Introduction to multirotor UAV configurations

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Overview of presentation:

- Different multirotor types:
  - Helicopter
  - Monospinner
  - Coaxial
  - Tricopter
  - Quadcopter
  - Other Multicopters
- Design considerations of multicopters
- Alternative implementations (VTOL/fixed wing blends)
- Components of Multirotor systems
- Payloads/uses

Helicopters

- Variable pitch, hinged
- Common for military applications, large scale rotorcraft drones

Monospinner

- Fixed pitch rotor, works by varying thrust as it rotates about CG
- Not capable of being used outside a lab
- Pretty cool, though – one single moving part

Coaxial Designs

- Passively stable
- Reasonably efficient
- Often used at small scale

Trirotor

- Good visibility for aerial videography
  - Better yaw control, less coupled with thrust
- Still have four moving parts – a tilt (typically servo) is required to balance yaw
- Cheaper (one less ESC/motor)
- Potentially more reliable (if we assume ESC's and Motors most likely to fail, this would have longer MTBF)

Quadrotor

- Most popular
- Four fixed-pitch, counter-rotating props
- Four moving parts (the motors)
- So many examples of this – most popular is DJI Mavic, Parrot Beebop, a few others

Hexacopter

- Two configurations – 6 individual motor mounts, or “Y6” – a tricopter with each boom having both an upward and downward facing motor
- More lift, potential added reliability (theoretically can remain flying with one motor incapacitated)
  - Keep in mind this is not always the case
  - In particular for Y6’s – one propeller failure can induce a second
- For heavier lift applications

Octocopter

- Again two main configurations
  - Standard with 8 separate arms
  - X8, like a quadcopter but with upward and downward facing arms

- For still heavier lift applications
- Can theoretically sustain two motor failures depending on configuration

Hexadecacopter, etc.

- No real limit to the number of propellers that can be added.
- Witness the Volocopter:
  - 16 propellers by my count
  - Specs difficult to find

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Primary Limitations of Multirotors

- Battery life
  - Ranges from a few minutes to at best 1.5 hours
  - Caused by the poor energy density of LiPo/LiIon battery packs when compared with gasoline
  - New companies making hybrid designs
- Poor maneuverability for large fixed pitch rotors
  - Typically swinging bigger props – larger angular momentum – slower reaction to input changes
  - Problem increases with size of rotor, as control is based on changing rotor speed
  - Variable pitch rotors is the answer, but less common due to complexity
- Must support its own weight
  - High energy consumption, limited range
  - High vibration
  - Noisy

Flight time considerations:

- Power/weight ratio is the key
  - Frame/payload/electronics weight decrease allows larger batteries, enabling longer flight times.
    - Light materials
    - Remove extra wiring, landing gear
    - Avoid connectors, particularly heavy ones
    - Remove plastic covering from components to reduce weight!
  - For heavy lift long endurance platforms, seek low kV motors (2-400kV)
  - High-power density batteries

Flight time considerations (cont'd)

- Selecting motors/props together
  - Motor/Prop combo is extremely important.
  - Test for efficiency, in g/W

- Not that well modeled mathematically
  - Experimentally optimized by big drone companies, just buy tuned kits

- Flying style also matters
  - Hover vs. "actual" flight times can be different!
    - E.g. Max throttle for racing

Fixed vs Variable Pitch

- Variable pitch can control UAV with fewer rotors
  - Swashplate used for control
    - Vary the overall pitch of blades or the distribution of the pitch of the blades in the plane
    - Each rotor can provide thrust and two control torques (roll and pitch)
    - Yaw torque cannot be separated from thrust
      - Compensated for with a second rotor (helicopter, coaxial)

  - Allows for faster control than fixed pitch multirotors
    - RPM held constant while engine responds to torque requirement variations

Fixed vs Variable Pitch (cont'd)

- Variable pitch is more capable than fixed pitch multi-rotors in many respects
  - Can change control actions more rapidly, no need to overcome rotor inertia
  - Fewer larger rotors more efficient in flight

- Disadvantages:
  - Larger blade -> larger kinetic energy
    - Potentially more hazardous
  - Perceived to be more difficult to control
  - Maintenance is more demanding

Single vs Coaxial

- Propellers in a coaxial configuration lose approx. 10% of their thrust for the same RPM (which equates approximately to power draw)
  - This is based on research of DraganFly X8 aircraft
  - Test stand results don't necessarily relate to flight performance

- Becomes a question of whether or not the weight saving from reducing to 4 arms is worth losing ≈10% of your efficiency
  - X8 will typically allow larger propeller sizes for the same diameter UAV, which means an X8 can be smaller than an octocopter for same motor/prop combination

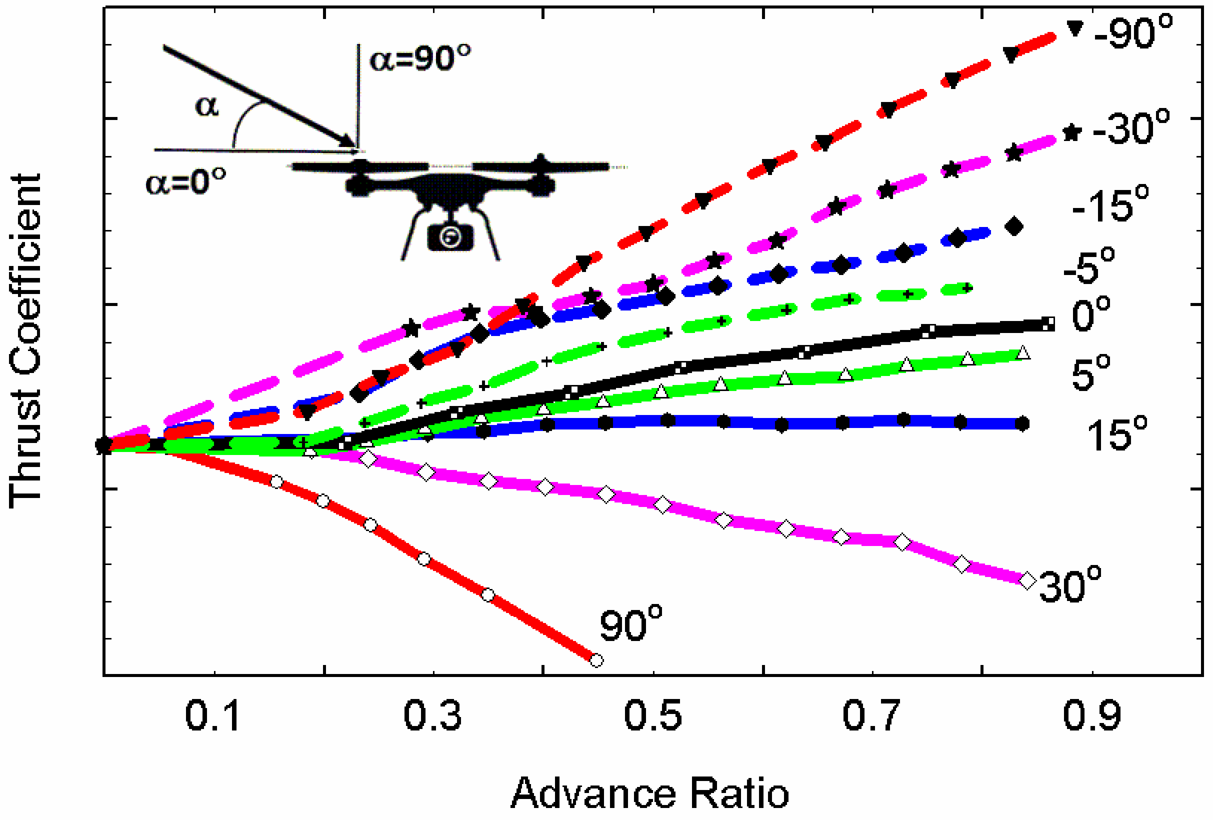
- No universal answer, multiple designs persist

Efficiency design considerations

- Bigger rotor is better (disk actuator theory)
  - $P = \sqrt{\frac{T^3}{2\rho A}}$
  - The higher the area, for equivalent thrust the lower the power
  - Large props also have more inertia, so as props get bigger, dynamic response slows

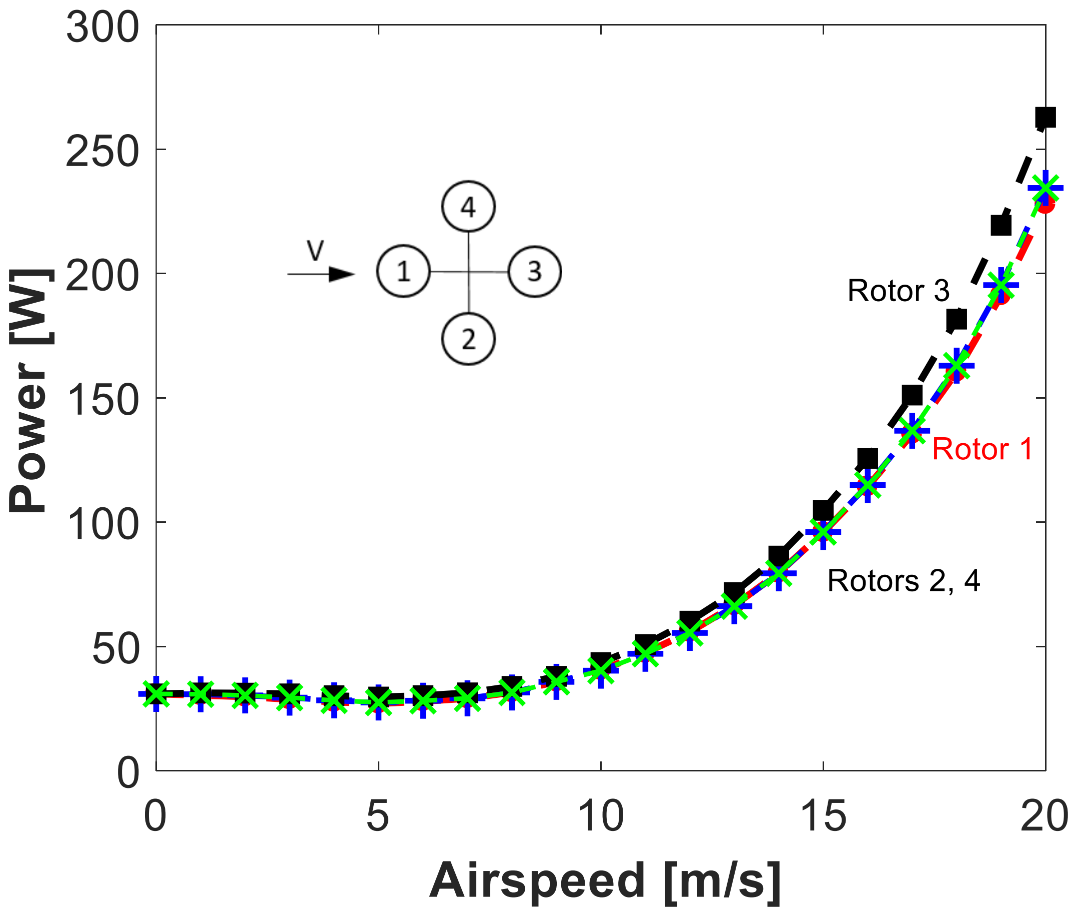
- Mounting propeller below arm is more efficient than above at low speed
  - Airflow hits motor arm, gets disrupted
  - 5% increase in thrust
  - 30% improvement in vibration, in hover with Aeryon Labs
    - Made control easier and improve flight time substantially
    - DJI now also have a large drone design that uses this
  - Effect reversed at speed, as arm wake disrupts inflow

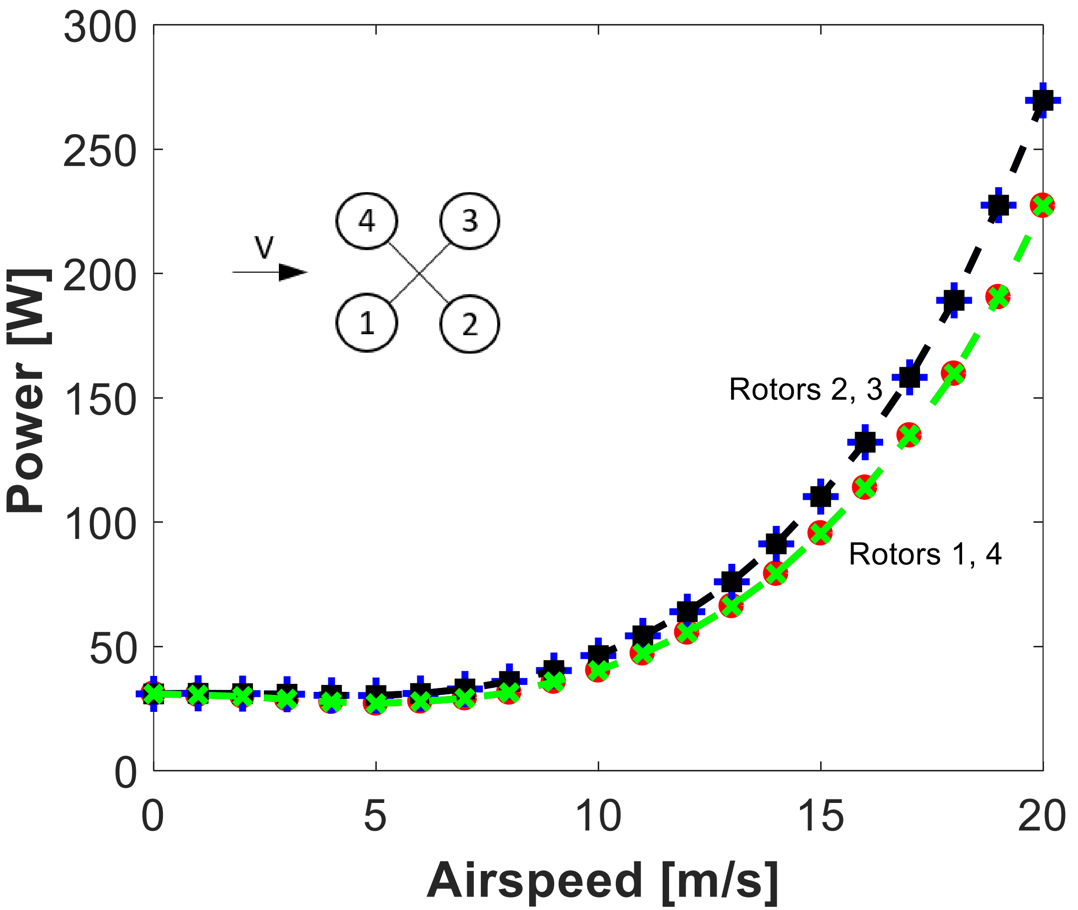
Single Rotor Performance
(courtesy of Prof. Goetz Bramesfeld, Ryerson)



The higher thrusts with increasing advance ratios are due to highly skewed wakes.

Rotor Power
(courtesy of Prof. Goetz Bramesfeld, Ryerson)





Total vehicle power required for force equilibrium is 6% higher in square configuration.

Center of Gravity considerations

- One might think it should be below rotor plane to maintain stability
  - Rocket pendulum fallacy
    - originally thought with rocket engine on top, the weight of the fuel would act as a pendulum and balance it
    - Incorrect – in a uniform gravitational field, C of G and C of M are the same → no stabilizing torque

- Moments caused by rotor and body drag affect stability
  - For forward flight, rotors above CG cause stabilizing pitch up
  - For hover in wind, rotors above GC cause destabilizing pitch down
  - Best practice to align rotors with CG to minimize unwanted moments

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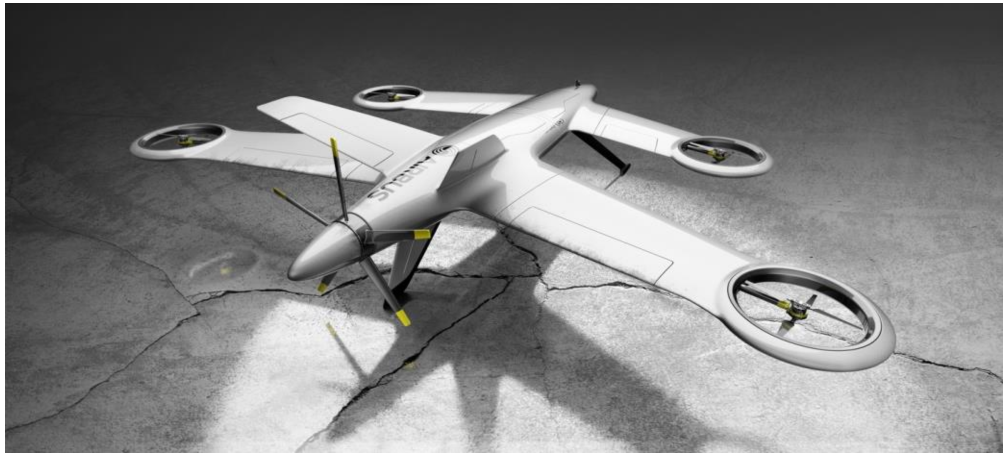
Alternative concepts

- Quite a few alternative concepts are proposed to try to balance the convenience of VTOL/hover capability with the efficiency and flight duration of a fixed-wing craft
  - Quadplane
  - Tailsitter
  - Tiltrotor
  - Tiltwing

Quadplane

- Popular these days
  - Brute force approach
- Advantage
  - Simplicity
- Disadvantage
  - Added weight, drag, airflow disruption



"TailSitter"

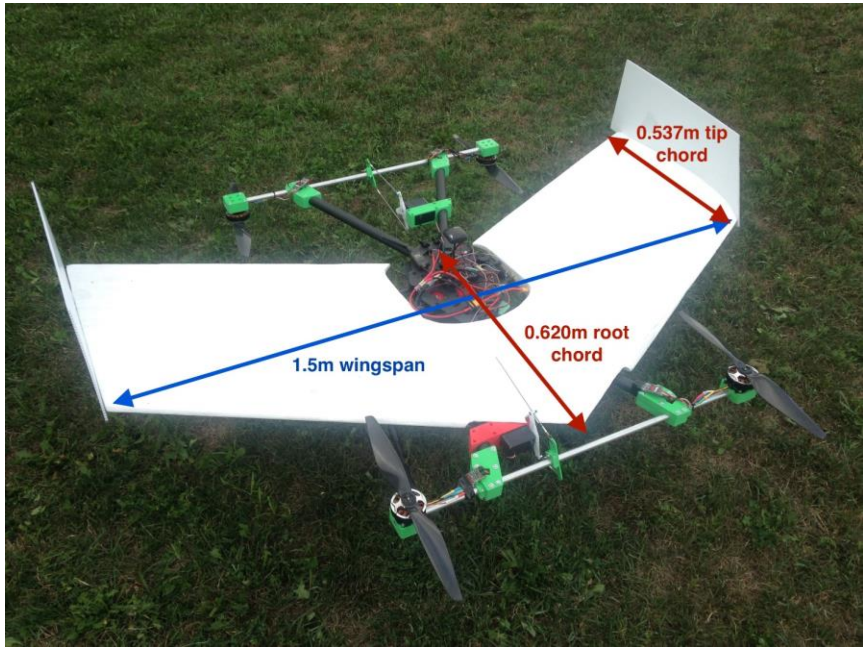
- XPlus One, google delivery drone prototype few others:
- Advantages:
  - Simplicity
  - Efficient at both operations
- Disadvantages:
  - Wind tolerance in hover, efficiency in forward fli

Tilt-Rotor

- Several early examples, including the X-22 aircraft which (eventually) let to the V-22 Osprey:

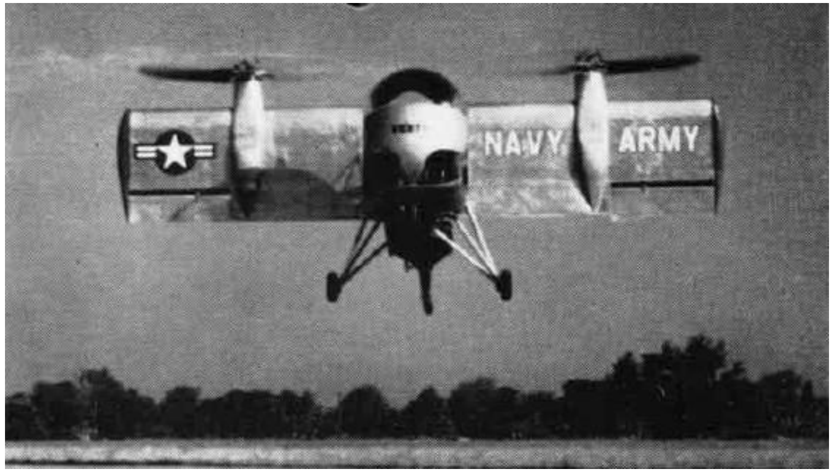
Tilt rotor (cont'd)

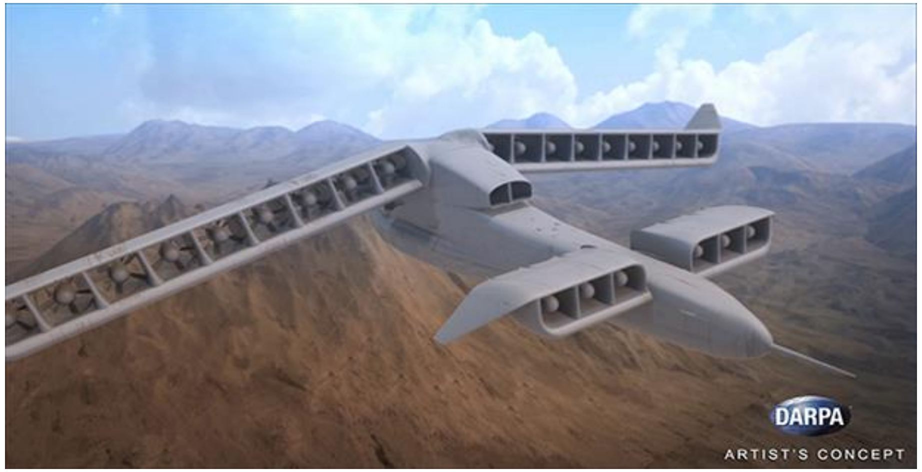
- Some interesting work in FSC Lab to develop controller for a Tilt-Rotor:



Tilt Wing

- Variation on the theme of tiltrotor
  - Wing tilts vertically in VTOL
  - Can be mechanically more complex
- Advantages:
  - More efficient than tilt rotor in climb and hover
  - Simpler transition?
- Disadvantages:
  - Rotation more difficult
  - Large surface area presented to cross-wind





Multirotor vs. fixed wing

- Multirotors
  - Shorter flights and range
  - Hover capability
  - Lower top speeds
  - VTOL, can be launched from anywhere
  - No need for “end turns” in mapping
  - Typically low redundancy
  - Can survive loss of motor *
- Fixed Wing:
  - Longer flights
  - Minimum speed
  - Higher top speeds
  - Typically requires launch equipment
  - “End turns”
  - Overflight of other property
  - Can survive loss of motor

* Redundent rotors, or through windmilling

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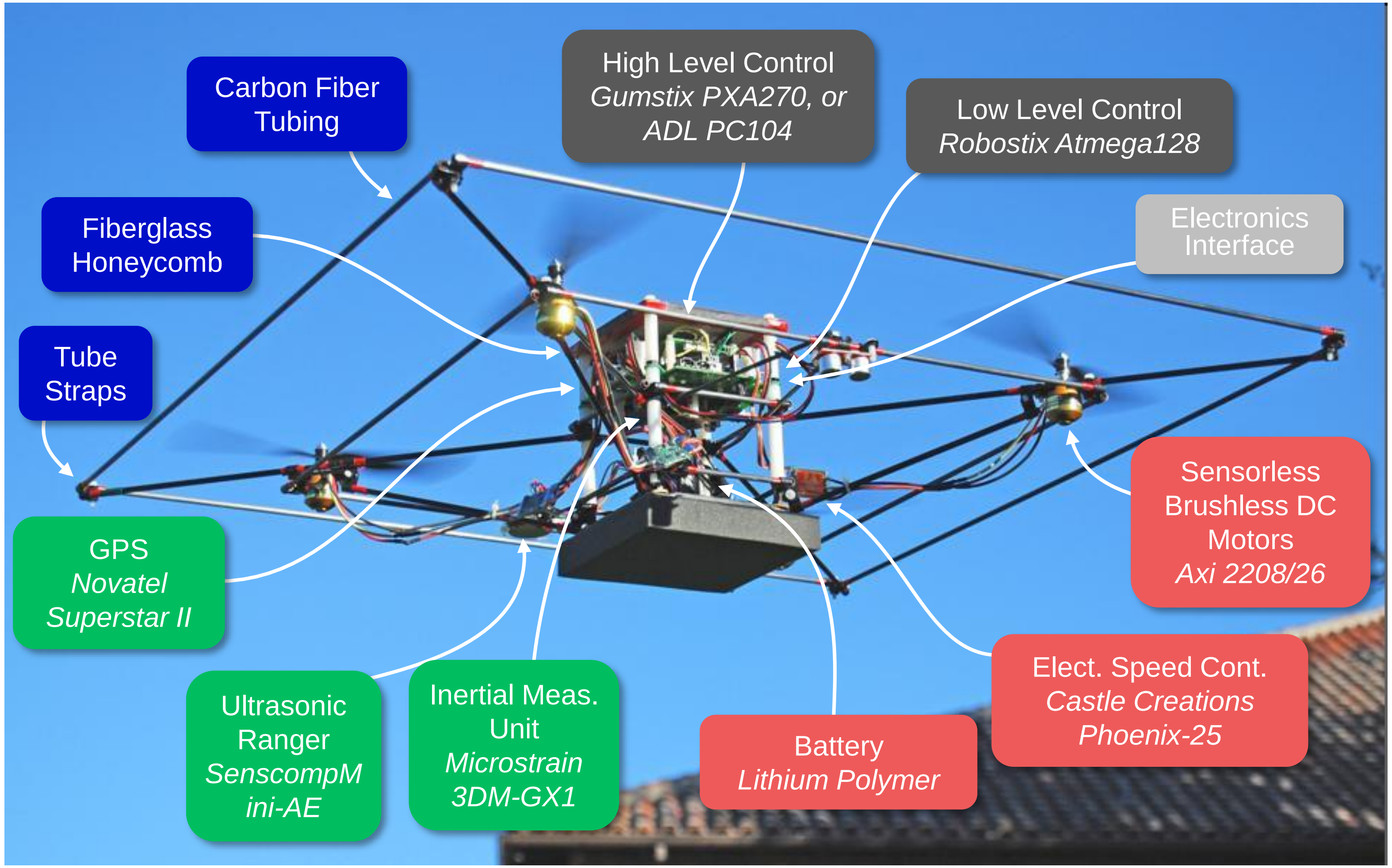
Components of a typical system

- Frame
- Motors
- Propellers
- Electronic Speed Controllers
- Batteries (power source)
- Power Distribution Board
- Flight Controller
- Radio Receiver
- GPS Receiver
- Payload

From the history books



STARMAC in flight

Motor categorization

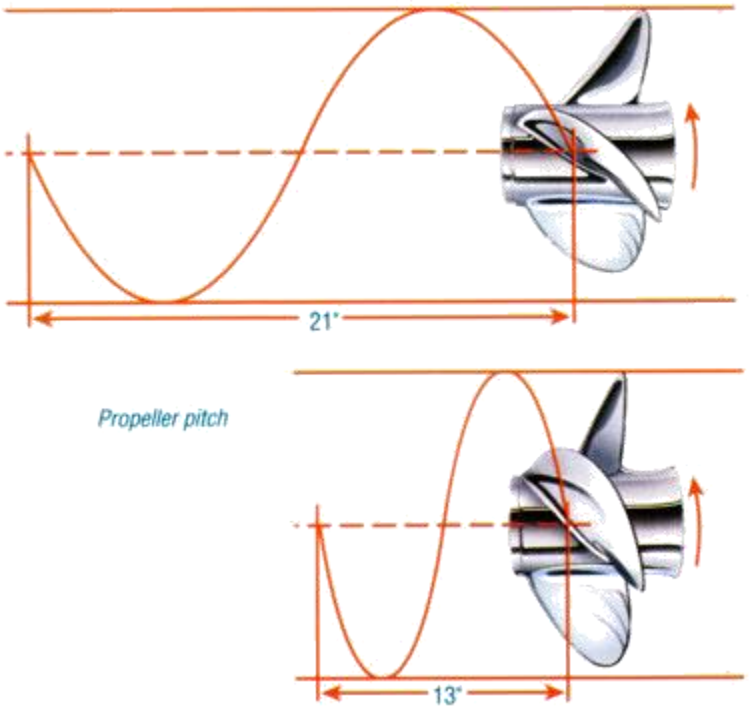
- Brushed DC motors (obsolete, too inefficient)
- Internal Combustion motors (prevalent in larger UAVs)
- Brushless DC – most common
  - Inrunner (core rotates – high RPM, low torque)
  - Outrunner (shell rotates – lower RPM, higher torque)
    - Better cooling, most common in quads

Motor categorization

- Brushless DC outrunners are most common for fixed pitch, electric multirotors
- Many different manufacturers – an approximate standard is that the letters will symbolize manufacturer, then the first two numbers are stator diameter and the third and fourth are stator length. The number of poles is indicated after a dash
  - This varies with motors – always double check!
- kV number – rotor speed with one volt and no load (not a kilovolt)
  - For multirotors, lower kV = more flight time, higher torque for bigger rotors

Propellers

- Rated by Diameter/Pitch
  - A 9x6 prop means it has a diameter of 9”, and a pitch of 6”
    - Pitch is distance the prop would travel forward in one rotation in a solid block
  - Of critical importance in efficiency
- Materials
  - Plastic (flexible, cheap, slightly less efficient)
  - Carbon Fiber – (stiff, slightly more expensive, more efficient, also more deadly)
  - Wood (uncommon, historically for RC aircraft) – too easily chipped, too heavy
- Propeller balancing is critical to avoid unwanted high-frequency vibrations and possible damage



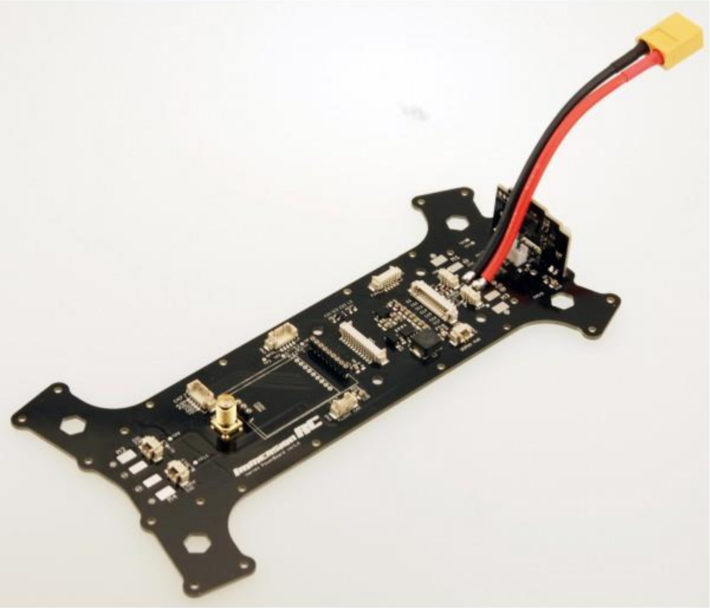
Electronic Speed Controllers (ESC)

- Takes the reference (PWM) signal from a flight controller and direct power from the battery to control to the motors
  - Usually closed loop speed control, linear response to reference
- One of the most common failure points
  - Rotor stall leads to high current, burning out Mosfets

- Rated to specific amperage – typically better to go high
  - At least double what is required at full battery voltage steady state
- When building your own from RC parts, typically contains a Battery Eliminator Circuit (BEC)
  - Supplies 5V power to the flight controller, can eliminate need for separate power distribution board
  - Commercial drones tend to integrate ESCs and power distribution onto a single board, and isolate flight controllers to eliminate supply voltage noise

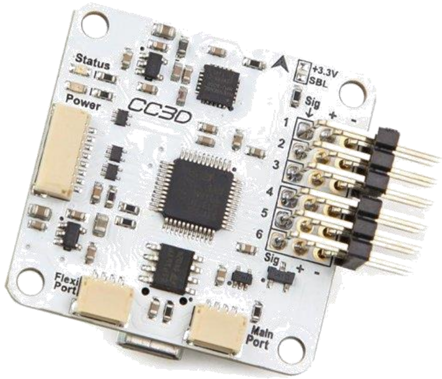
Power Distribution Board (PDB)

- A convenience feature included on many frames, necessary in other situations
- Exactly what it sounds like – a board capable of carrying high current loads, typically:
  - Takes Voltage input from Battery
  - Redistributes this voltage to many pads for use with ESC's
  - Contains a 5V DC-DC rectifier to provide power to the flight controller
  - Often contains a 12V rectifier as well, to provide power to
    an onboard camera or video transmitter/receiver



Flight Controllers

- Possibly the most critical piece of Hardware
  - Failure often (always?) leads to crash
  - Responsible for stabilizing the multirotor from gyro, accelerometer, barometer data
  - Receives information from GPS for position, velocity control
  - Receives commands from the Radio Receiver, onboard computer, ground station
  - Outputs motor speed commands, typically through PWM ports
  - Can be set up to control gimbal or other component (gripper arm, trigger camera, etc)



Flight controllers (cont'd)

- Many choices, will outline a few of the most popular below:
  - DJI – full autonomy, many safety features
    - Naza-m v2, N2 or the A3 – a triple redundant autopilot
  - Pixhawk – full autonomous and safety features, open source
    - Open source hardware, careful who you order from
  - Auterion SkyNode
    - Polished, integrated version of the Pixhawk with comms and additional compute
  - CC3D / Naze32 / KISS - Drone racing
    - Typically for smaller builds – limited I/O and processing
    - Many can handle FPV as well

Flight Control Software Packages

- Proprietary (Aeryon, Microcopter, DJI, etc)
  - Useful API for some of the DJI Matrice line allow building on top of established controller

- Open Source:
  - PX4
    - Developed by Lorenz Meier, now supported through DroneCode initiative, Auterion
    - Most consistently developed in the open source community, keeps getting better
    - Focus on full autonomy, commercial applications like videography, survey, inspection
  - Ardupilot, Paparrazi – alternative less well supported
  - CleanFlight/BaseFlight – best lightweight control software
    - Focus on drone racing, small embedded hardware

Radio Receiver

- Typically will come with your transmitter
  - Several good brands available (Taranis, Spectrum, etc)

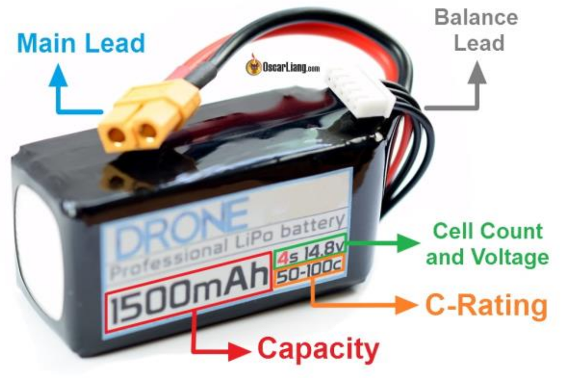
- Typically in North America will operate on the 2.4GHz range (same as WiFi) but implement channel-hopping.
  - Can also be 5.8GHz or 900MHz (long range)

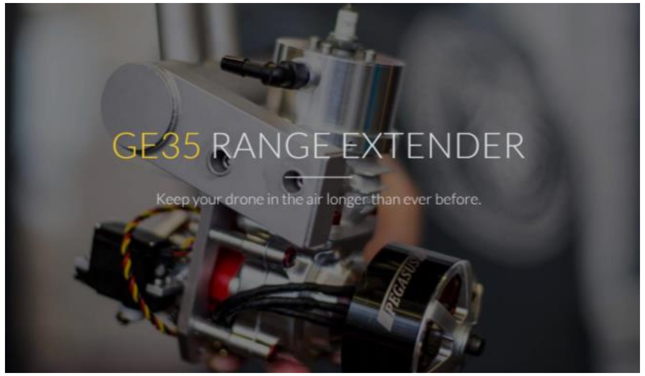
GPS

- Constellation of satellites which broadcast on several frequencies and allow any number of earth-based receivers to pinpoint their location.
- Antenna/Receiver
- Typical to have the two put together in a casing for the DIY market
- More advanced applications may have the antenna separate from the receiver, requiring shielded cabling to preserve the signal
- Active/Passive antennas (amplifier vs. no amplifier)
- Filtering of the signal
- Accuracy measured in meters in good conditions

Power Source

- Most commonly Lithium Polymer Batteries
  - Typically given capacity (in mAh), # of cells (Voltage), and C rating (max charge/discharge rate)
  - Max charge/discharge = Capacity * (C rating)
  - 14.7V, 1000mAh, 20C battery has a max discharge rate of 20A continuous
    - 1C depletes batteries in an hour
    - 10 C can deplete in 6 minutes
- Fuel Cells are being investigated
- Hybrid gas/electric being developed in Ontario
- Distance powering – via lasers or radio waves, even induction
  - see http://diydrones.com/profiles/blogs/get-distant-wireless-power-solution-for-drone-industry
- Tethered
  - umbilical cord to ground power





Li-Po vs Li-Ion

- Li-Po
  - Energy density around 150-225Wh/kg
  - Discharge rates of 10-50C are the norm
  - Lots of current available, can blast through batteries in 10 minutes
- Li-Ion
  - Can have higher energy density of 250-350 Wh/kg
    - 70%-100% more than Li-Po
  - Lasts longer (1000's of cycles if treated properly)
  - Has a max discharge rate around 2C
    - Limits its use in anything carrying a significant payload
  - Has been used in all battery powered endurance quads – 1h30 minute + flights, and electric vehicles

Flight times

- Battery capacity: C defined in W h
- Battery voltage: V_b in volts
- Peak discharge rate: $I_p = X\ C$, defined as a multiple of capacity
- Nominal discharge rate: $I_h = 1/2\ I_p$
- Flight time

$$t_f = \frac{C}{V_b I_h}$$

Payloads

- Often a camera
  - video or photography
  - Infrared, Hyperspectral, UV
- LiDAR (rare, but increasing in popularity)
- Can be a pizza, beer, or medical supplies
- Typically the whole reason the UAV exists in the first place
  - Check out Aerobugs for inspiration

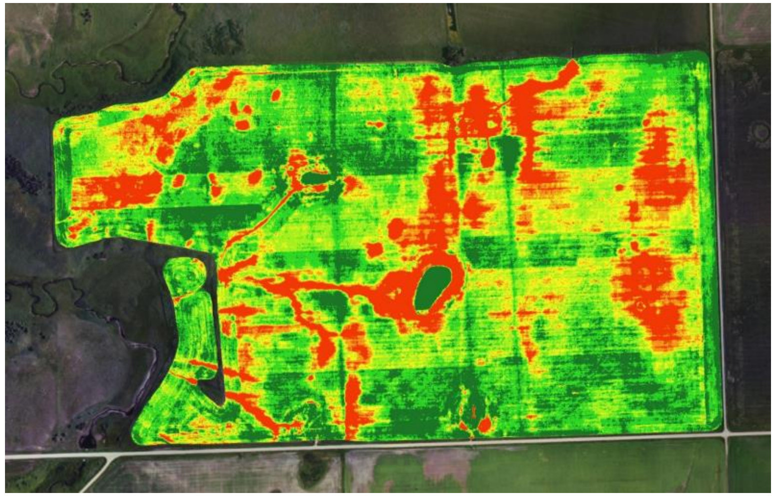
Applications

Applications: Mapping

Application: Agriculture

- Typically agriculture is interested in a few things:
  - Precision agriculture – new, developing field.
    - Imagery/information collection
    - Application (pesticide, bugs, seeds, etc)

- Most uses involve having a Near Infrared (NIR) camera to calculate normalized difference vegetation index (NDVI)
  - indication of vegetation health
  - Still some debate as to utility, but gaining acceptance



Application: Videography

Questions?