the satellite clock. Each satellite has a different C/A code, so that they can be uniquely identified.
    - The P ("precise") code is identical on the L1 and L2 channel. The P code repeats every 267 days, the code is divided into 7 day segments; each with a "PRN" number. The basic information is the satellite clock time with ten times the resolution as the C/A code. Unlike the C/A code, the P code can be encrypted by a process known as "anti-spoofing", or "A/S".
    - The navigation message is on the L1 channel, transmitted at 50 bps. It is a 1500 bit sequence, and takes 30 seconds to transmit. The navigation message includes the broadcast ephemeris (satellite orbital parameters), satellite clock corrections, almanac data, ionosphere information, and satellite health status.
    - Thanks, DARPA.

Directional antennas

- A 2 meter parabolic antenna has a beam width of about 2.6 degrees in the X-band.
- This can be used to get a distance and noisy direction when locating a drone from a single X-band radar.
- If you have several, differently sited X-band radars, you can get a good idea where a drone is.
- $HPBW = k\,\frac{\lambda}{d}, k \approx 60$.

Drones, part 4 : real life drones

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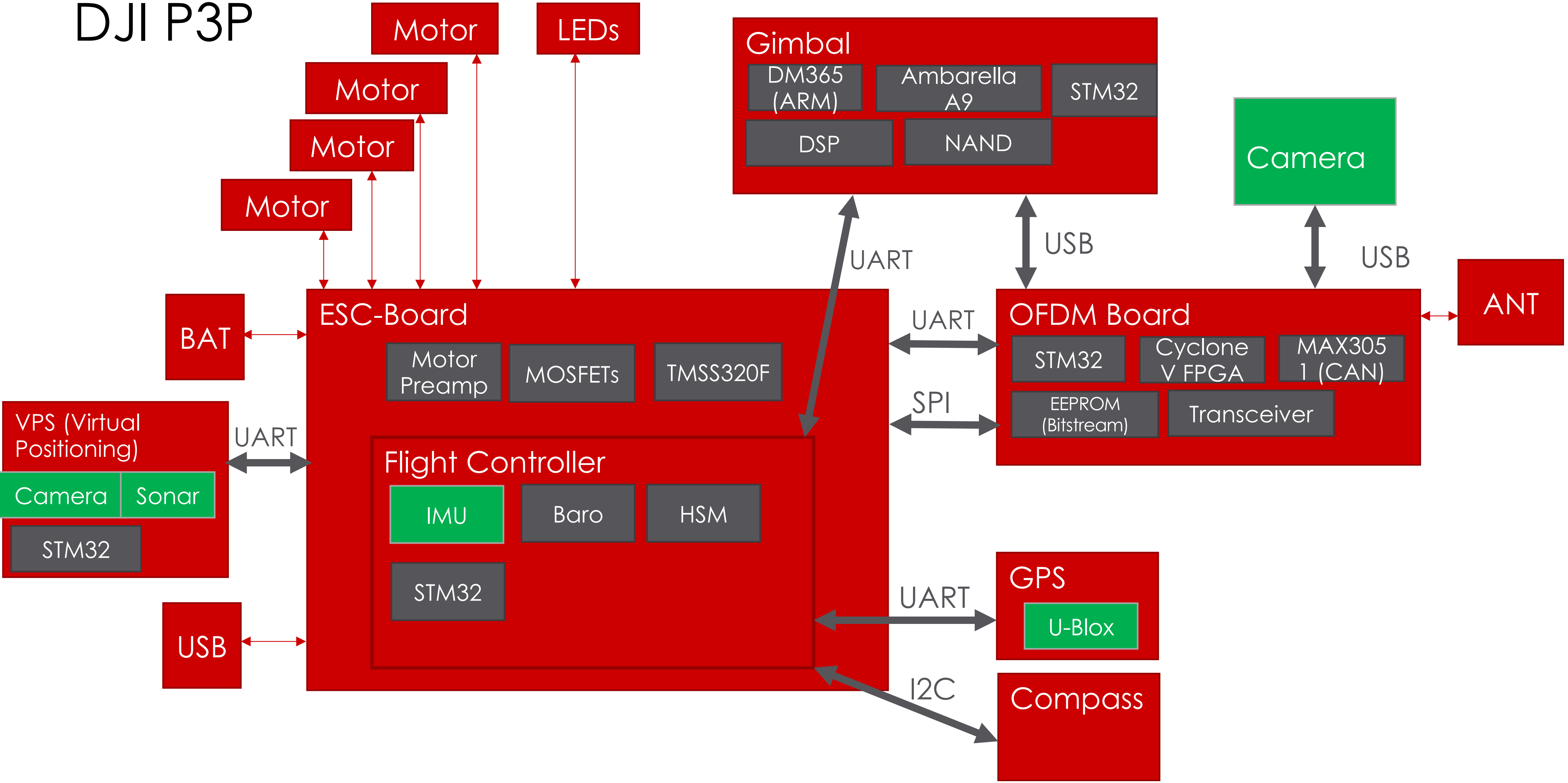
DJI P3P


Motor
LEDs
Motor
Motor
Motor
Gimbal
DM365 (ARM)
Ambarella A9
STM32
DSP
NAND
Camera
UART
USB
USB
ANT
BAT
ESC-Board
Motor Preamp
MOSFETs
TMSS320F
UART
OFDM Board
STM32
Cyclone V FPGA
MAX3051 (CAN)
SPI
EEPROM (Bitstream)
Transceiver
VPS (Virtual Positioning)
UART
Camera
Sonar
STM32
Flight Controller
IMU
Baro
HSM
STM32
GPS
UART
U-Blox
USB
I2C
Compass

Drone software

- Software supporting drones includes:
  - Device firmware
  - Navigation and flight control
  - Image processing
  - Sensor processing
  - Operating system
  - Applications
- There is proprietary software like DJI.
- There is open source software like PX4.

References

1. Sandia, UAS Detection, Classification, and Neutralization: Market Survey 2015.
2. Dept 13, Anatomy of DJI's Drone Identification Implementation.
3. DJI Drone manual.
4. Boeing 737 aircraft manual.
5. Karl Koscher, Securing Embedded Systems: Analyses of Modern Automotive Systems and Enabling Near-Real Time Dynamic Analysis. Thesis, UW.

Exercises

1. Find measurable quantities (rise/fall times, ...) to fingerprint and subsequently identify a drone.
2. Identify a drone using protocol parameters.
3. What is the GPS signal strength you'd expect?
4. If you had to rely on commercial grade (MEMS) gyroscope alone, using dead reckoning, how far off would you be in an hour?
5. What about a navigation grade gyroscope?
6. What is the height error when your barometer is off by 20 mbar? (1 bar is standard atmospheric pressure at sea level)

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