Multicopter Systems 101

DC Area Drone User Group

Photo Credits: Christopher Vo
A depiction of Nadar, the first known aerial photographer

DH.82B Queen Bee (UK - 1935)
Radio-controlled gunnery target
Radioplane OQ-2
The first mass-produced drone in the USA
“Drones, as the radio-controlled craft are called, have many potentialities, civilian and military. Some day huge motherships may guide fleets of long-distance, cargo-carrying airplanes across continents and oceans. Long-range drones armed with atomic bombs could be flown by accompanying mother ships to their targets and in for perfect hits.”

- *Popular Science*, November, 1946
Chris Anderson and his son Daniel with their homemade drone in 2007
τᵢ = bω²
τᵢ is thrust magnitude of motor i
ω is rotational speed of rotor

P ∝ Kᵥω
Kᵥ is motor constant
P is electric power
Hovering Flight

Thrust / Lift = Weight / Drag
Vertical Flight

Thrust / Lift > Weight / Drag
Forward Flight (Pitch)

Pitch forward: (2 and 4) > (3 and 1)
Sideward Flight (Roll)

Roll Right: (2 and 3) > (1 and 4)
Turning Flight (Yaw)

Yaw: torque from (1 and 2) dominates torque from (3 and 4)
Multicopter Species

- QUAD +
- QUAD X
- HEXA +
- HEXA X
- OCTA +
- OCTA X
- X8 (OCTA QUAD)
- OCTA V
- TOP
- BOTTOM
Coastal erosion measured as point cloud differences from UAV-mounted stereo cameras

UAV-based LIDAR capture of forestry in Guyana
Remote Sensing

- Mineral identification
- Stockpile volume mapping
- Monitoring of mine subsidence
- Thermal monitoring of coal stockpiles
- Flare stack inspection

Precision Agriculture using UAVs
Aerial photo showing individual diseased lettuce
Aeryon Scout, used for Flare Stack Inspection
Photo: Aftermath of Typhoon Haiyan in the Philippines. Wally Santana / Associated Press
Technical Open Problems / Opportunities

• Communication
  • Reduce bandwidth
  • Decentralized topology

• Sensing
  • “Sense and avoid”
  • Localization – know where you are
  • Target detection and tracking

• Path Planning and Trajectory
  • Precision flying (e.g. auto-land, cinematographic moves)
  • Follow-me
  • Sensor coverage
  • Optimization of fuel, wind, time

• Controls / Aerodynamics
  • Trajectories / Aggressive maneuvers
  • Fault tolerance e.g. dealing with hardware faults (dead motor/ESC)
  • Vehicle types / Control and estimation

• Software / Hardware Architectures
  • User Interfaces
  • Redundancy, reliability, logging
  • Cloud computing

• Data management
  • Processing of sensor data – e.g. mapping / GIS, photogrammetry
  • Data workflow and storage
Who’s Writing Software for Drones?

- ***3DR***
  - Sponsor of APM project
  - Makes PixHawk, Solo, IRIS

- ***DroneDeploy***
  - Mapping Automation Workflow Tools

- ***Amazon***
  - Package Delivery Autonomous Fleets

- ***LATITUDE***
  - Custom UAV, Ground Station Autonomous Landing

- ***SkyWard***
  - Fleet Management Logging, Charting

- ***PIX4D***
  - Data Processing Software

- ***openrelief***
  - Disaster Relief Sensing Search and Rescue

- ***SQUADRONE SYSTEMS***
  - Makers of HEXO+ Follow-Me Drone

- ***Zubax***
  - Positioning / GNSS Sensor

- ***SKYCATCH***
  - Mapping Automation Workflow Tools

- ***Airware***
  - Platform / OS Workflow Tools Compliance

- ***CyPhy***
  - Command / Control Ground Station Tethered Operation

- ***PRECISIONHAWK***
  - Mapping Software “Track and Avoid” Airspace Mgmt

- ***Intel***
  - Collision Avoidance
UAV Architecture

**Internet / Cloud**
- Data Processing Services
- Tracking / Management / Logs
- Global Network
- Air Traffic Data

**In-Air**
- Autopilot
- Sensors / Payloads
- Companion Computer

**Ground Station**
- User Interface
- Mission Planning / ATC
- Short Range Network
- Data Processing
User Input (Remote Control Rx, Mission Command) → Command Interpretation → Control Algorithms (PID, etc) → Motor Mixer

On-Board Sensors (IMU, Baro, etc) → Sensor Processing and Filtering → Desired Attitude, Heading, etc. → Norm. Rates → Motor Mixer

ESC → Motor
ESC → Motor
ESC → Motor
Multicopter Autopilot Units

- DJI Naza / Wookong / A2 ($400 / $1100 / $1300)
  - Solid performance for R/C, mature product, many users
  - Closed box / lacks programmability and mission planning

- ArduCopter on APM ($80)
  - High flexibility and configurability
  - Open Source
  - Mission planning capability
  - Performance highly dependent on tuning and configuration

- 3DRobotics PixHawk ($200)
  - Designed to replace the APM
  - Faster processor, NuttX RTOS
  - Currently runs ArduCopter firmware, but can also run PX4 native firmware

- Others
  - OpenPilot, Naze32, KK, Multiwii, so many more!
Batteries

• Multicopters use a lot of power!
  ○ DJI Phantom (stock) uses 120W just to hover
  ○ DJI F550 Hexacopter uses 320W to hover

• Batteries are heavy!
  ○ Just 100g weight can reduce flight time significantly!
  ○ Need light weight, high energy density

• So far, Lithium Polymer (LiPo) is the leading battery technology for small unmanned aerial vehicles
LiPo Terminology

- **S and P**: the number of cells in series and parallel respectively
  - Each LiPo cell is 3.7V
  - More cells in series = higher voltage e.g. 1S = 3.7V, 2S = 7.4V, 3S = 11.1V

- **C rating**: the maximum continuous current draw for battery expressed in multiple of capacity
  - Example: 5000mAh 3S 25C battery:
  - 5A * 25 = 125A max output

- **mAh**: the storage capacity measured in steady current of mA for 1 hour

- You can estimate flight time based on motor/prop power consumption
  - Power = Current * Voltage (Ohm’s law)
  - You can find power consumption (in W) on motor test chart, or by testing.
LiPo Safety

- **LiPo Batteries are quite volatile and require special precaution.**
- **Always** supervise lipo batteries when charging.
- **Always** store and charge batteries in a safe environment
  - Room temperature and dry
  - Ideally, away from flammable things
  - Some people use a fireproof container such as LipoSack or a fireproof cash box
- **Always** keep a fire extinguisher nearby
- **Never** overcharge or overdischarge the battery
- **Rule of thumb: 80/20 rule:** Discharge no more than 80% of the battery. 80% battery is used approximately when the no-load voltage is equal to the nominal voltage. (e.g. 11.1v for 3S).
- Keep track of physically damaged or “crashed” batteries – mark them and get brand new ones. New batteries are cheaper than new copters (or anything else you crash into)
Motor Systems

- **Stator**: The part of the motor that stays still (the fixed part with the wires wound around it)
- **Rotor**: The part of the motor that spins (the bell part that has magnets glued to it)
- **Kv or KV**: the RPM of the motor per 1V applied with no load (NO PROPS)

Configuration example: 12N 14P
- N is the number of wound poles in stator
- P is the number of magnets on the rotor bell

Labeling convention example: 3510 motor
- 35 is the stator's inside diameter
- 10 is the stator height

Rule of thumb:
- Go for a 2:1 power-to-weight ratio. Ideal: hover at 50% throttle.

Other factors to consider
- Larger motors generally dissipate heat better.
Calculating Flight Time

\[
\text{[Flight Time in minutes]} = \frac{(X \times \text{[battery mAh]} \times \text{[motor eff. in g/W]})}{\text{[AUX in g]}}
\]

\[
X = \text{[battery voltage in V]} \times \left(\frac{60}{1000}\right) \times 80\%
\]

e.g.
For 3S battery: \(X = 0.53\)
For 4S battery: \(X = 0.71\)
For 6S battery: \(X = 1.07\)

Motor eff. can be obtained experimentally or from manufacturer spec.
Example

3500g AUW, 8000mAh 4S Battery, Eff at hover 9g/W
No payload:
\[
\left(0.71 \times 9 \text{ g/W} \times 8000\text{mAh}\right) / 3500\text{g} = 14 \text{ minutes 36 seconds}
\]
Add gimbal + GoPro: 450g: (Efficiency falls to 8.8g/W at hover)
\[
= 12 \text{ minutes 39 seconds}
\]
Add landing gear: 250g (Efficiency falls to 8.9g/W at hover)
\[
= 11 \text{ minutes 45 seconds}
\]
Add sloppy wiring job, excess wire: 270g (Efficiency 8.6 g/W at hover)
\[
= 10 \text{ minutes 55 seconds}
\]

Moral of story:
All other factors staying the same,
Reducing weight directly translates to better flight time.
Criteria of a good radio Tx/Rx

- 5 or more channels

- Mode 2 (North American standard, mimics full scale airplane controls)

- Uses interference-resistant modulation
  - DSMX (Spektrum)
  - FASST (FUTABA)
  - ACCST (FrSKY)

- (optional) PPM/CPPM output - single wire connection to flight controller

- Suggestions: FrSky Taranis, Futaba T8FG, Turnigy 9XR w/ FrSky modules
Safety?
Should FAA regulations apply to *unmanned* aircraft? What Size, Altitude, Weight is considered “safe”? Should Line-of-Sight be a requirement? Should we require a license or permit to fly? What makes a drone “airworthy”?

Commercial Operations?
Should hobbyists be exempt? Should commercial operations be limited?

Property / Airspace?
Who owns the air? Can the feds tell me what to do in my own backyard?

Privacy Invasion, Trespass, Nuisance, Stalking, Harassment?
Do we need new laws to cover bad behavior via drone?

Law Enforcement and Journalism
Ethical issues related to enforcing the law and journalism from remote.
Subject: MODEL AIRCRAFT OPERATING STANDARDS

1. PURPOSE. This advisory circular outlines, and encourages voluntary compliance with, safety standards for model aircraft operators.

2. BACKGROUND. Modelers, generally, are concerned about safety and do exercise good judgement when flying model aircraft. However, model aircraft can at times pose a hazard to full-scale aircraft in flight and to persons and property on the surface. Compliance with the following standards will help reduce the potential for that hazard and create a good neighbor environment with affected communities and airspace users.

3. OPERATING STANDARDS.

   a. Select an operating site that is of sufficient distance from populated areas. The selected site should be away from noise sensitive areas such as parks, schools, hospitals, churches, etc.

   b. Do not operate model aircraft in the presence of spectators until the aircraft is successfully flight tested and proven airworthy.

   c. Do not fly model aircraft higher than 400 feet above the surface. When flying aircraft within 3 miles of an airport, notify the airport operator, or when an air traffic facility is located at the airport, notify the control tower, or flight service station.

   d. Give right of way to, and avoid flying in the proximity of, full-scale aircraft. Use observers to help if possible.

   e. Do not hesitate to ask for assistance from any airport traffic control tower or flight service station concerning compliance with these standards.
In 2007, FAA issued a policy clarification in the Federal Register (72 Fed. Reg. 6889) which asserts that “no person may operate a UAS in the national airspace without specific authority.”

Public UAS are authorized via COA, Civil UAS are authorized via SAC-EC Model aircraft are authorized via AC 91-57
In 2012, Congress issued FAA Modernization and Reform Act of 2012 (FMLA) also known as PL 112-95.

A set of directives for the FAA, which include some items about creating regulations for model aircraft and UAS by 2015.

Among the items: In Section 336, FAA is prohibited from promulgating any rules about “model aircraft”.

Public Law 112–95
112th Congress

An Act

To amend title 49, United States Code, to authorize appropriations for the Federal Aviation Administration for fiscal years 2011 through 2014, to streamline programs, create efficiencies, reduce waste, and improve aviation safety and capacity, to provide stable funding for the national aviation system, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE; TABLE OF CONTENTS.

(a) SHORT TITLE.—This Act may be cited as the “FAA Modernization and Reform Act of 2012”.

(b) TABLE OF CONTENTS.—The table of contents for this Act is as follows:

Sec. 1. Short title; table of contents.
Sec. 2. Amendments to title 49, United States Code.

SEC. 336. SPECIAL RULE FOR MODEL AIRCRAFT.

(a) IN GENERAL.—Notwithstanding any other provision of law relating to the incorporation of unmanned aircraft systems into Federal Aviation Administration plans and policies, including this subtitle, the Administrator of the Federal Aviation Administration may not promulgate any rule or regulation regarding a model aircraft, or an aircraft being developed as a model aircraft, if—

(1) the aircraft is flown strictly for hobby or recreational use;

(2) the aircraft is operated in accordance with a community-based set of safety guidelines and within the programming of a nationwide community-based organization;

(3) the aircraft is limited to not more than 55 pounds unless otherwise certified through a design, construction, inspection, flight test, and operational safety program adminis
In 2013 FAA pursued enforcement action against Raphael Pirker (Administrator v. Raphael Pirker NTSB Docket CP-217)

Pirker flew over UVA campus, FAA pursued $10,000 fine

Pirker moved to dismiss the case, and the NTSB judge granted dismissal, and found there was no enforceable FAA rule or FAR regulation applicable to model aircraft at the time.

Settlement for $1,100 earlier this year
No precedent set
In 2014, FAA published a Notice of Interpretation regarding Section 336 of the FMLA. In this notice, the FAA

Claims that “model aircraft” are not exempt from rules that FAA may apply to “all aircraft” e.g. 14 CFR (FAA Regulations) and 49 USC (Transportation Law)

Claims that the FMLA definition of model aircraft should be taken literally, and any aircraft that doesn’t fall into that definition is fair game for FAA to regulate, citing specific examples:

No FPV flying
Strictly hobby use

Asserts that 14 CFR 91 applies to all aircraft including model aircraft, and the FAA can take enforcement action under 14 CFR 91.13
Section 333 of FAA Modernization and Reform Act allows the Secretary of Transportation to decide if certain UAS can be operated safely before the completion of the plan.

Pilot in command (PIC) must still be a licensed pilot

More than 1000 granted exemptions so far.

Most exemptions allow operations along the lines of proposed Part 107 rules.
February 2015
FAA Releases Notice of Proposed Rulemaking for small UAS (applied no sooner than 2017)

Key Proposed Rules:
- Mostly covers commercial LOS operation
- < 100 mph, < 55 lbs, < 500 ft AGL
- Daylight only, VLOS only
- FPV not sufficient for “see and avoid”
- Class B C D E allowed with ATC perms
- Class G allowed without ATC perms
- Report accidents that cause damages
- Operator must be
  - At least 17 years old
  - Passed aeronautical test
  - Has a sUAS operating cert
  - Vetted by TSA
- Aircraft must be registered and marked
What to do for now?

1. **Hobbyists**
   Stick to existing R/C guidelines (e.g. AC91-57) and follow local laws and park rules

2. **Public sUAS operations**
   Get a Certificate of Authorization (COA)
   Or declare as civil operation (see #3)

3. **Commercial sUAS Line of Sight operations**
   Get a Section 333 waiver AND either be a licensed pilot or hire one
   Consider outsourcing drone ops to a company that already has 333 and licensed pilots
   Refer to NPRM for proposed rules.

4. **Commercial ops with unlicensed PIC, or BVLOS, or > 500 ft**
   Rules being developed by FAA. Stay tuned.
   Move to a different country?
Other rules may apply

National Parks

Drones NOT allowed at 400+ National Parks
Nuisance, Safety, and Wildlife disturbance concerns

Local Laws

45 states have considered 166 bills. 26 pieces of legislation passed.

Louisiana regulates use of UAS in agricultural operations

Virginia HB 2125 and SB 1301 require that a law enforcement agency obtain a warrant before using a drone for any purpose, except in limited circumstances. Virginia's governor also issued an executive order establishing a commission on unmanned systems.

RC aircraft not permitted at Fairfax County parks in general

Most parks owned by cities and towns in NOVA area have their own prohibitions

Mostly related to nuisance and safety, sometimes privacy
Airspace Classification
NOTAMs and TFRs

NOTAM - Notice to Airmen;
TFR - Temporary Flight Restriction

Notable TFR:

**DC FRZ**: Washington DC Metropolitan Area Flight Restricted Zone

Around 13NM to 15NM from DCA

Explicitly prohibits “Unmanned Aerial Vehicles” and “Model Aircraft”

No major enforcement cases yet against any model aircraft operator flying in DC FRZ despite several examples:

- Catholic Church - Washington Archdiocese used drones in May 2014.
- LDS Church - Flew drones several times to capture video of the Temple in MD, in some cases also paid for the footage.
- Adam Eidinger crashed his quadcopter in Adams Morgan in 2012. FAA did speak with him - received a cease and desist letter.

Many Youtube videos of drone footage in DC.
UAS Service Industry in Europe

Thousands of UAS operators
95% of operators are using systems < 15kg

France and Norway allow operations beyond line of sight for small UAS

United Kingdom
UK CAA requires that commercial uses (“Aerial Work”) obtain permission. Obtaining permission requires licensing (national exam).
Below 7kg does not require permission, just VLOS
BVLOS allowed, but only with specific permission
Other countries

Canada
   Permission not required if aircraft weighs less than 35 kg or used for recreational purposes.

Australia
   Well developed UAS regulatory framework, lots of operational rules
   Certification AND approval required for commercial use
   Hobby use is very relaxed, simple rules (similar to AC91-57)

Japan
   Active UAS crop spraying industry (> 30%)
   Regulatory framework coming!

Latin America
   Brazil put rules up for public comment last month