“Small UAS and Delivery Drones: Challenges & Opportunities”

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Presentation at: 14th Symposium on Overset Composite Grids and Solution Technology

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During the past one-decade, there has been phenomenal growth of small-unmanned aerial systems (UAS) for hobbyists and rapidly expanding commercial and military applications. Impetus for this dramatic expansion has been due to explosion of mobile technology in terms of microelectronics, data processing and transmission capability, superior batteries, miniaturized integrated programmable chips, and innovations in computer vision and videography/photography. However, there are many challenges to overcome before these small UAS can be used for routine commercial and military applications, which include sizable payload and range, stringent navigation/guidance requirements, and precision takeoff/landing and robust autonomous flight in constrained and low-altitude gusty environment. The objective of this presentation is to cover state-of-the-art of small UAS and delivery drones, identify technology gaps and key scientific barriers, and present future research needs for high payoff applications.

Alfred Gessow Rotorcraft Center

UNIVERSITY OF MARYLAND

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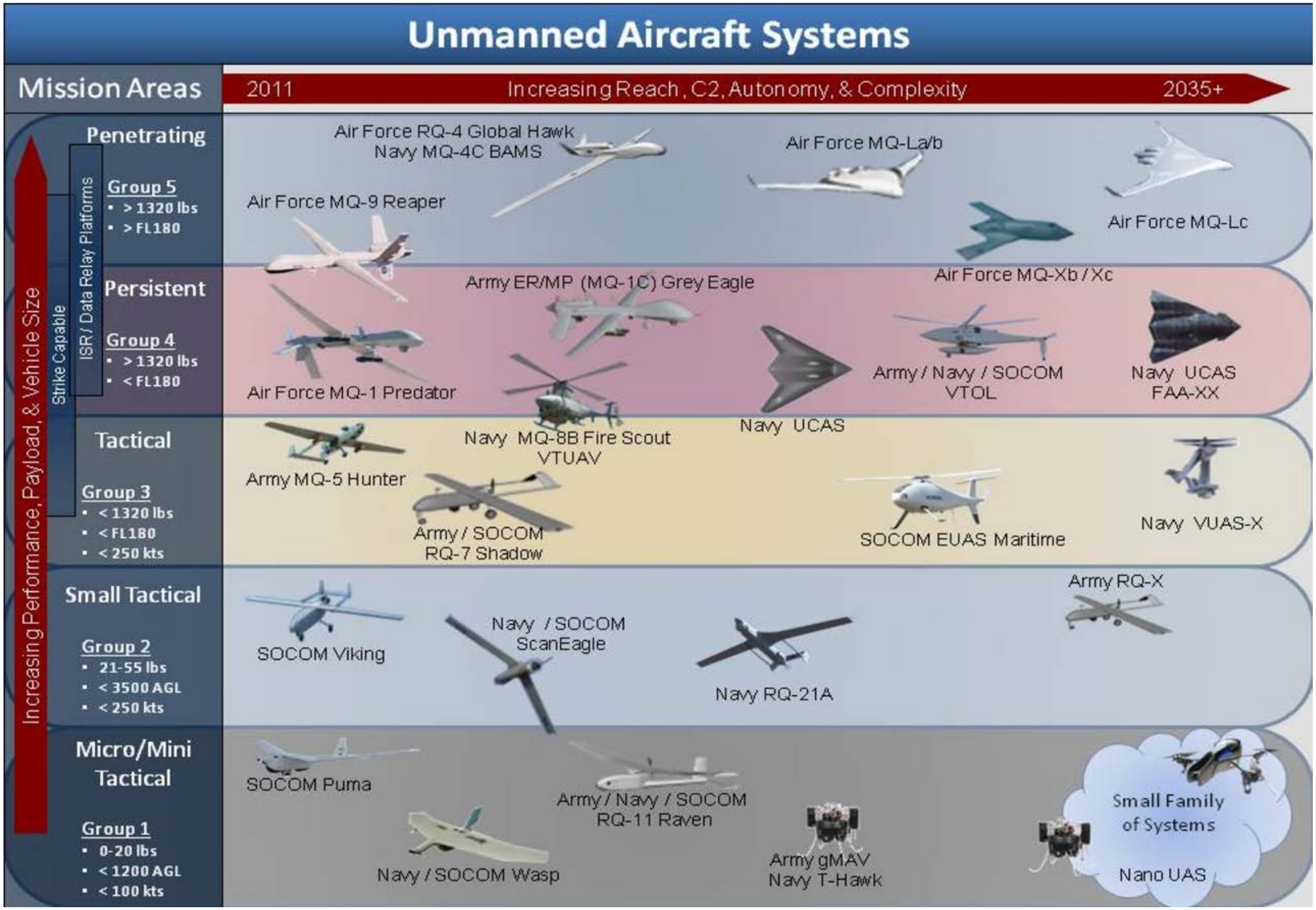
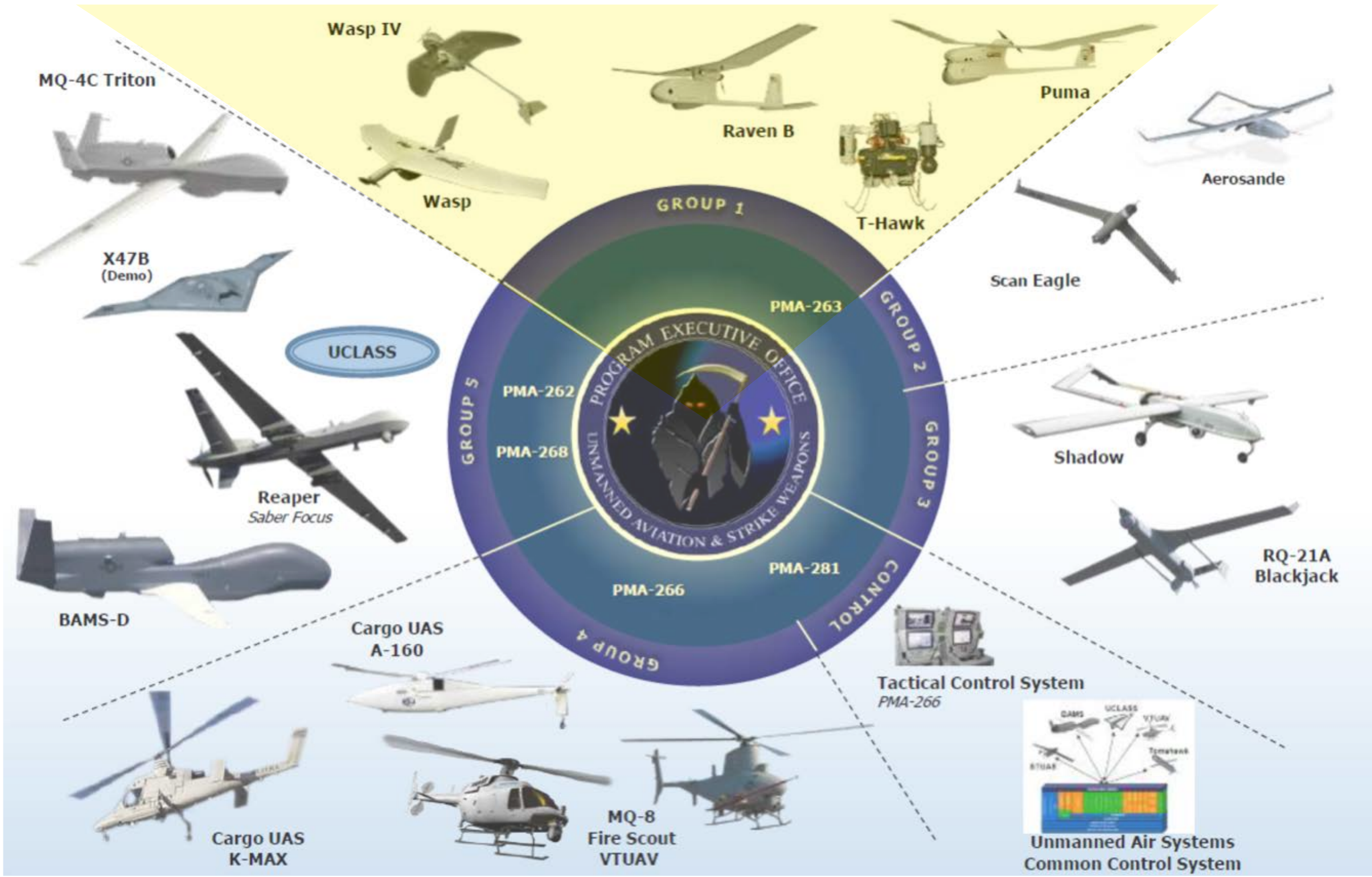
Small Unmanned Aircraft Systems (sUAS) & Delivery Drones

UAS Categories



UAS Categories

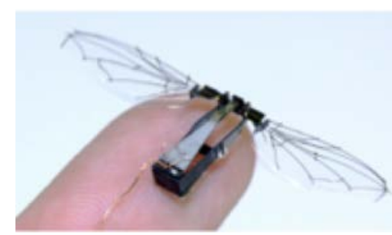


Small UAS: Definition

- **Micro Air Vehicle (MAV) (1997, DARPA)**
  - No dimension exceeds 15 cm (6 inch)
  - Gross weight <100 gram
  - Endurance ~ 60 minutes
  - Payload capacity of ~20 gram

- **Nano Air Vehicle (NAV) (2007, DARPA)**
  - No Dimension exceeds 7.5 cm (3 inch)
  - Gross weight < 25 gram
  - Payload ~ 2 gram

- **Pico Air Vehicle (PAV) (Harvard)**
  - No Dimension exceeds 1-2 cm
  - Gross weigh < 10 grams



Delivery Drones: Definition

- Payload: 5-lb (covers 86% of packages)
- Radius: 10-mile
- Altitude: 130-200 ft
- Endurance: 60 minutes

- Google
  - Tail Sitter with wing: 5-ft
  - 4 Propellers
  - Gross weight 22 lb (3 lb package)
  - Height 2.5-ft
- Amazon
  - Octocopter

Google: Tailsitter

Amazon: Octocopter

Delivery Drones

Google for burrito and pharmaceutical deliveries; max speed 75 MPH; radius 6 mile

Google project wing, payload 1.5 kg

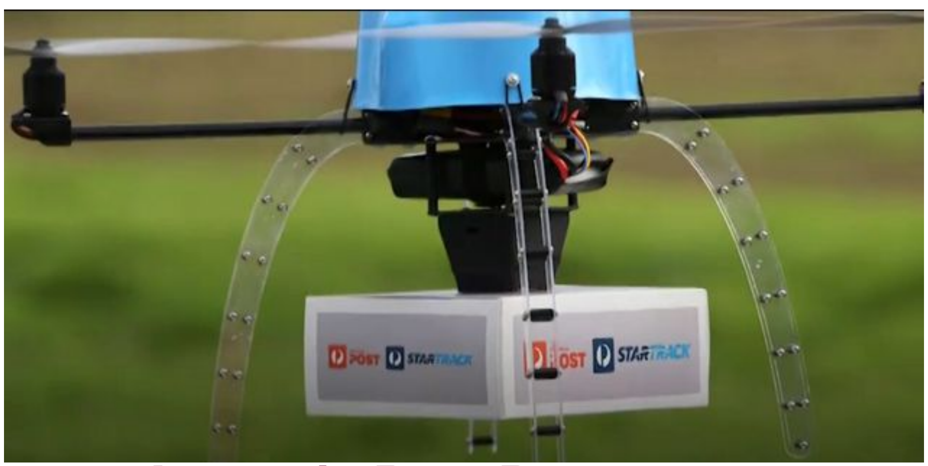
Amazon Prime Air delivery up to 4 lbs

Amazon Prime Air delivery

Delivery Drones

DHL Parcel Drone, 4.4-lb payload; 5 mile; speed 40 mph

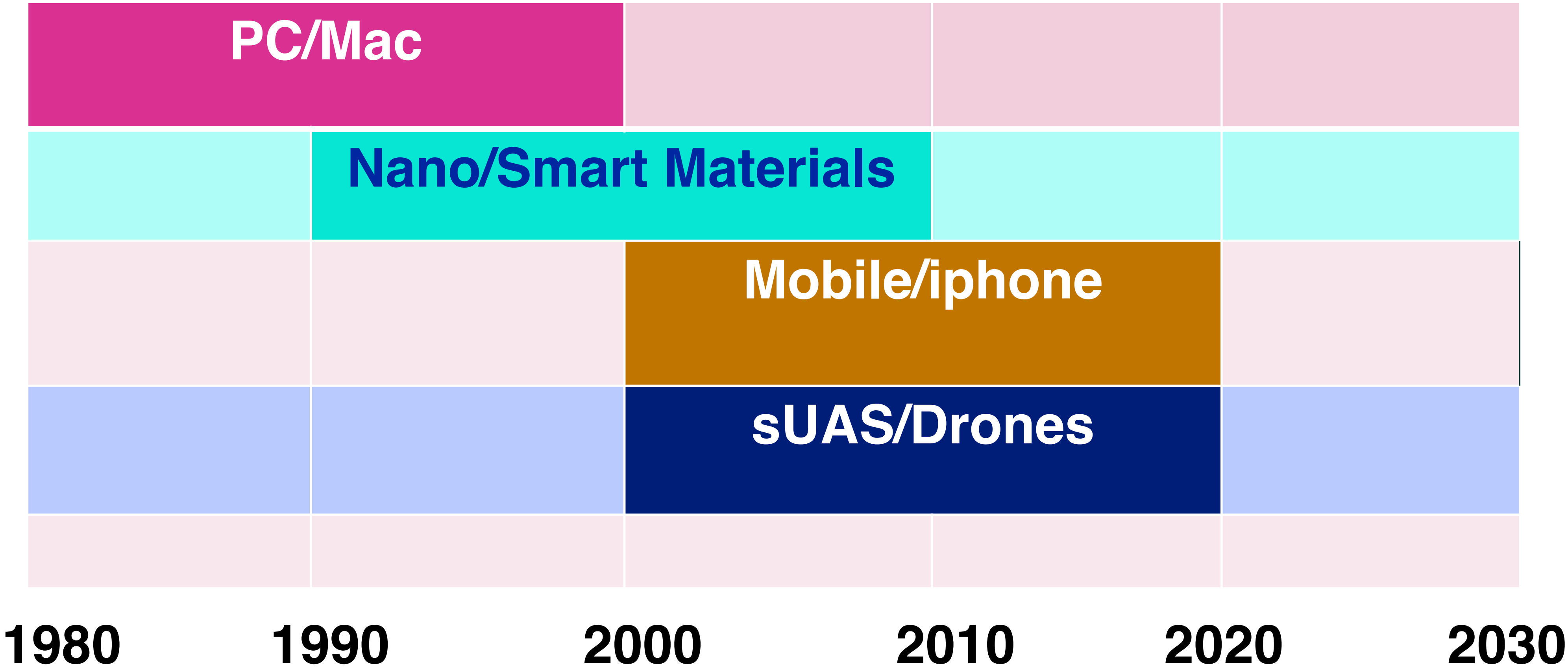
Flirtey Delivery Drone 6-rotors 10 miles radius, 5.5 lb payload



Australia Post Drone

Dominos Pizza Delivery Drone

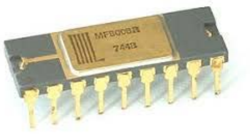
Technology Developments 1980-2020



Small UAS: Key Drivers

- **Microelectronics: Miniaturized sensors, servos, and autopilot availability**

- **Microprocessing: IT and transmission power growing (mobile technology)**



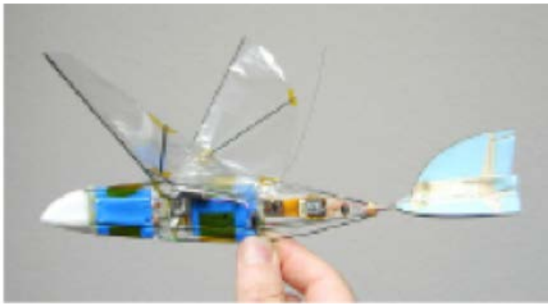
- **Advances in microfabrication and 3D printing**

- **Numerous potential defense/civil applications**

- **Low cost systems**

Small UAS: Advantages

- Compact and lightweight (portable)
- Rapid deployment (low risk)
- Real-time data acquisition
- Low radar cross-section & stealth system (low noise)
- High Maneuverability
- Low cost systems



Small UAS: Disadvantages

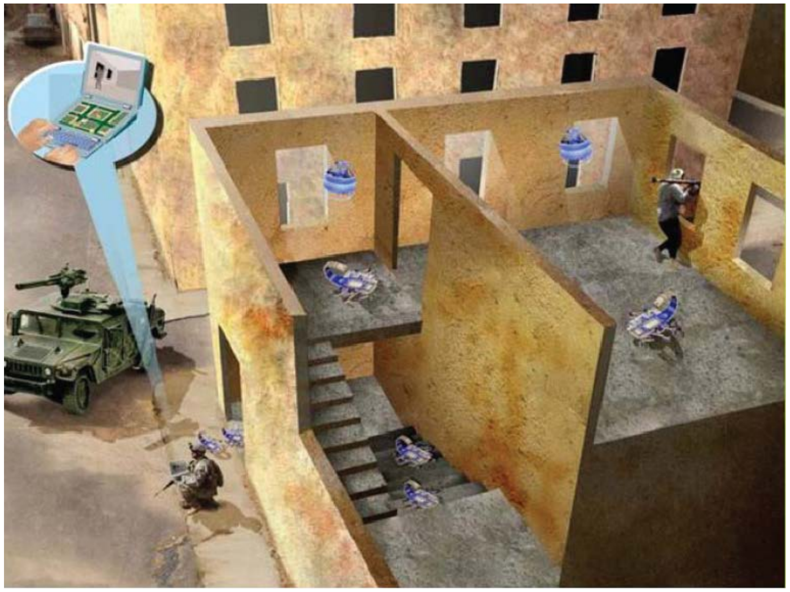
- Safety concern (Collision with other flying objects, can cause personal injury)
- Potential for weaponizing

- Security threat (stealth)
- Privacy issues (legality)
- Susceptible to damage (gust etc.)

- Need of countermeasures against multiple sUAS (swarms & collaborative groups)

Potential Applications

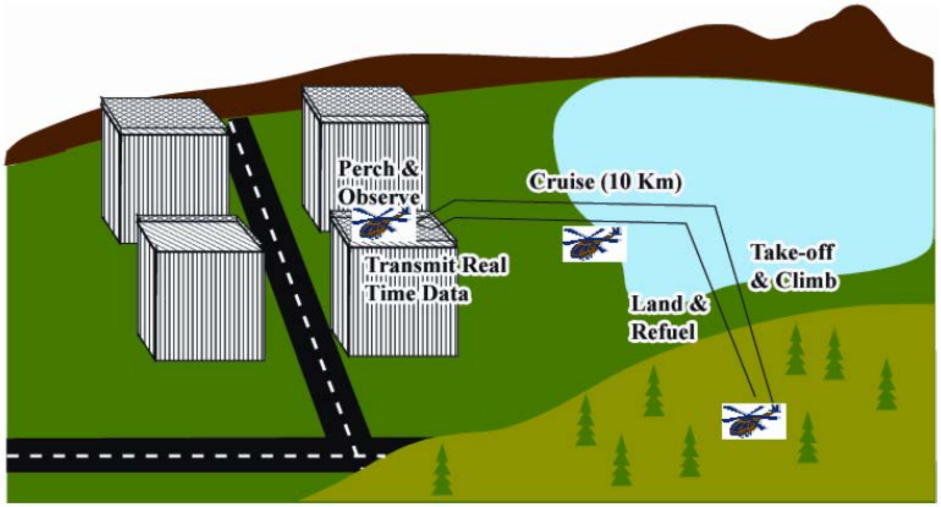
DoD Applications: Small UAS



Scenario 1: Small unit building search
Challenges: Hover and low speed, compactness, quiescent airflow

Scenario 2: Small unit cave / demolished building search
Challenges: Hover and low speed, Compactness, medium gust

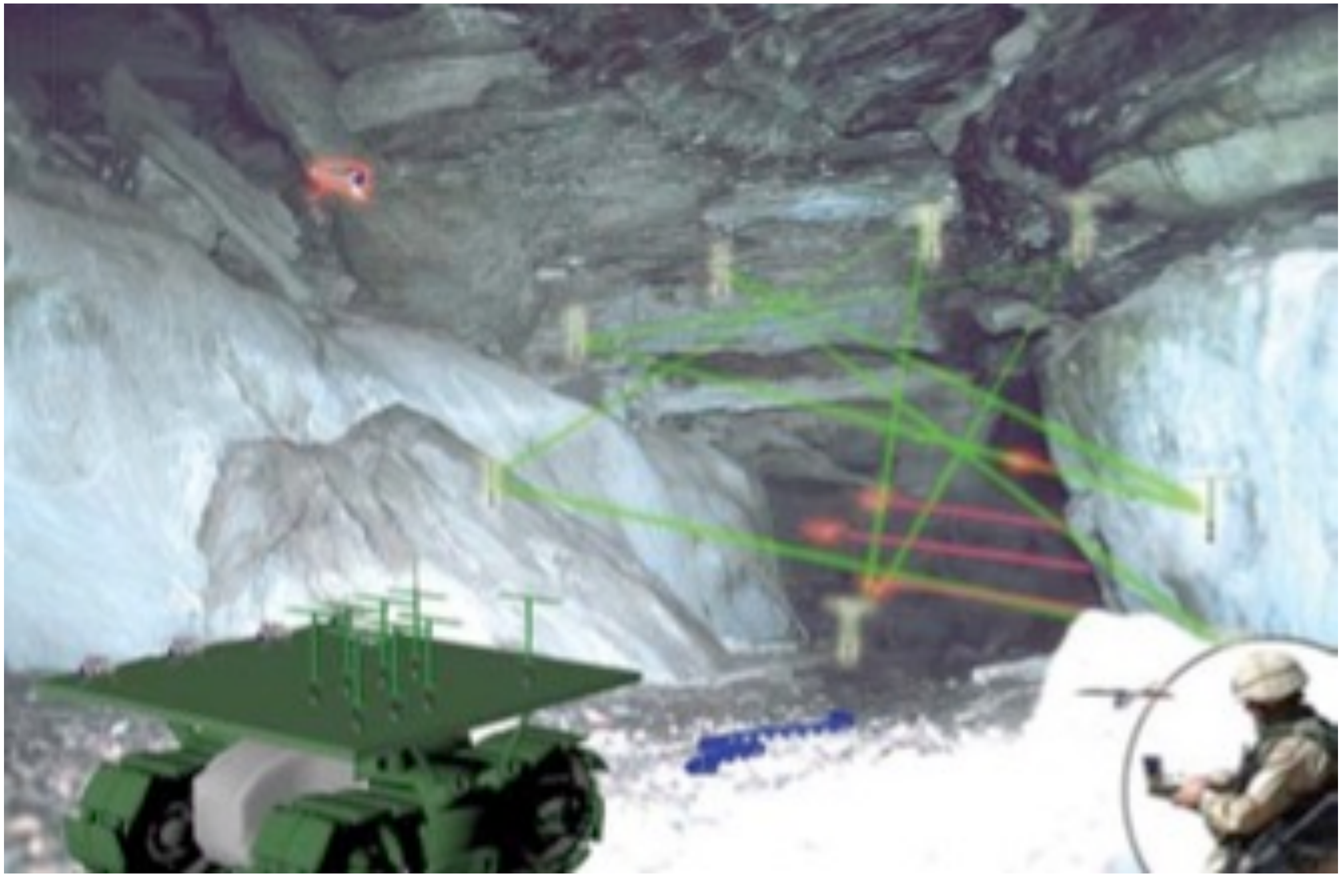
DoD Applications: Small UAS



Scenario 3: Autonomous small unit perimeter defense
Challenges: High speed, range and endurance, strong gusts

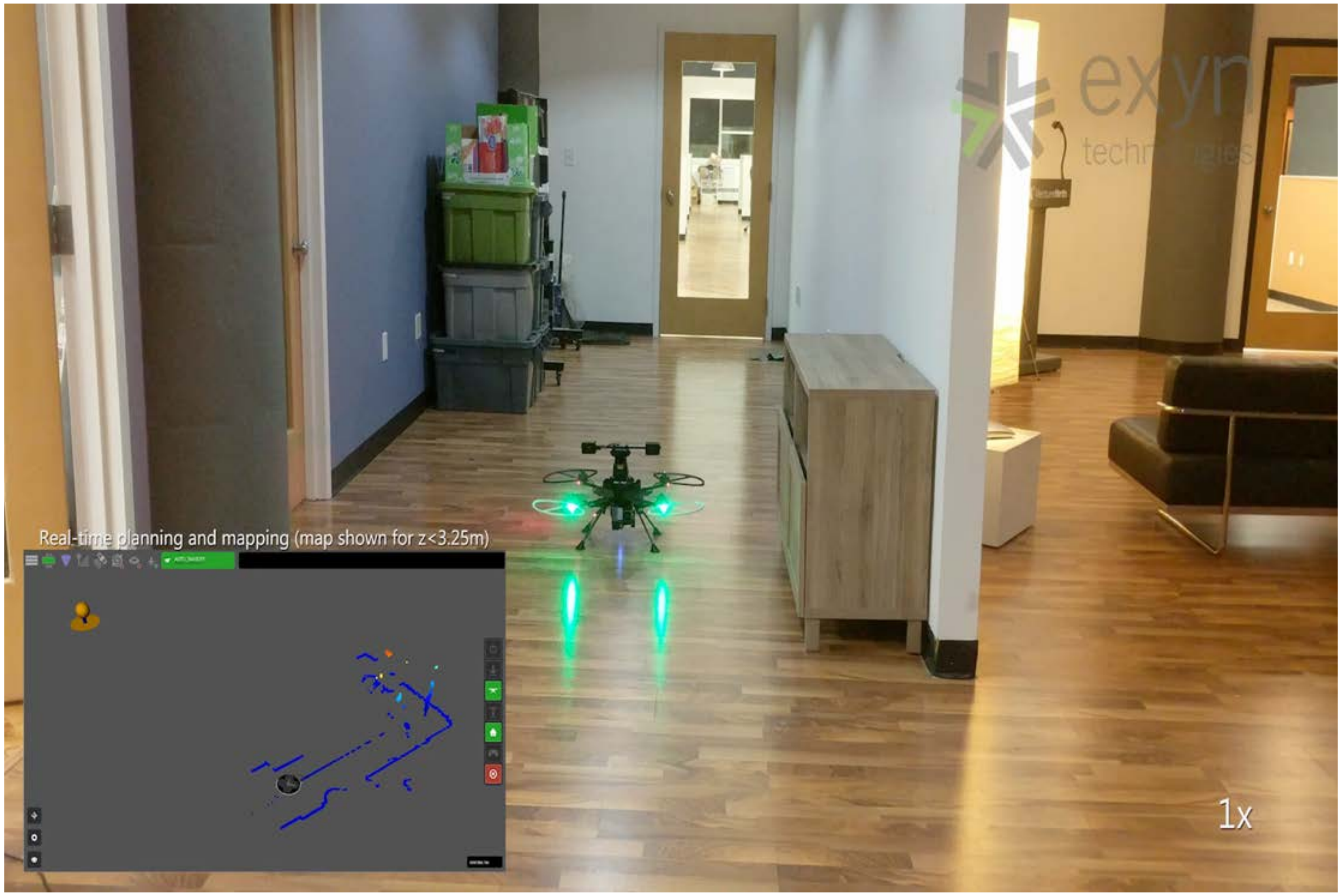
Scenario 4: Over-the-Hill; Around the corner Reconnaissance mission
Challenges: Out-of-sight operation, low noise, strong gust

DoD Applications: Small UAS



Scenario 5: Operations in D3 (Dull, Dangerous, Dirty) Environments
Challenges: Low light, Stealth, strong gusts

Indoor/Outdoor Navigation & Mapping



Civil Applications: Small UAS

Drug delivery in remote places

Videography/Photography

Fire rescue operations

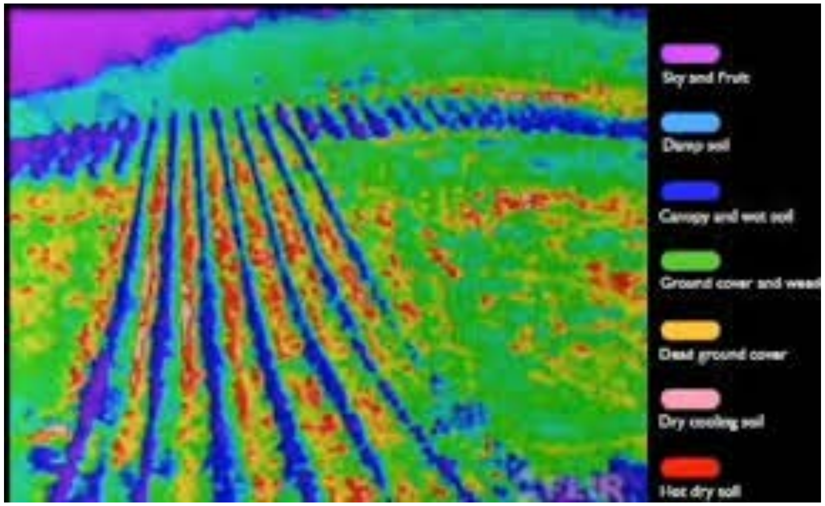
Traffic monitoring

Agriculture Applications: Small UAS

Crop spraying

Crop estimation

Agriculture mapping



Crop health Monitoring

Civil Aviation Applications: sUAS

Danger: Can Crash into airplane; suction into engine inlet

Scanning runway for debris using high resolution cameras

Inspection of Airliner: UK

Drones for scaring birds at Edmonton Airport

Civil Aviation Applications: sUAS

Drones for scaring birds at Edmonton Airport (Sonic bird repeller)

Civil Applications: sUAS

Infrastructure Inspection:
Bridges
Wind turbines
High voltage cables/towers
Fuel/Gas pipes
Paving lots and roads

Detection Hazard Agents:
Nuclear
Biochemical
Mines

Security:
Tagging and targeting
Border law enforcement
Counter drug operation
Hostage rescue operation

Asset Mapping: sUAS

Courtesy Exyn Technologies

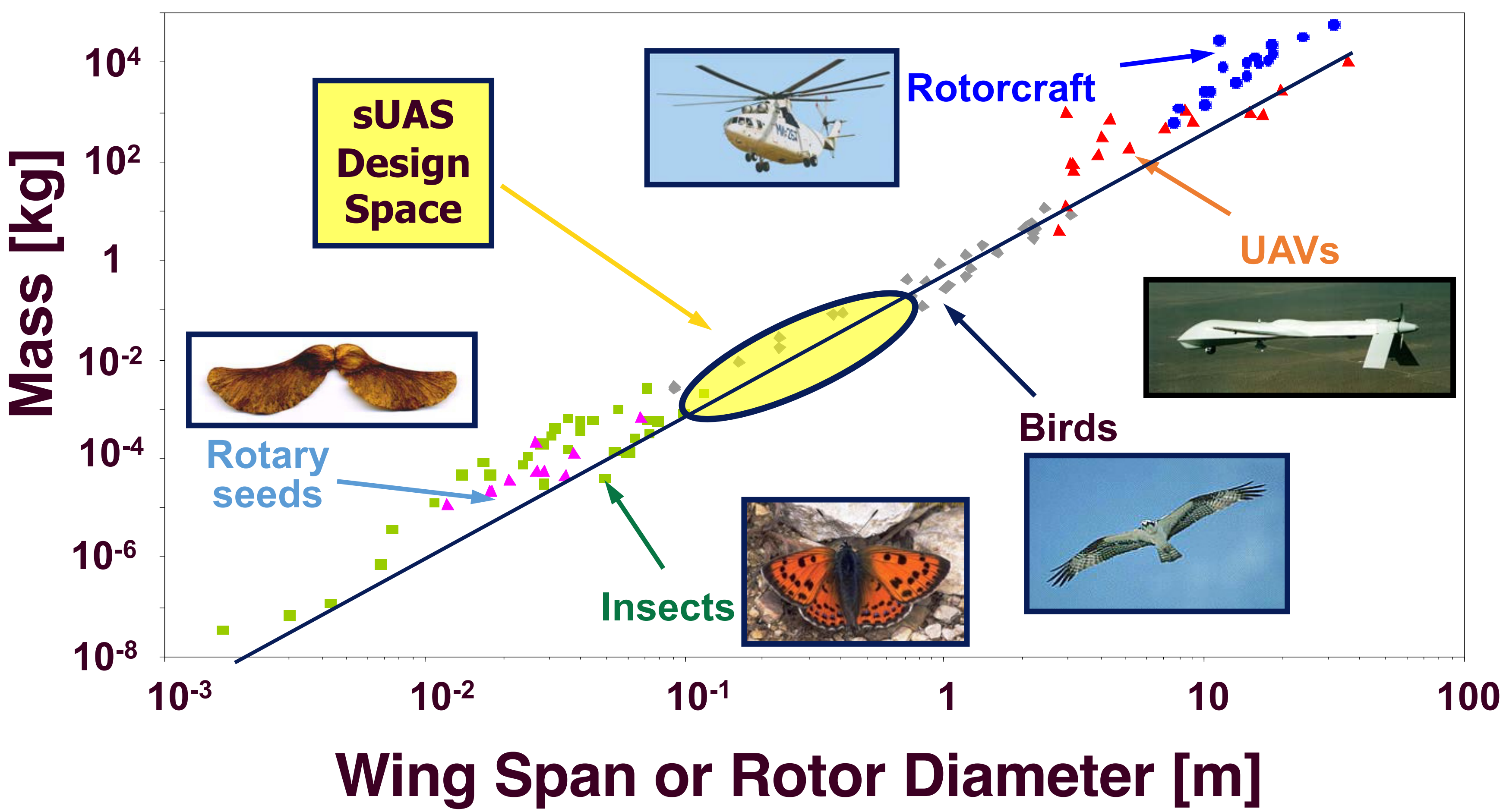
Hurricane relief surveillance

Capability for sUAS platforms

Capability = (Mobility)(Intelligence)(Multiplicity)

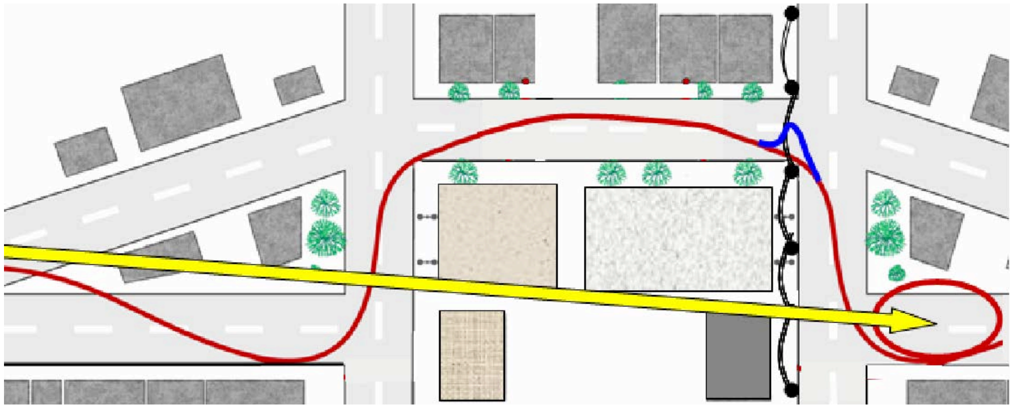
	Larger	Smaller	N*small=large
Mobility	↓	↑	↑
Gust Sensitivity	↑	↓	No chanage
Frequency	↓	↑	No change
CPU MIPS	↑	↓	no change
Multiplicity	↓	↑	N/A
Sensing	no change	no change*	$O(N^2)$ ↑
Communication	↑	↓	$O(N^2)$ ↑

Perspective on Scale



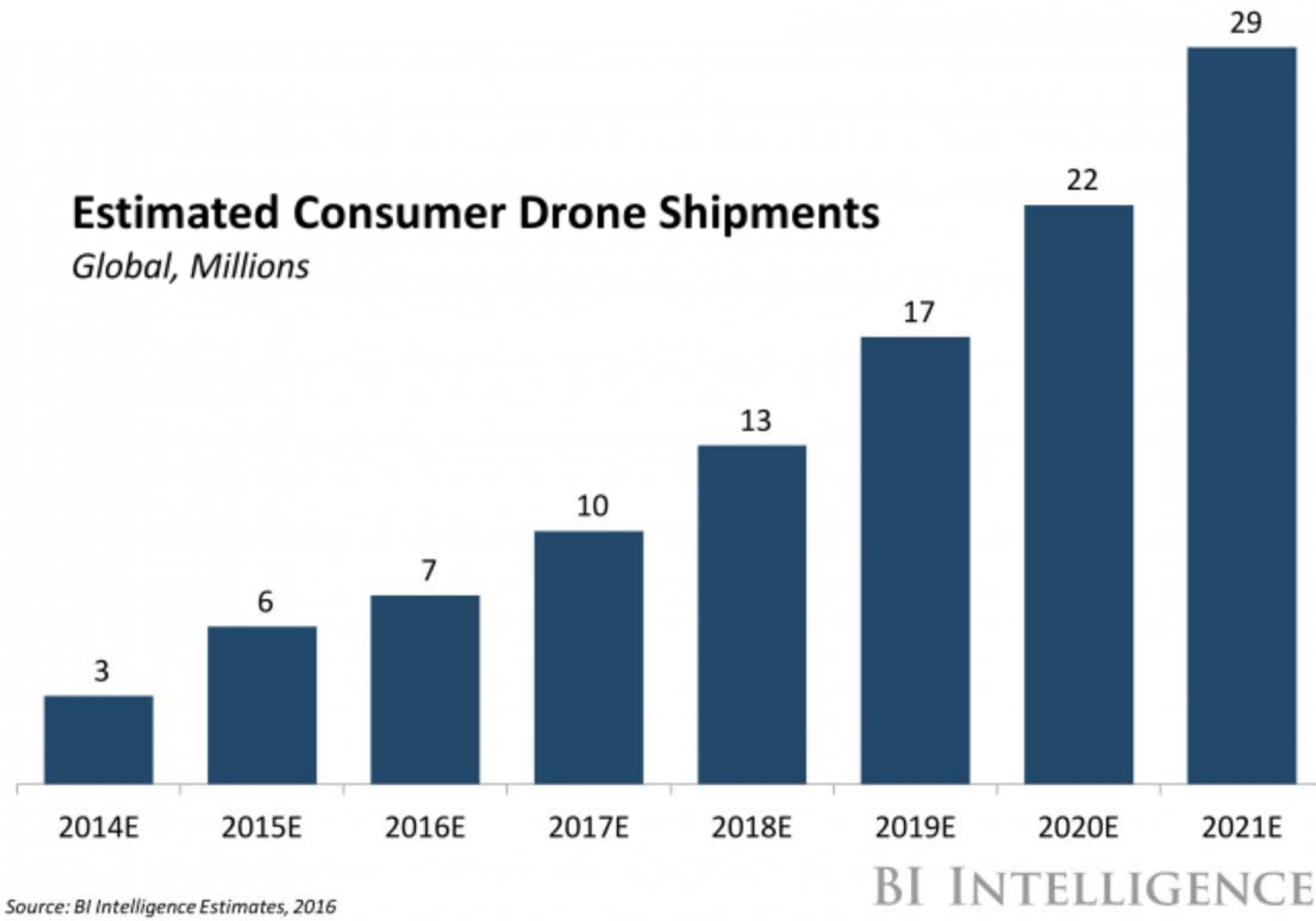
Small UAS: Challenges

- Size, weight, power (SWaP) constraints for sensing/processing
- Low Reynolds aerodynamics (Limited performance)
- Susceptibility to gust (disturbance of order of capability)
- Small scale sustained power generation/storage
- Operate in obstacles-rich environment (un-mapped)

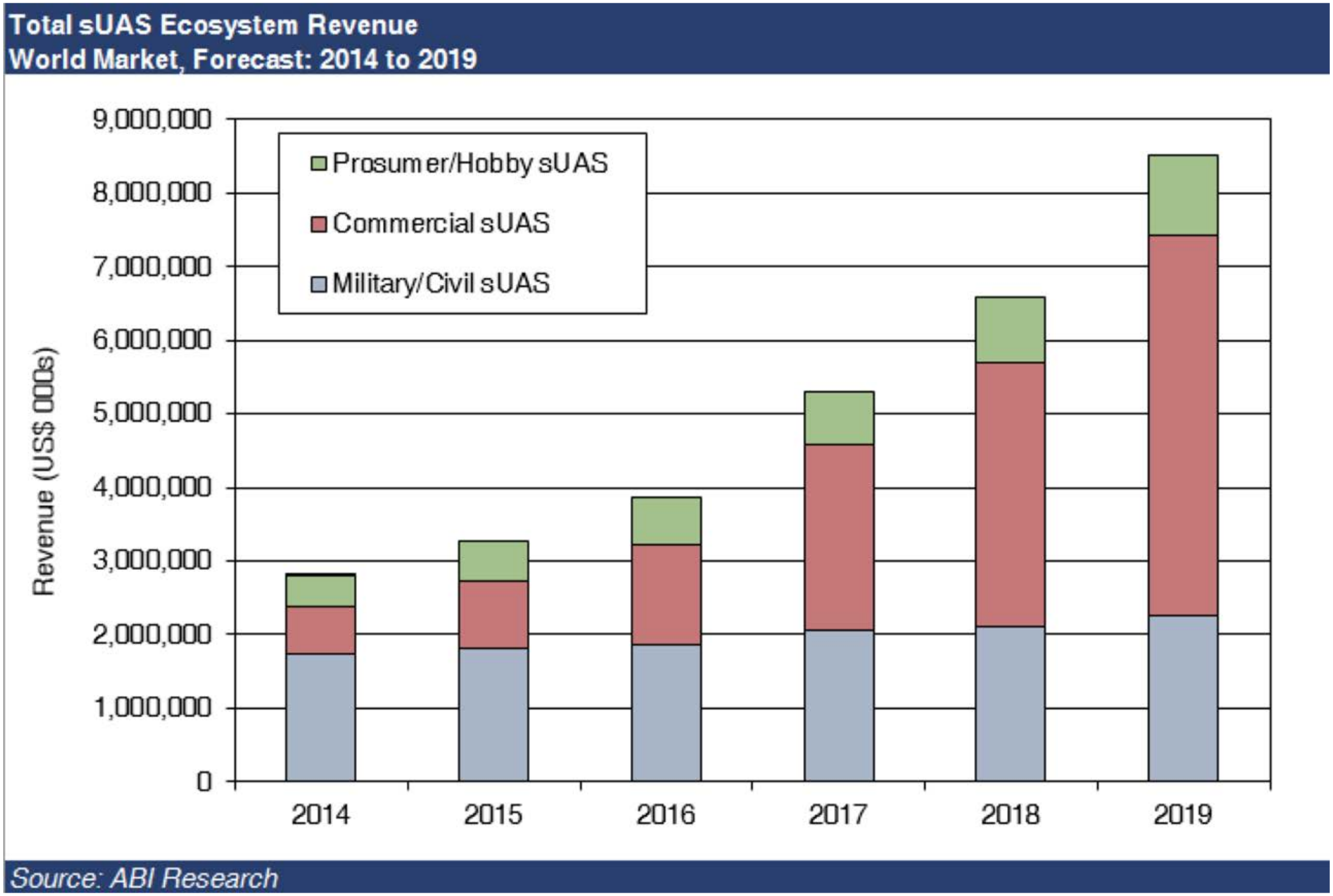


Navigation in Urban Clutter

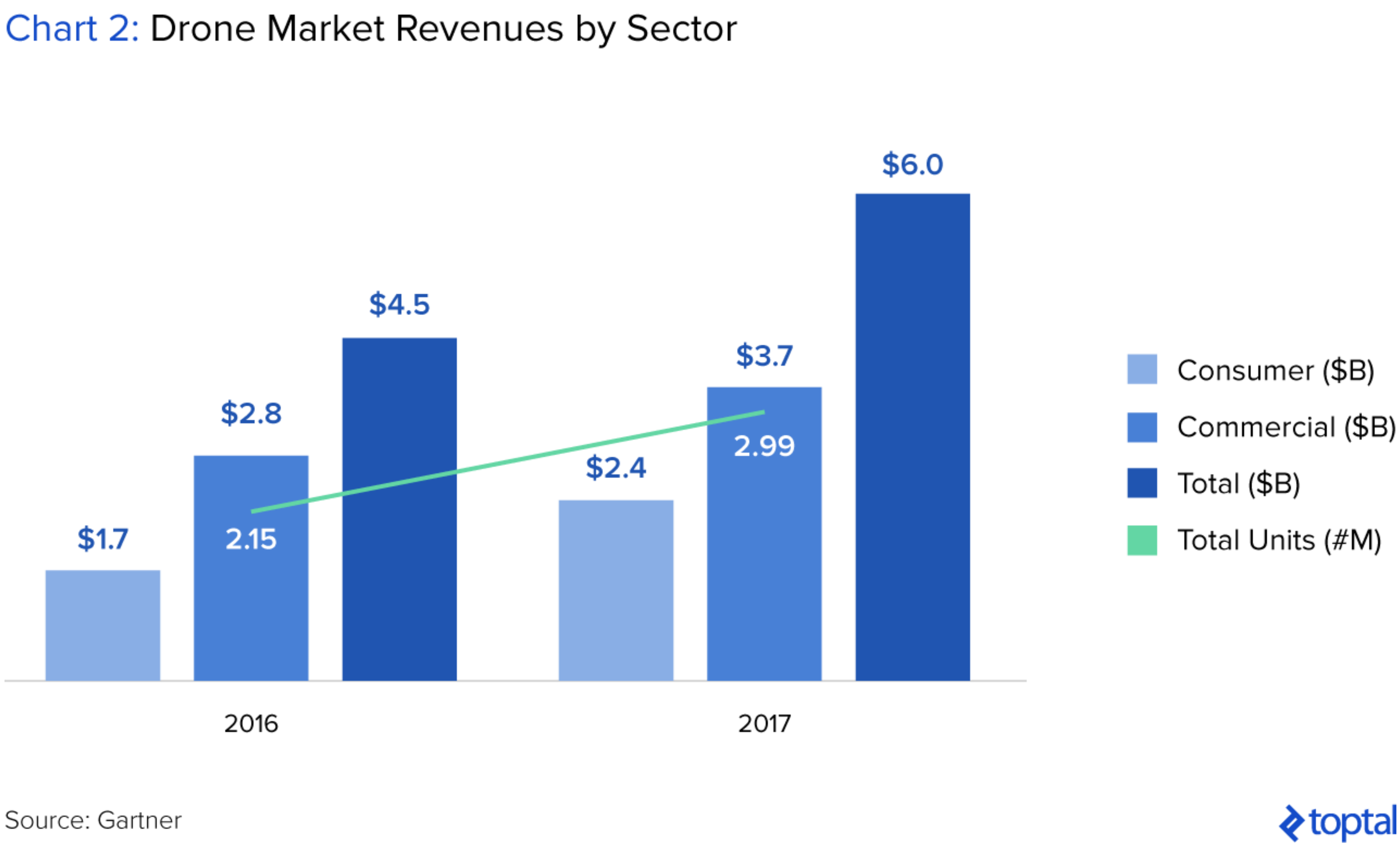
Market:
Small Unmanned Aerial Vehicles (sUAS)



Market:
Small Unmanned Aerial Vehicles (sUAS)



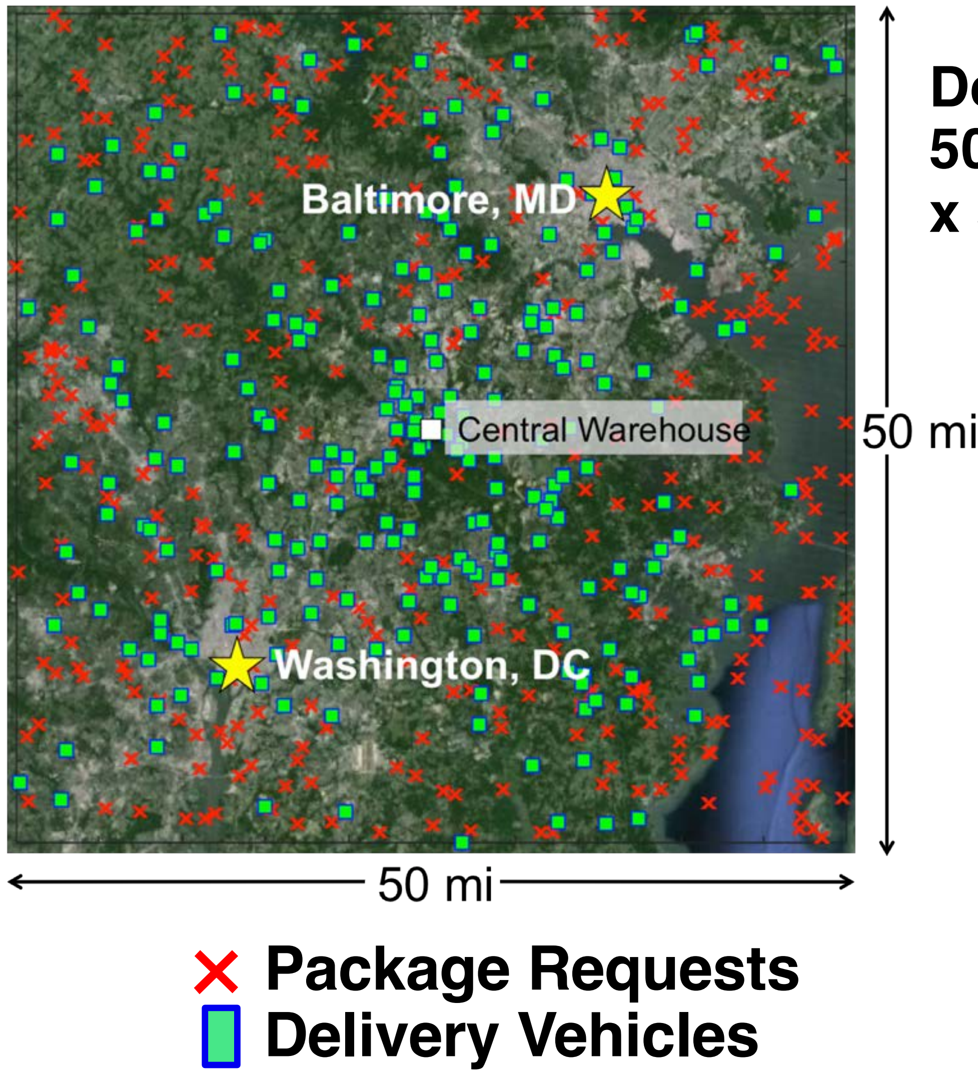
sUAS & Drones Market



sUAS Market:

$15B industry, projected to grow to $25B by 2020

Package Delivery: DC Region

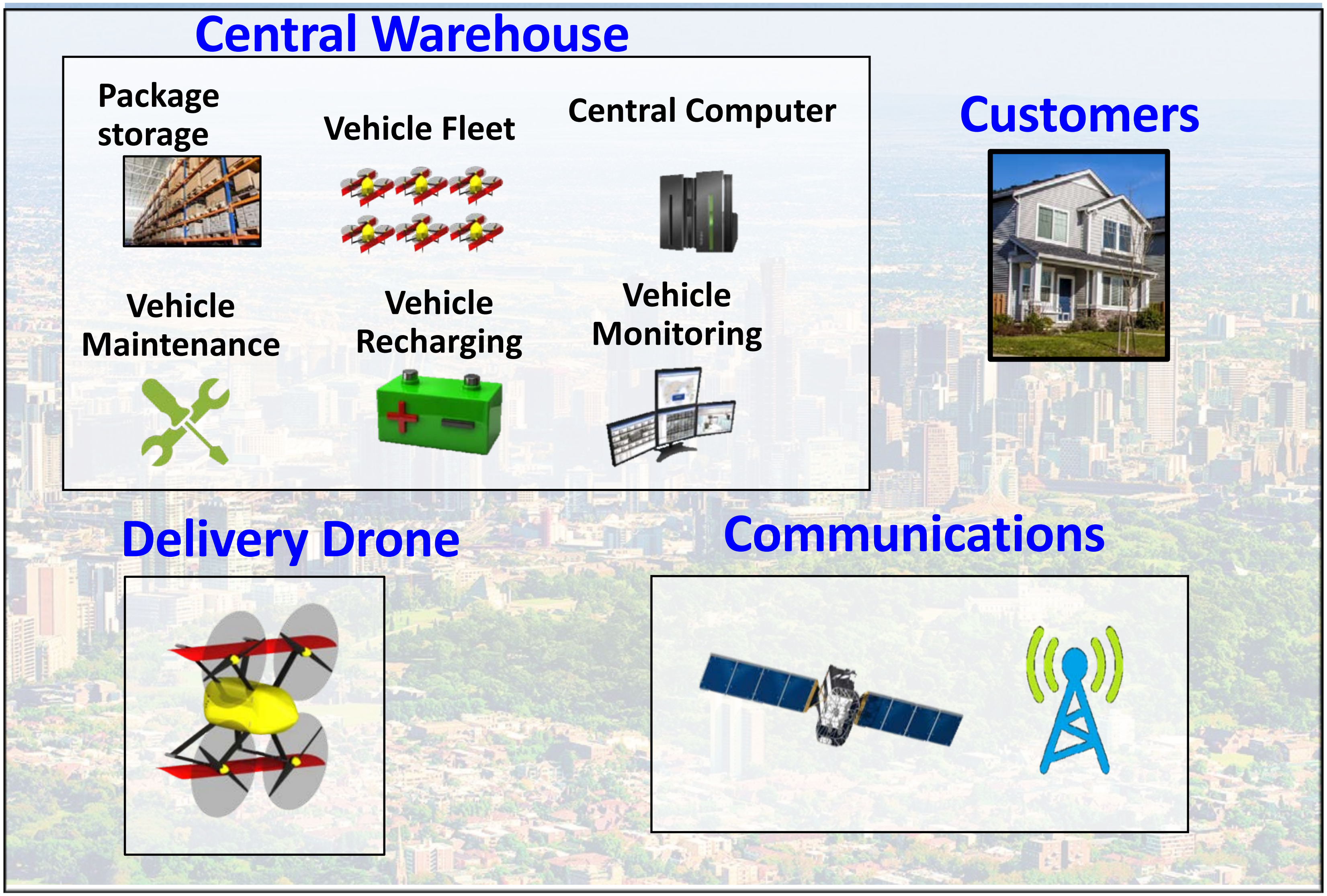


Delivery within 2 hours
5000 packages per day in 50 x 50 mile delivery area

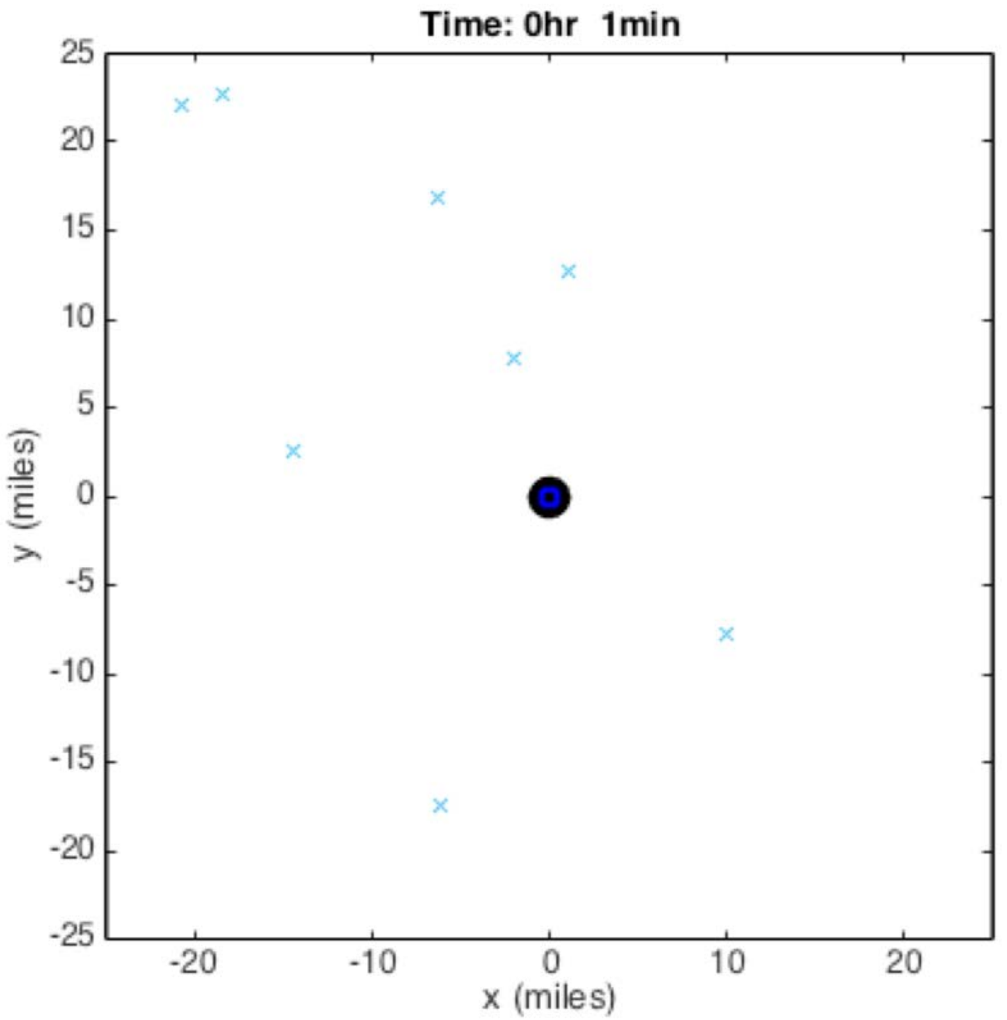
443
Peak package requests

300
vehicles in air at a time

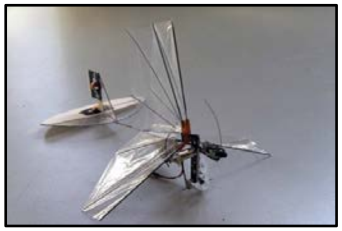
Package Delivery: DC Region



Package Delivery Simulation



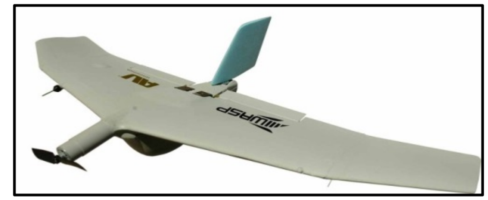
Existing sUAS: State-of-Art



Delfly II

AR Parrot Drone

DJI Phantom

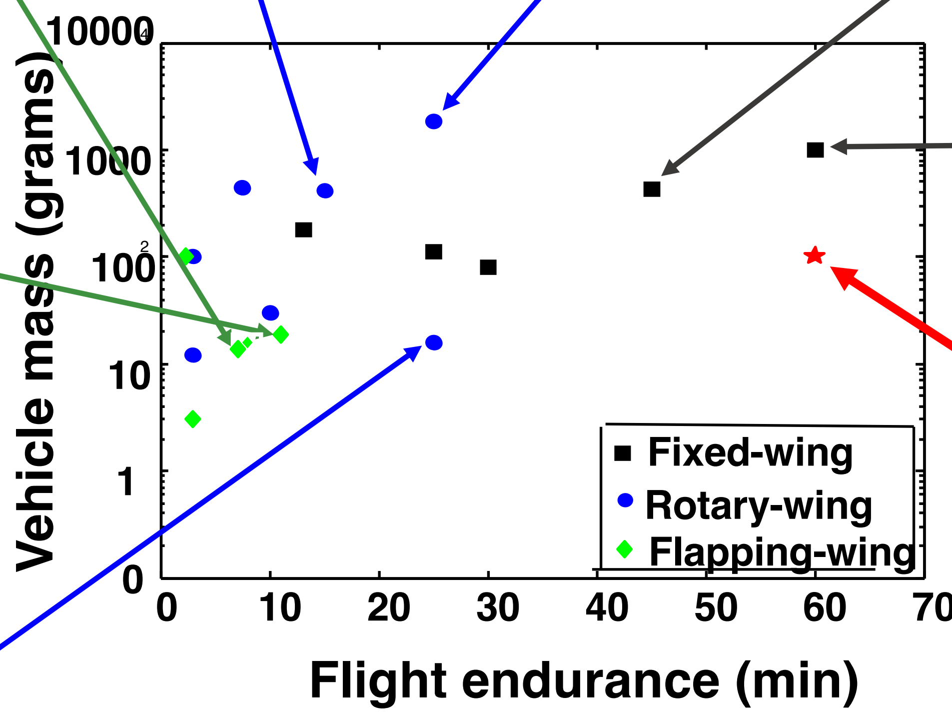


AV Wasp III

Aurora Skate

AeroVironment Hummingbird

Proxdynamics Black Hornet



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Target MAV (100g, 60 min)

Required Capabilities: Aerial Vehicles

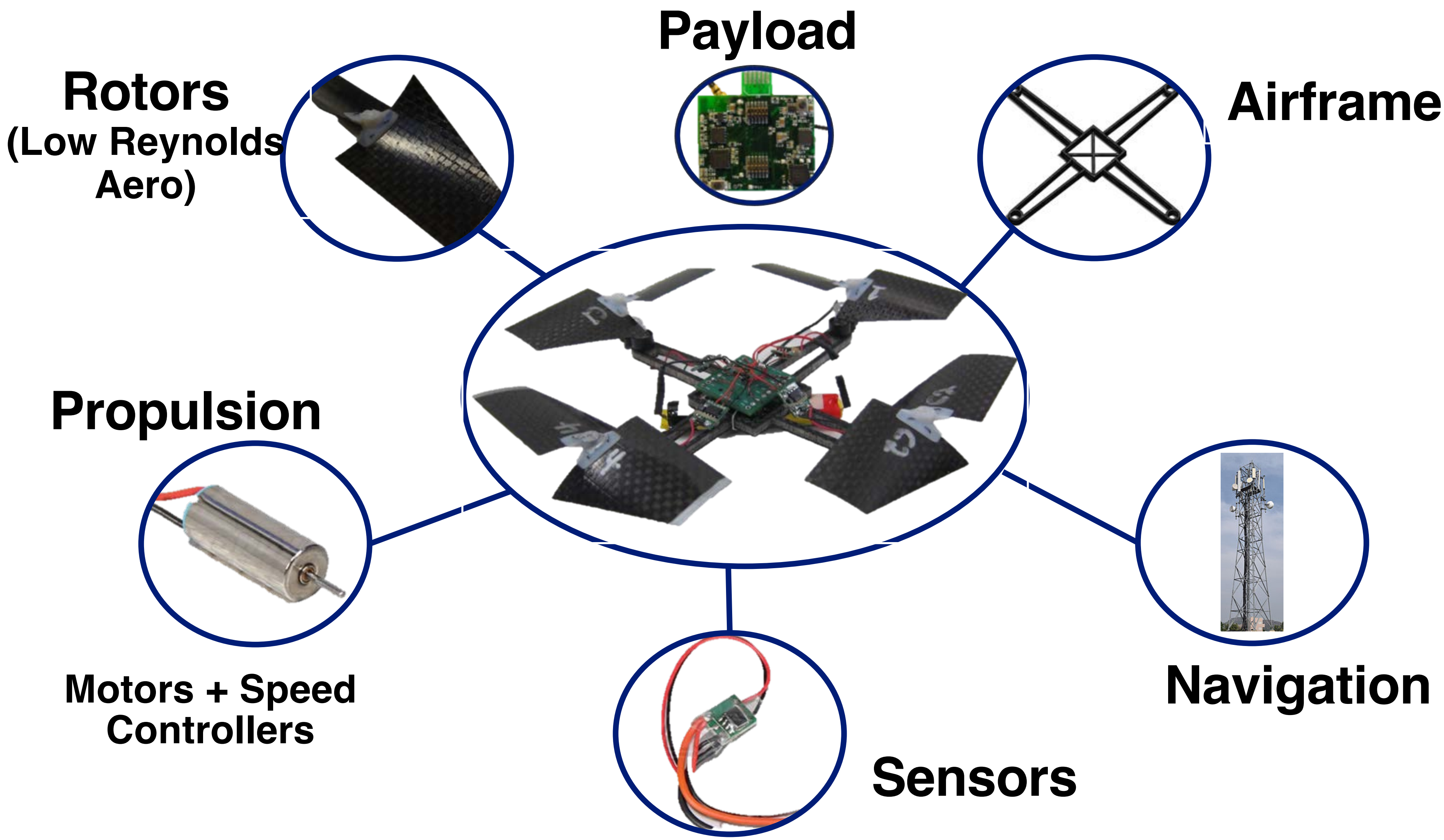
Flight
- Hover in place (no fixed-wing)
- Forward speed
- Gust tolerance
- Maneuverable (control authority)

Mode Transition
- Land/perch
- Pick-up/drop-off payload

Autonomy
- Control, estimation & trajectory planning (onboard capability)
- Obstacle avoidance capability

Need feedback control: fast, computationally simple and robust

sUAS: Constituents



Low Reynolds Number Aerodynamics

Reynolds Number

$$\text{Reynolds Number} = \frac{\text{Viscous Force}}{\text{Inertial Force}} = \frac{\rho U L}{\mu}$$

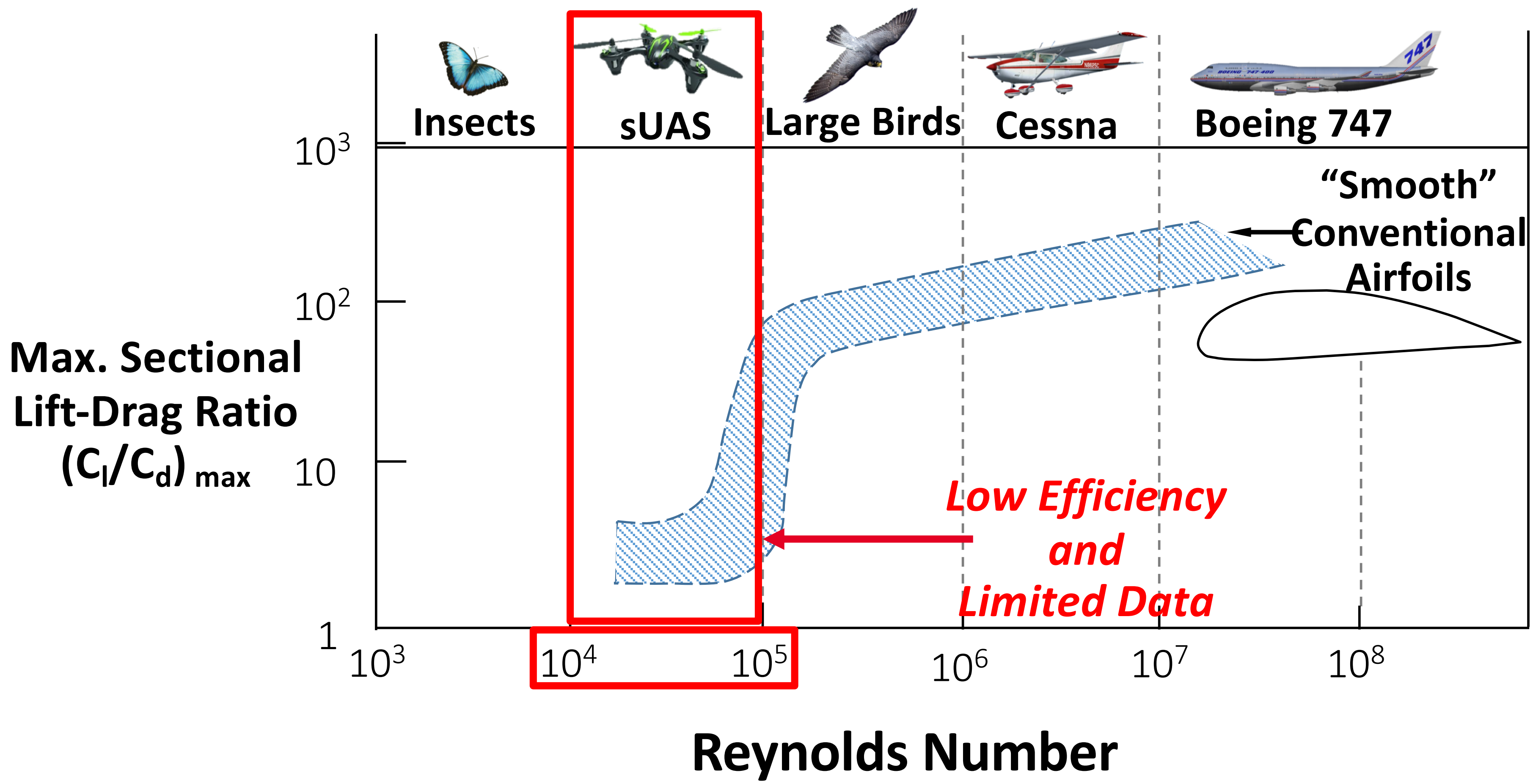
Full-Scale Helicopter Reynolds > 10^6
sUAS Reynolds Numbers = 10^4 to 10^5

Laminar Flow → Turbulent Flow

Transition
10^4 to 10^5

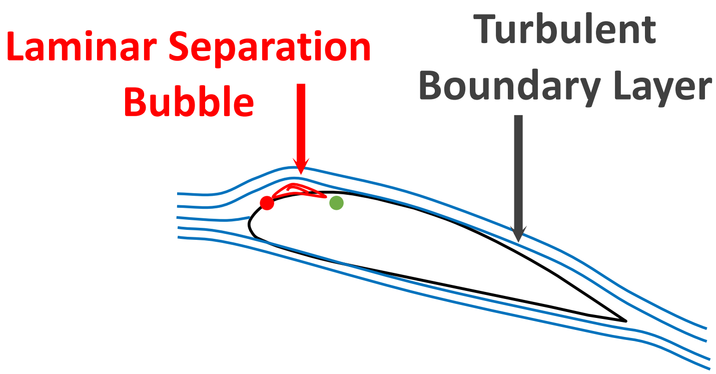
Laminar Flow: Viscous forces dominate, more vulnerable to separation to adverse pressure gradient; C_l /C_d, C_{lmax}, C_{dmin} are function of Reynolds number.

Low Re Aerodynamic Losses

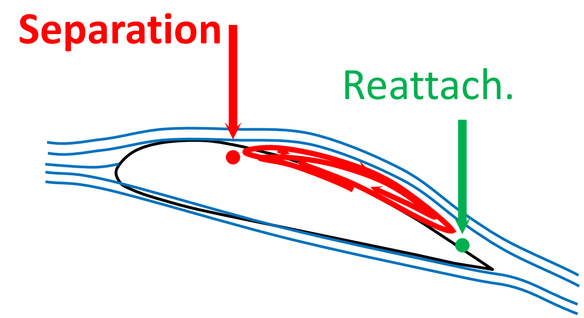


Low Reynolds Flow

"High" Reynolds Number
100,000 < Re < 1,000,000

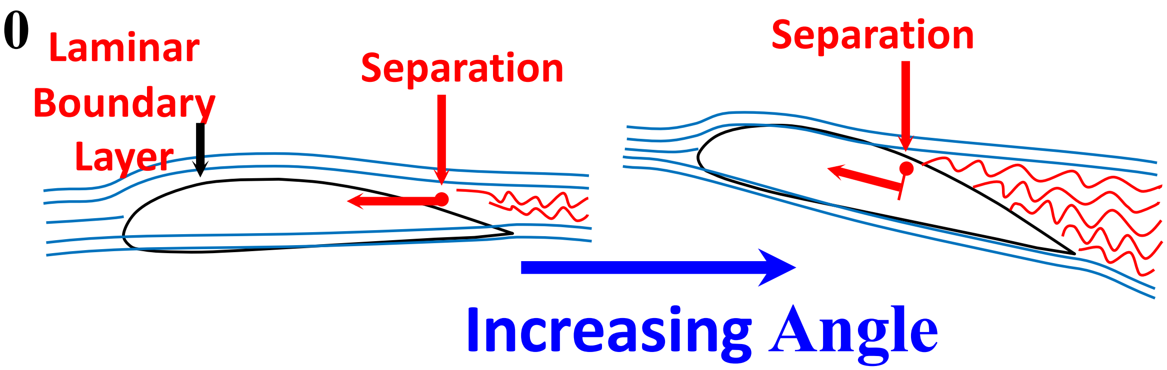


Moderate Reynolds Number
50,000 < Re < 100,000



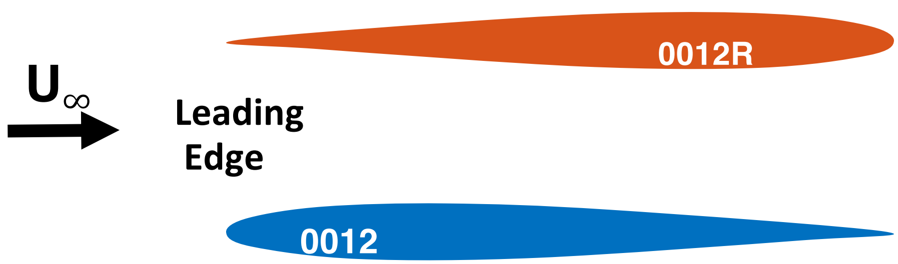
Low Re Flows Prone to Complete Separation

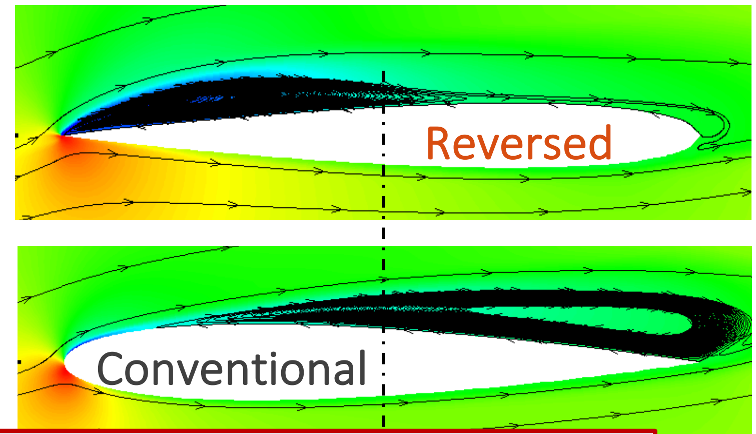
Very Low Reynolds Number
10,000 < Re < 50,000



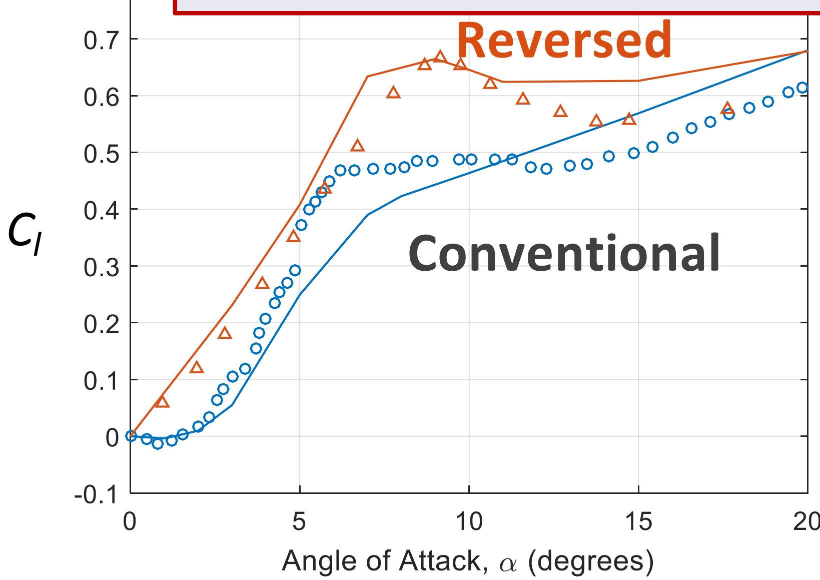
Conventional vs Reversed

Reynolds Number = 20,000

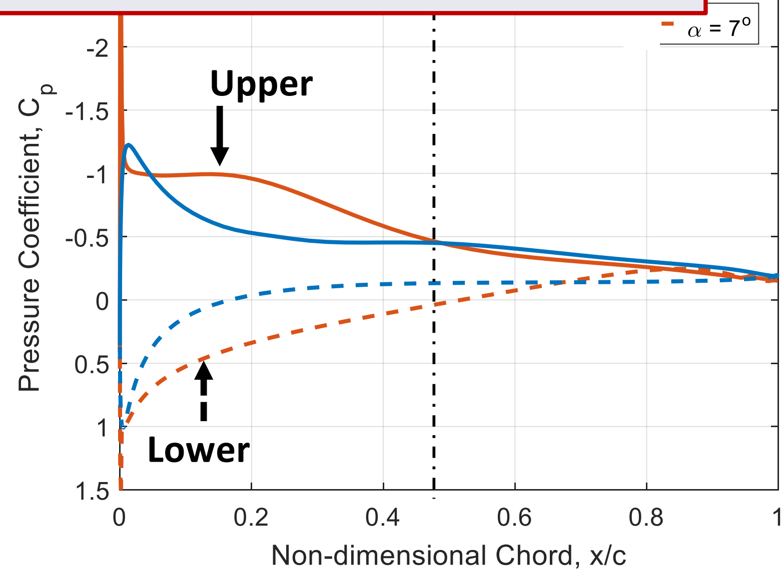




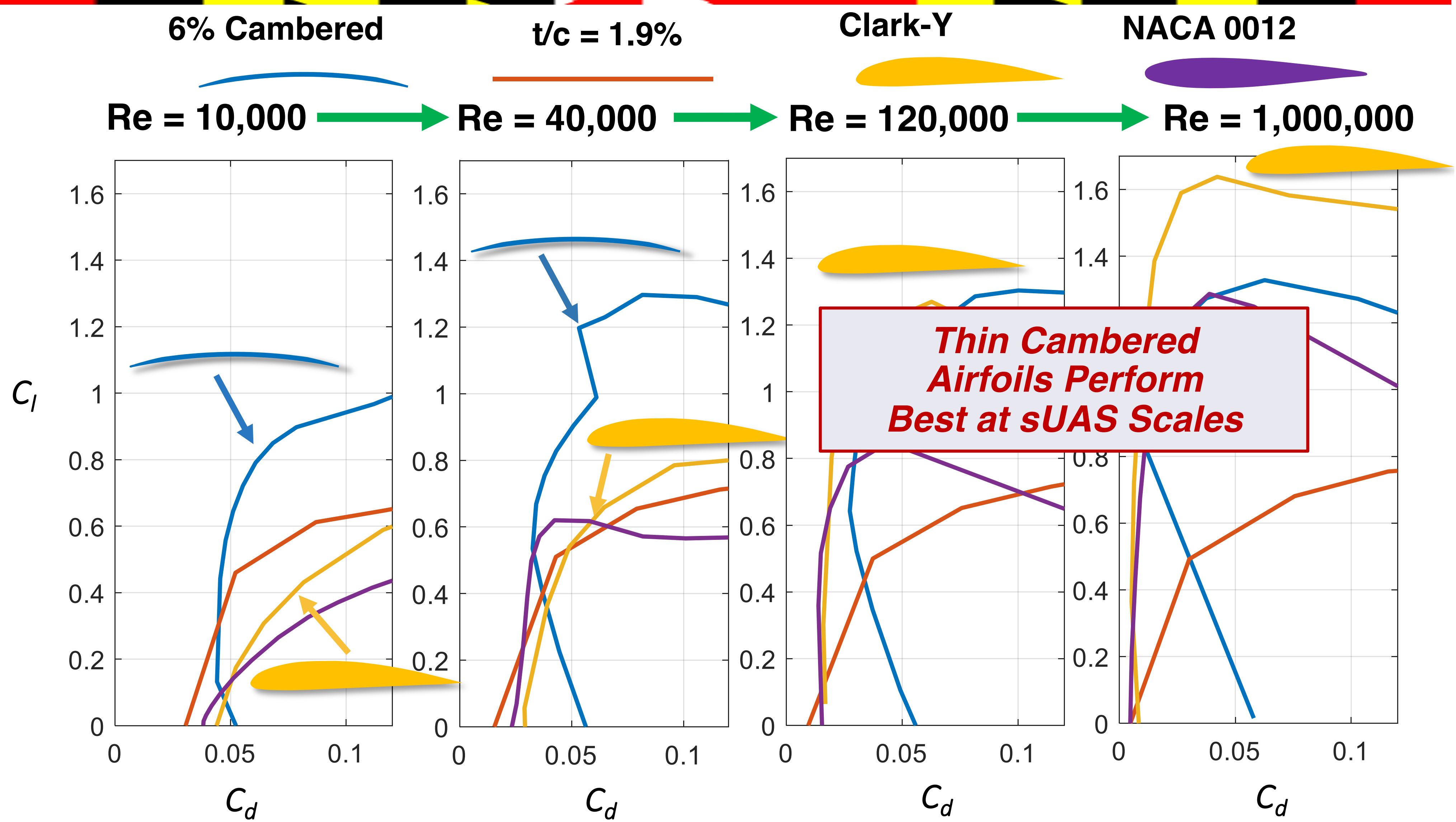
Decreasing LE Bluntness Improves Low Re Performance



Exp: Ohtake, (1996), Laitone (1997)

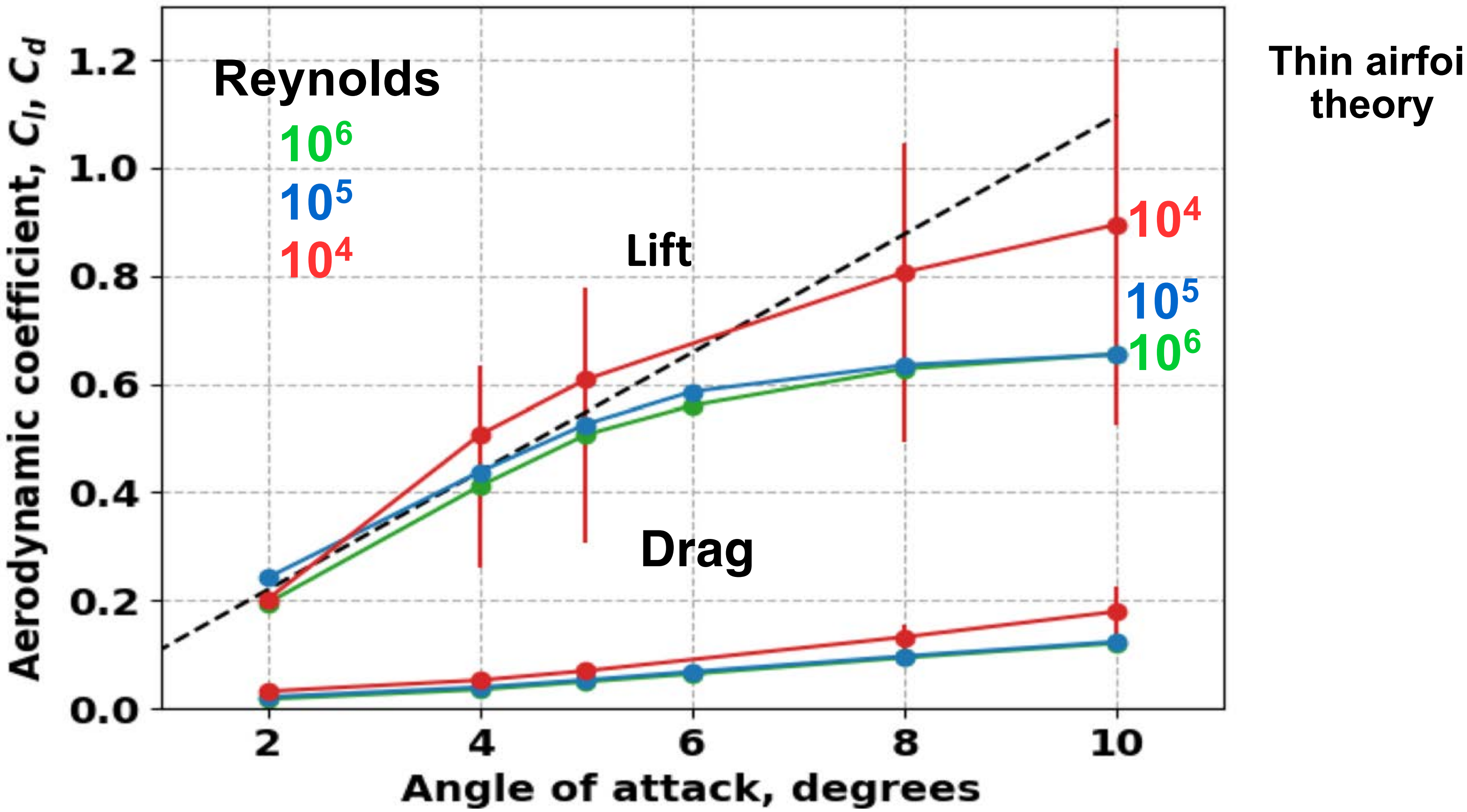


Effect of Reynolds Number



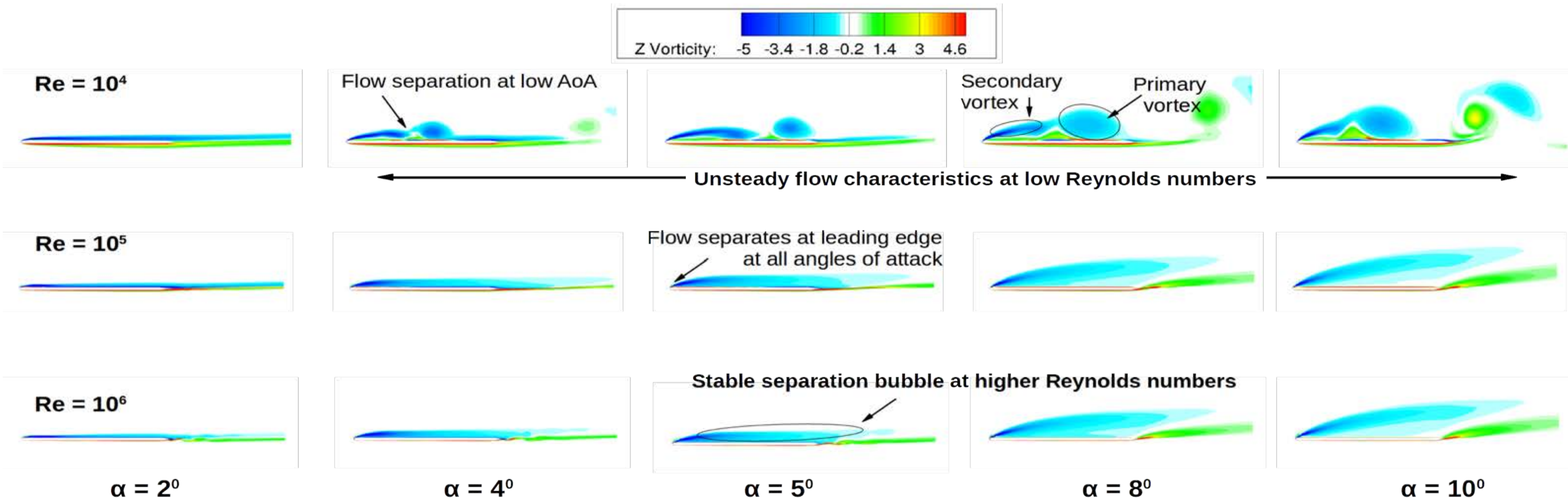
Flat Plate in Steady Flow

Steady flow, Flat plate, Reynolds number 10^4, 10^5, 10^6



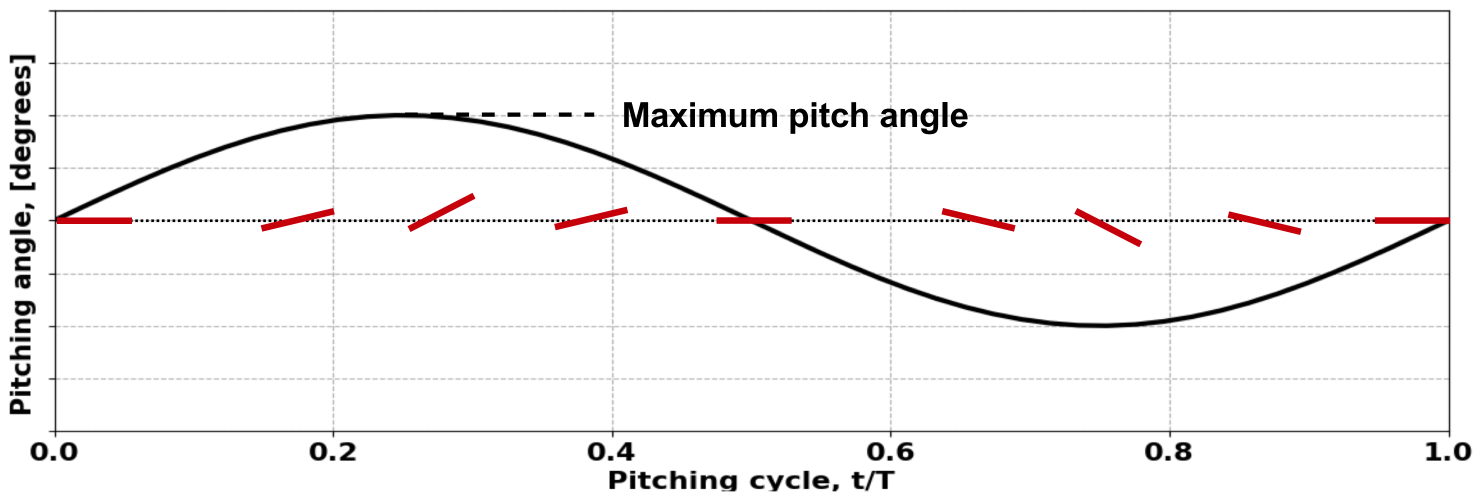
Large oscillatory aerodynamic forces at 10^4

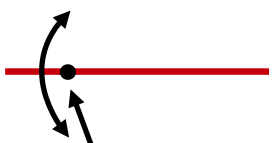
Effect of Reynolds Number



Harmonic Pitching Flat Plate

Reynolds number 10,000, Pitch amplitude 5^0 sin(ωt)





Quarter-chord

Reduced frequencies examined: *k* = 0.005, 0.05, 0.5

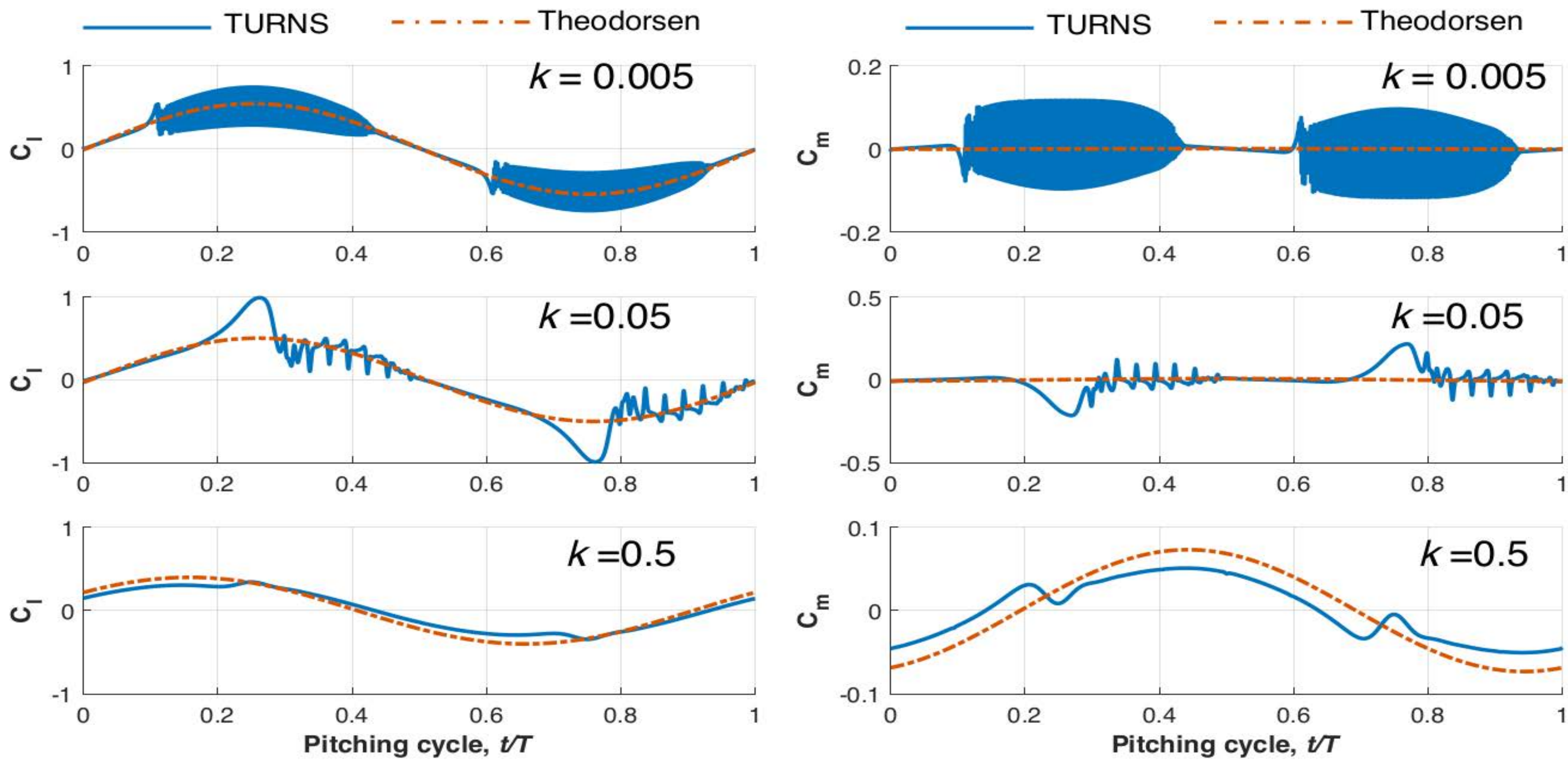
Quasisteady — Unsteady — Highly unsteady

Reduced frequency k = $\frac{\omega c}{2U}$

U is free stream velocity
c is chord
ω is frequency of oscillation

Effect of Reduced Frequency

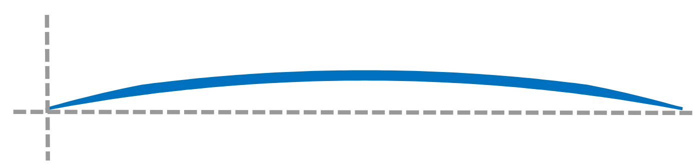
Reduced frequency k 0.005, 0.05, 0.5 Reynolds number 10,000, Pitch amplitude 5^0 sin(ωt)



As reduced frequency k decreases, increased presence of higher frequency content

Low Reynolds Aerodynamics: Conclusions

- Low *Reynolds* flows are very susceptible to separation
  - Airfoil characteristics (C_l, C_d and C_m) are ***nonlinear and sensitive to Reynolds number***
- Minimum thickness, moderate camber and sharp leading edge are important for airfoil efficiency at low *Re*ynolds (10,00 to 100,000)
  - 1% *t/c*
  - 6% Camber
  - Sharp Leading Edge



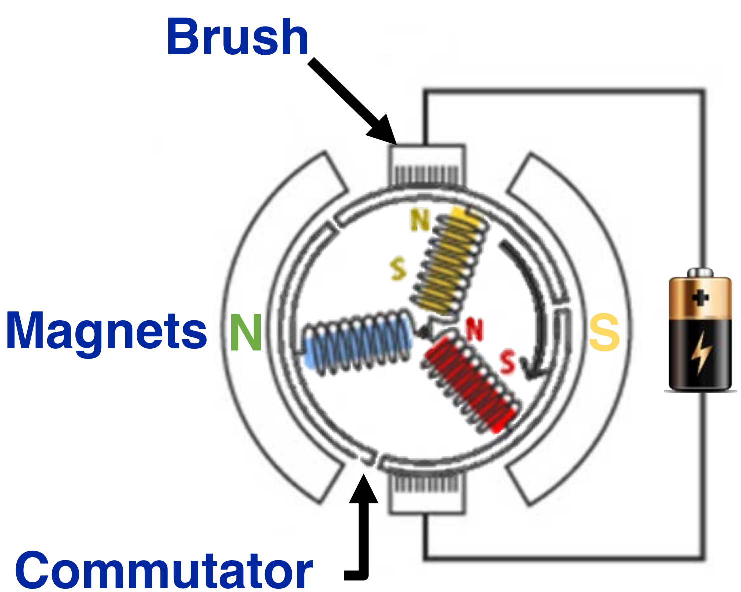
Low Reynolds Aerodynamics: Recommendations

- CFD Modeling: requires refined transition and turbulence models
- Need detailed experimentations including pressure distribution and PIV measurements for steady and non-steady flows for a range of Reynolds numbers

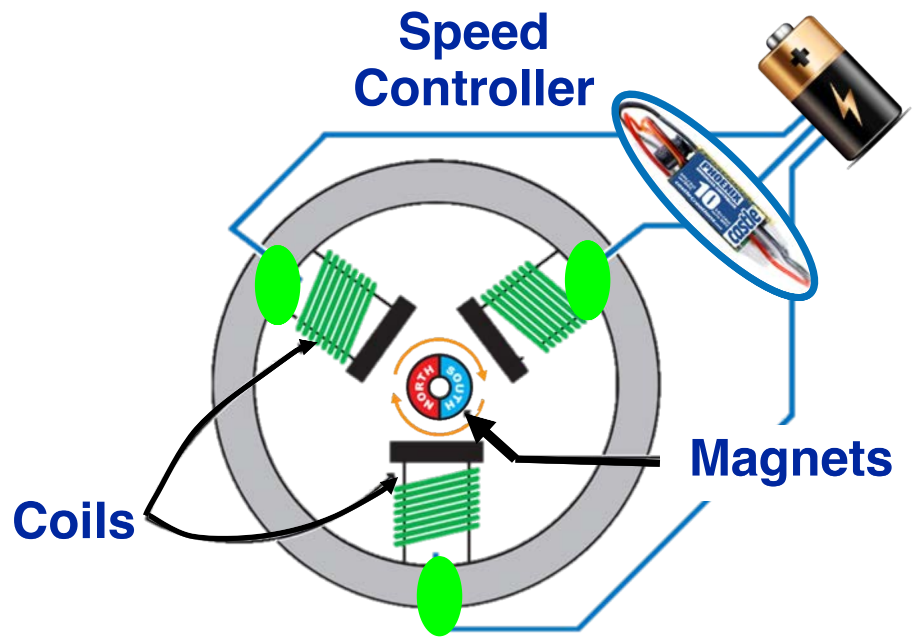
Propulsion
Electric Motors, Batteries, IC Engines

Electric DC Motors

Brushed



Brushless



Pro: Simple Design

Con: Brush Friction

Appropriate for MAVs < 100 g

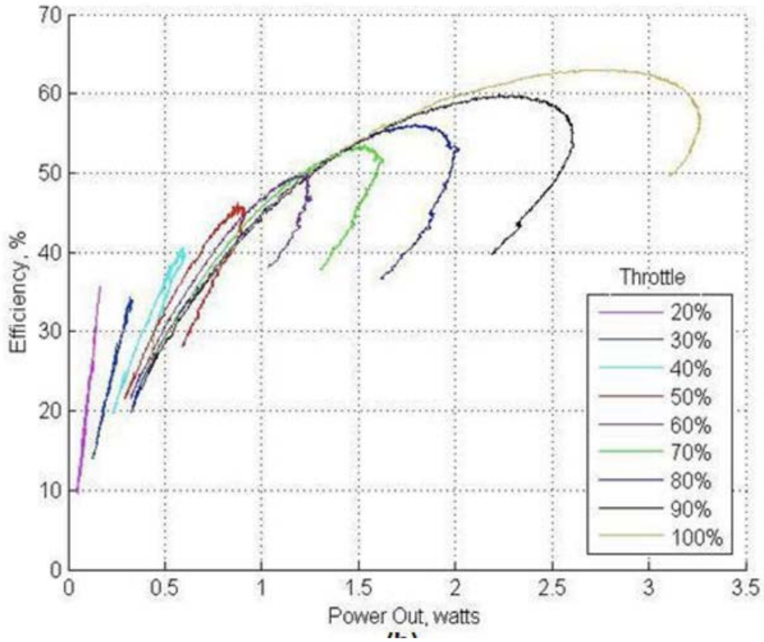
Pro: No Friction

Con: Heavier

Appropriate for MAV >100 g

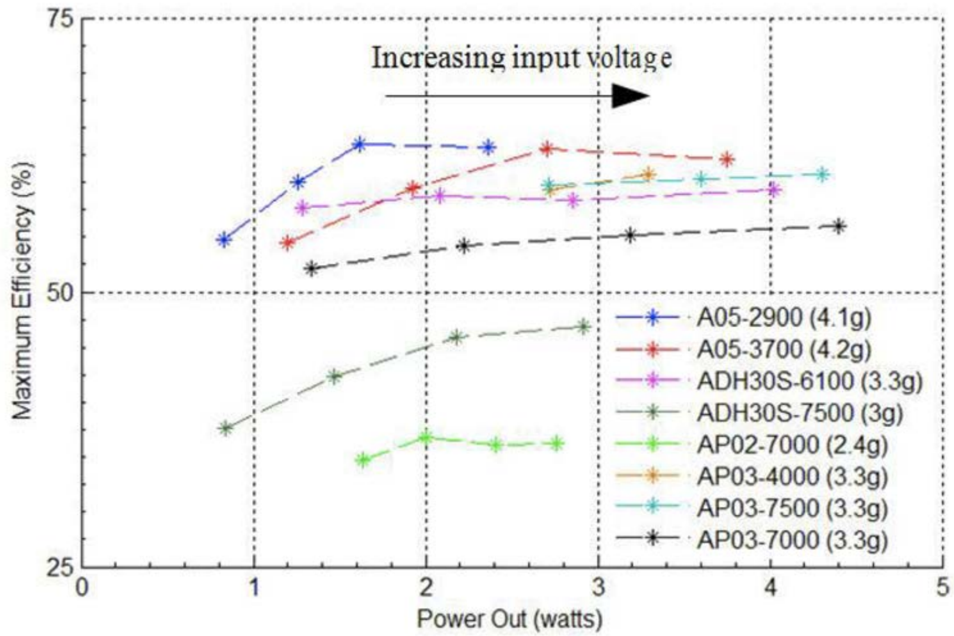
Maximum Efficiency

Brushed



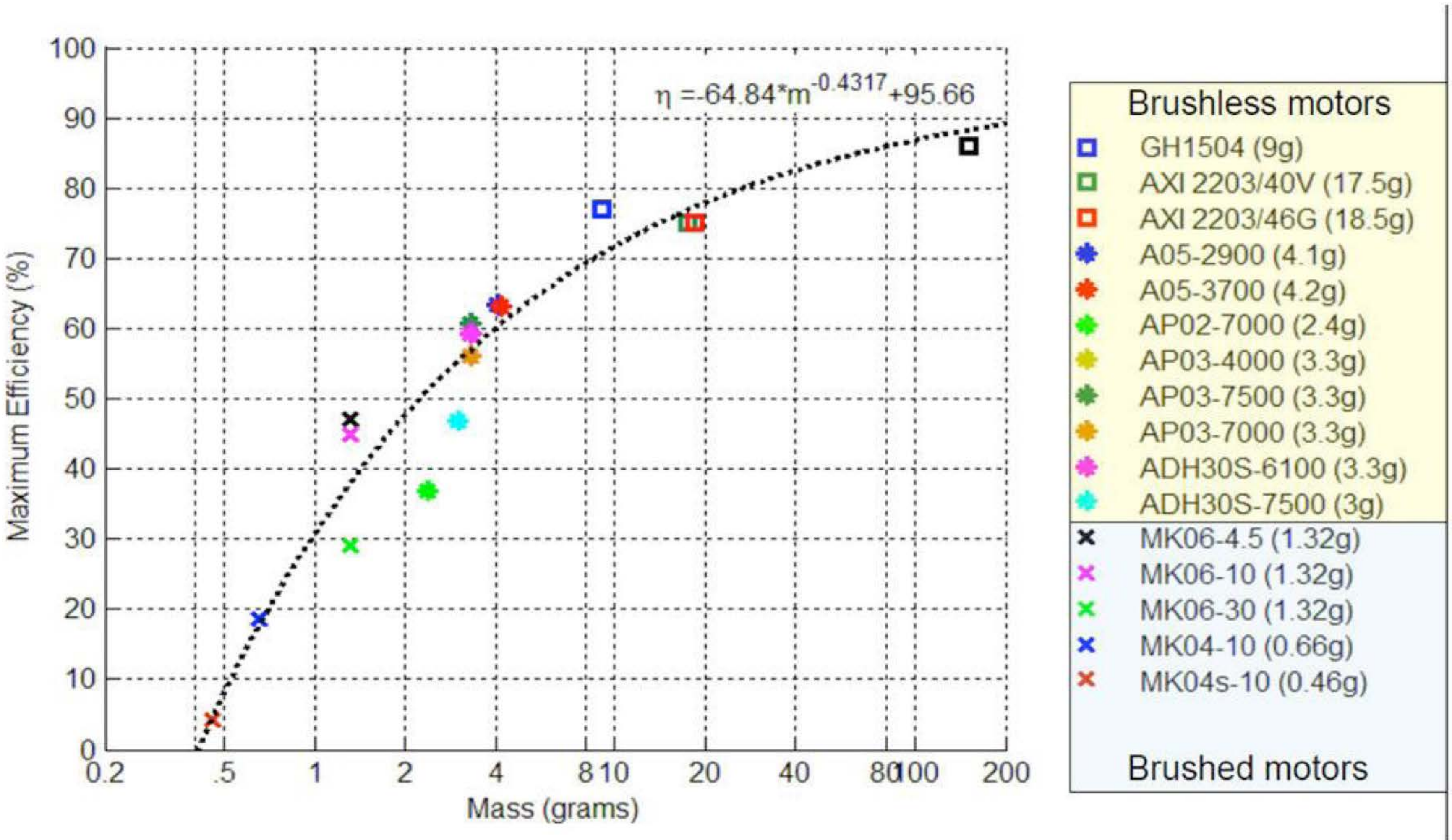
Max efficiency in a narrow range of power output
Good for direct drive, high RPM and low torque

Brushless



Max efficiency in a wide range of power output (gentle drop)
Keep throttle 100% and vary voltage for max efficiency

Maximum Operating Efficiency vs. Motor Weight



Maximum operating efficiency decreases as size decreases

DC Electric Motors: Conclusions & Recommendations

Conclusions:

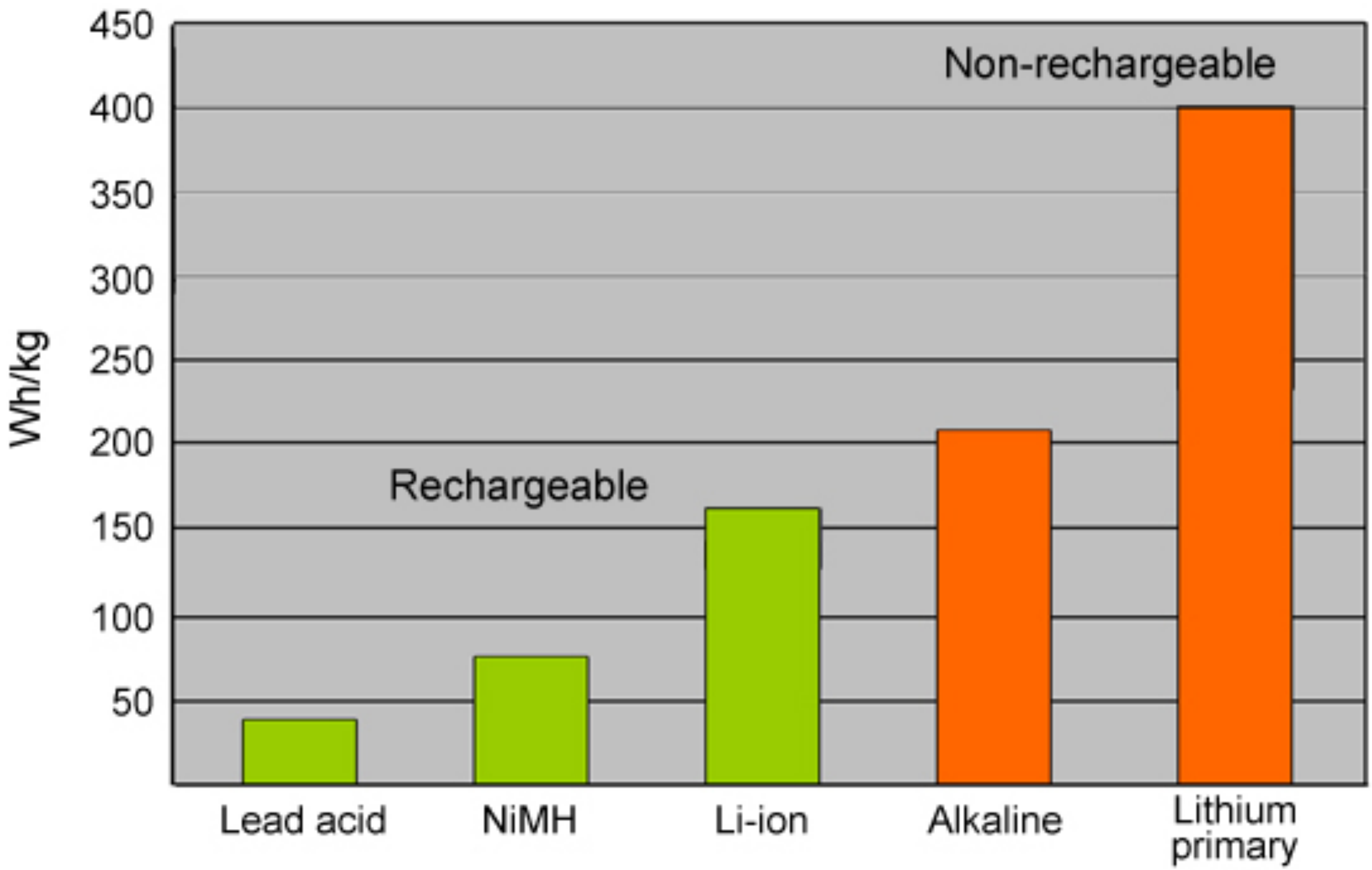
- Brushless and brushed DC motors are choice for sUAS
- Brushed for sUAS < 100 gram
- Brushless for sUAS > 100 gram
- Efficiency decreases with lower size

Recommendations:

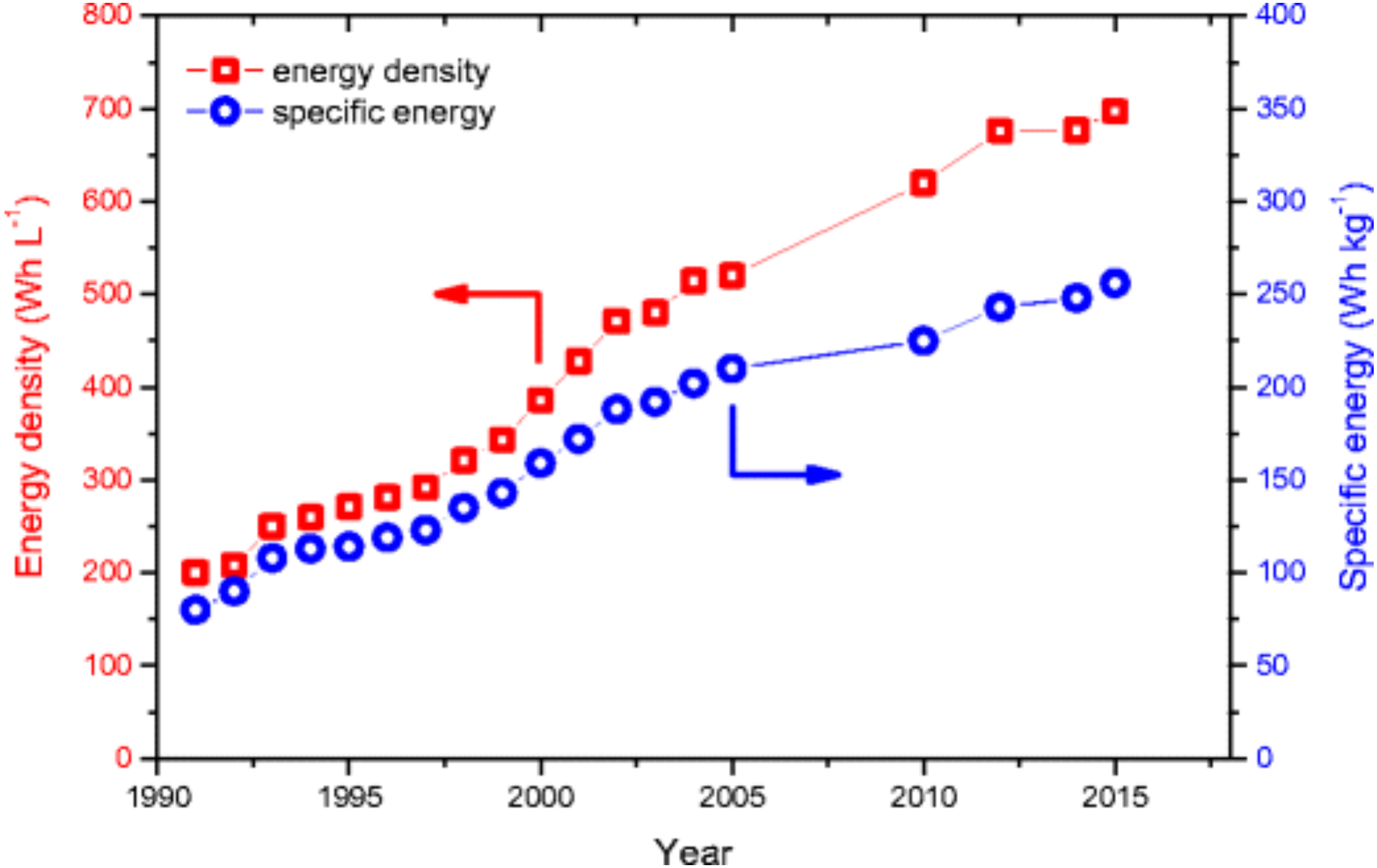
- Examine electromechanical parameters for small size motors
- Develop efficient speed controllers for brushless

Batteries

Batteries: Specific Energy Comparison



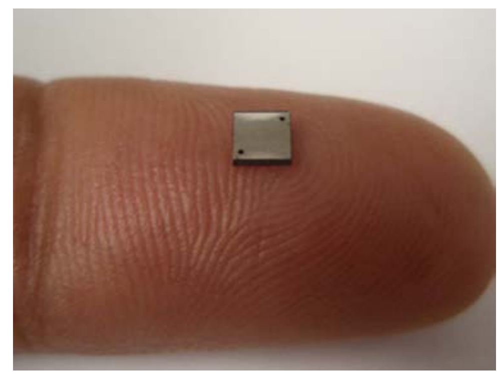
Li-ion Batteries Growth



8% yearly battery capacity increase over last 15 years

Batteries: Future Growth

- Specific energy ↑
- Price ↓
- Life ↑
- Recharge time ↓
- Flexibility ↑

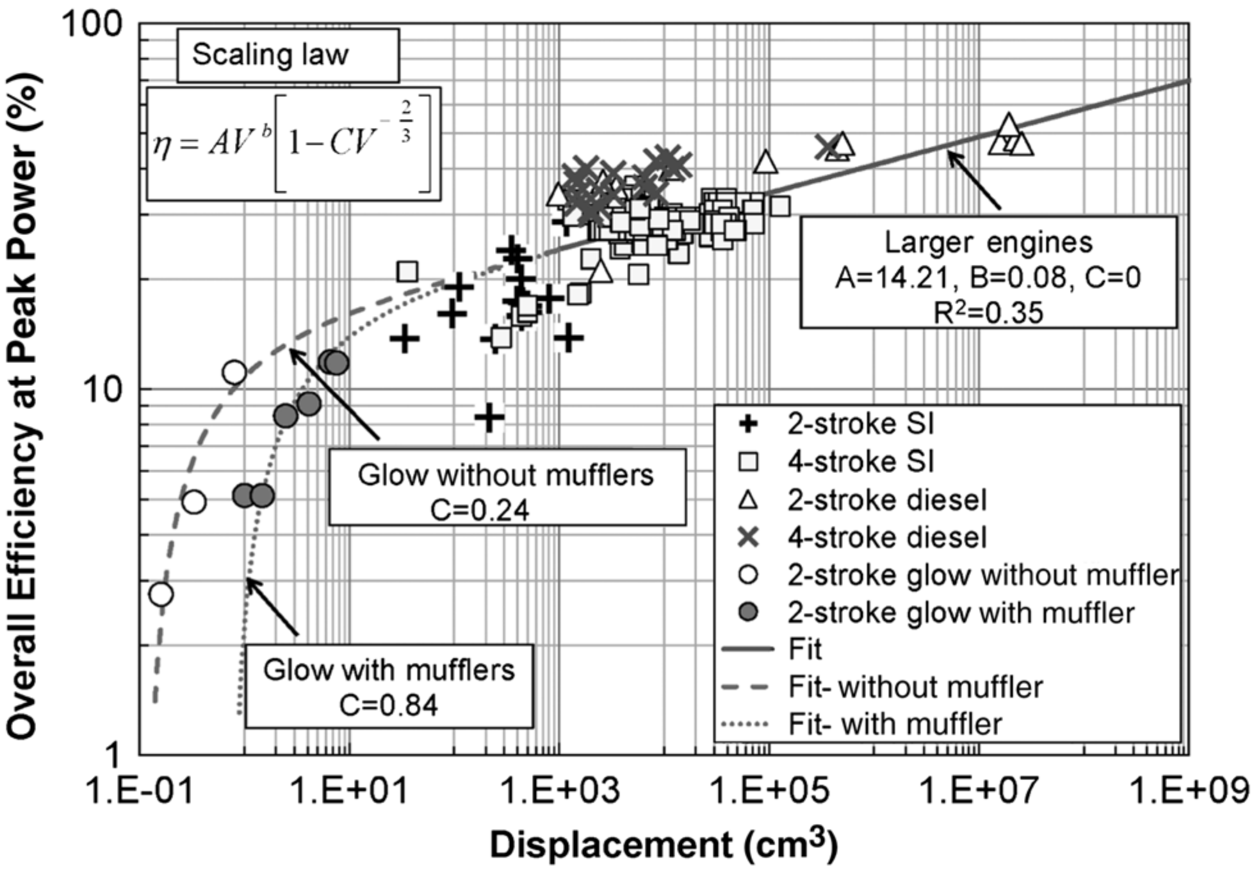


TFOT: Smallest fuel Cell

Internal Combustion (IC) Engines

Small Internal Combustion (IC) Engines

- Specific energy of hydrocarbon fuel is about 100 times of electrochemical materials used in batteries
- Mass produced and cheap



AP 'Yellowjacket'

150g, 158 W, 8.5% efficiency

Enormous potential of miniaturized IC engines, especially when coupled with small generators

Small Internal Combustion (IC) Engines Major Issues

Because of increased losses with heat transfer, fluid friction and leakage with smaller size, performance efficiency falls rapidly with miniaturization; Not possible to maintain adequate thermal isolation between hot & cold sides

Small IC	Power	Efficiency
15-500 gram	8-650 watts	3-12%

Based on present technology, small thermodynamically viable piston engine bore diameter 5 mm with displacement of 0.1 cm^3

Enormous potential to develop miniaturized IC engines:

- **Materials with higher thermal isolation**
- **Increase combustion efficiency**
- **Improve acoustics**

Microfabrication & 3D Printing

Fabrication: 3D Printing

3D printing suited for fabrication of small batch parts

- Rapid prototyping and additive manufacturing
- Saving of material (addition layer-by-layer)
- Adaptation from CAD
- Materials: polymers and metals

U-Print

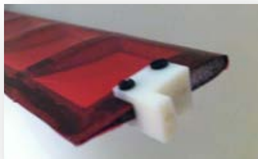
- Prints ABS and dissolvable support plastic
- Layer thickness: .254 mm (.010 in)

Creality CR-10

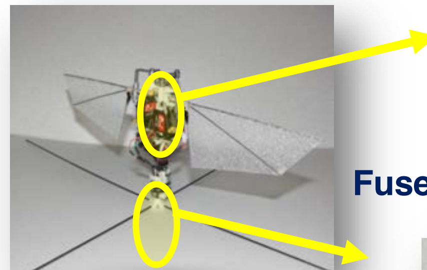
- Prints ABS, PETG, and PLA plastic
- Layer thickness: .300 mm (.011 in)

3D printed small batch parts

Lightweight stiff structures, fuselage interconnects, landing gears



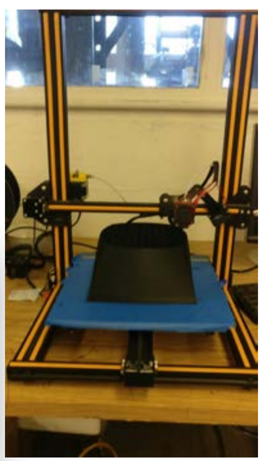



65 gram (two wings)
Hover capable flapper

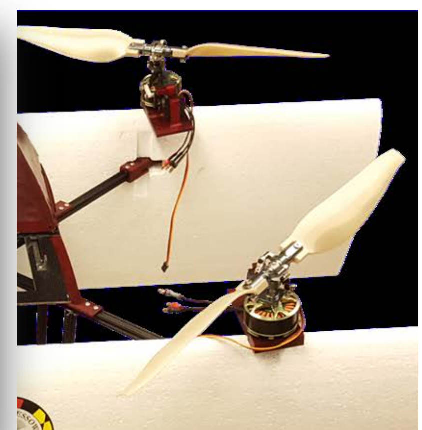
Fuselage frame and gear box

Landing gear joint

Molds for blades, aerodynamic fairings

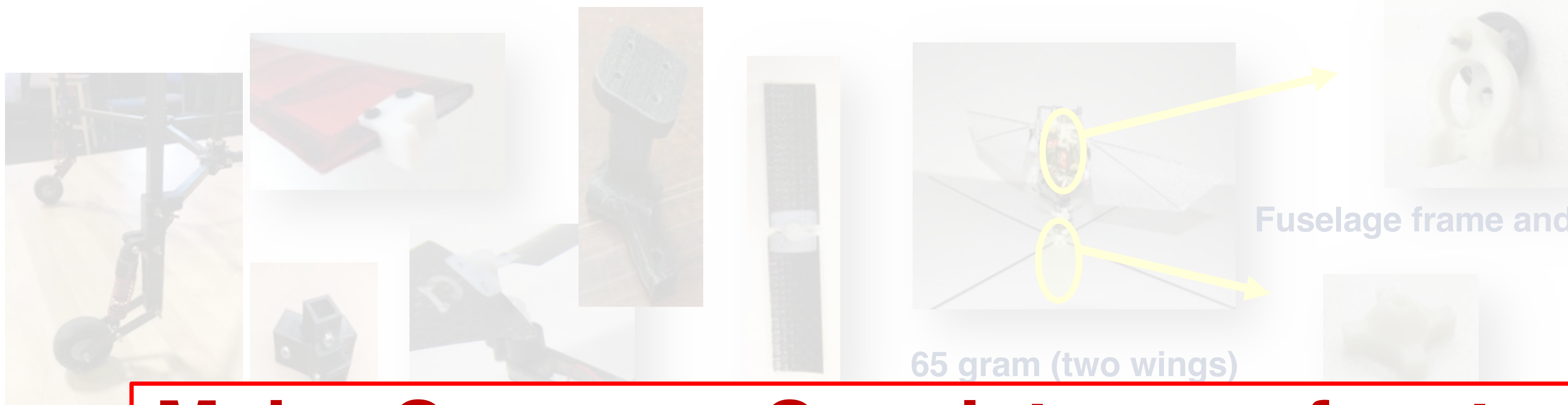




Rotor blades

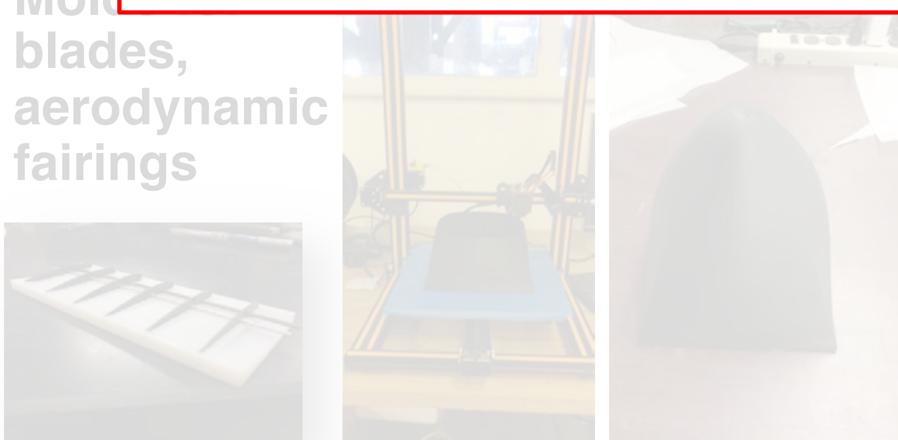
3D printed small batch parts

Lightweight stiff structures, fuselage interconnects, landing gears



Major Concern: Consistency of material properties over batches and time

Molc
blades,
aerodynamic
fairings



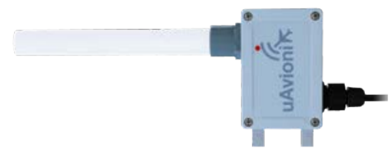
Microelectronics
Lidars/Radars, GPS, Cameras, Processors

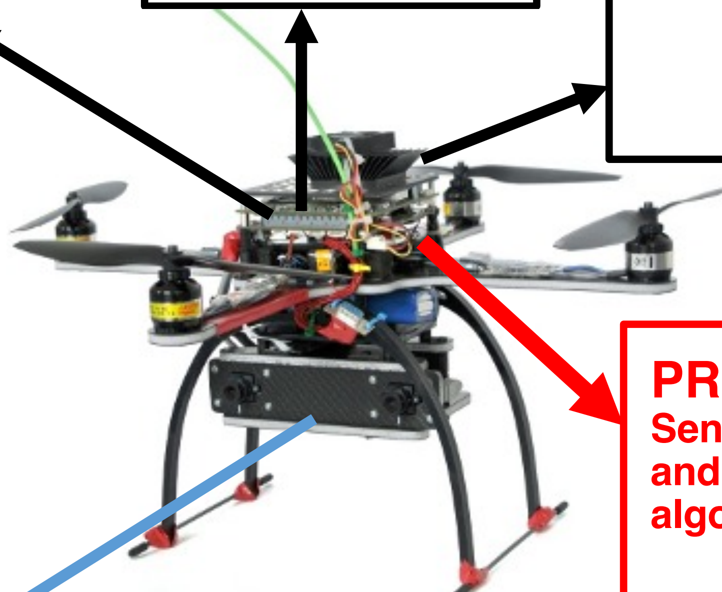
Autonomous UAV Components

NAVIGATION
GPS, Cell Tower (LATAS Location tracking)

FLIGHT CONTROL HARDWARE
- Actuator control
- Flight Stabilization

COMMUNICATION
Wireless A/V Transceivers, ADS-B



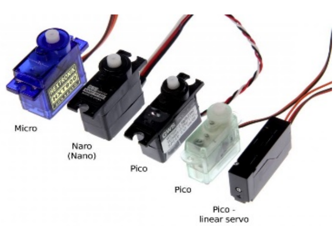


SITUATIONAL AWARENESS
Mapping, Obstacle Avoidance, GPS-Denied Navigation (Cameras, LIDAR, Sonar, Optic Flow)

PROCESSING
Sensor Fusion, Guidance and Navigation algorithms

sUAS Sensors: Needed Attributes

- Compact
- Lightweight
- Low power requirement
- Low processing requirement
- Robust (nonsteady environment)
- Cheap

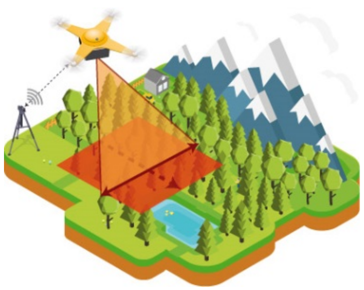




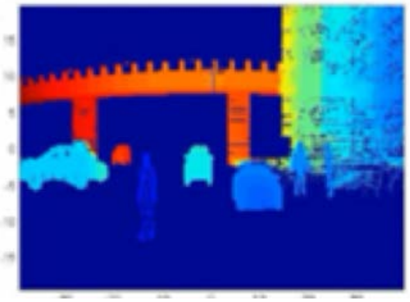

LIDAR vs. RADAR

Light Detection And Ranging

Uses pulse laser light to measure and detect distance of object (wavelength ~ 1μm).



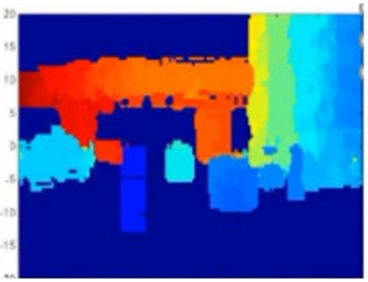
High resolution, can detect small objects (cloud particles, power wires). Can sense nearby objects



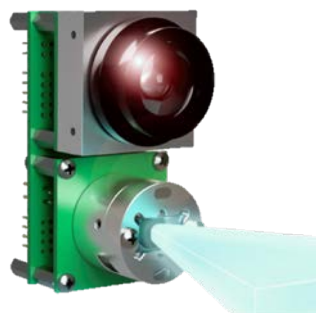
Radio Detection And Ranging

Uses radio waves to measure range and velocity of objects (wavelength ~1 cm)

Lower resolution, suitable for larger objects. Can sense velocity, direction and distance of faraway objects

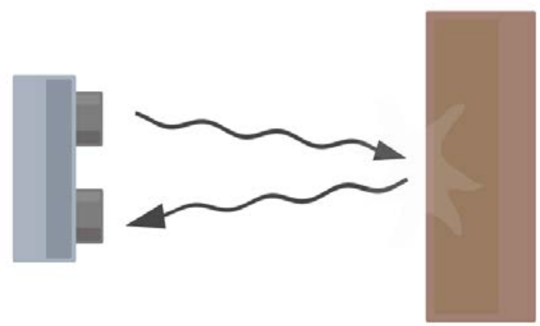


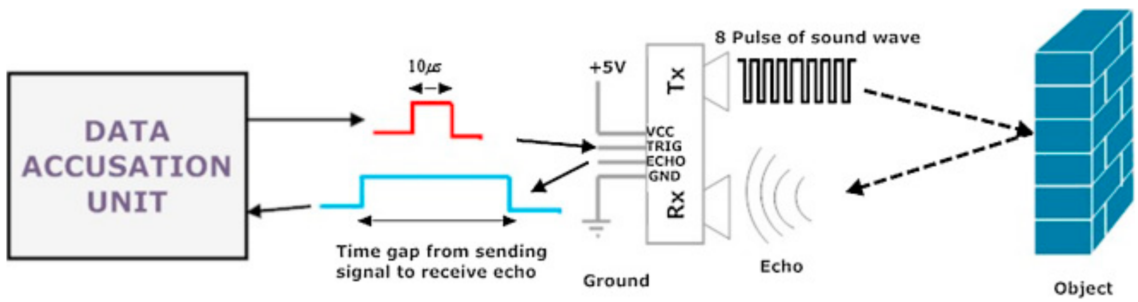
LIDAR sensors for UAVs

	Leddertech Vu8	HDL-32E	Velodyne VLP-16 'Puck'
			
Range	700 ft	300 ft	300 ft
Weight	75 grams	1300 grams	830 grams
Cost	$ 450	$ 29,900	$ 7999
Angular resolution	0.25°	1.33°	N/A
Application	Collision avoidance	Autonomous navigation, 3D mapping	Autonomous navigation, 3D mapping

Ultrasonic Sensor

Measures distance using bouncing back of sound wave of specific frequency from an object





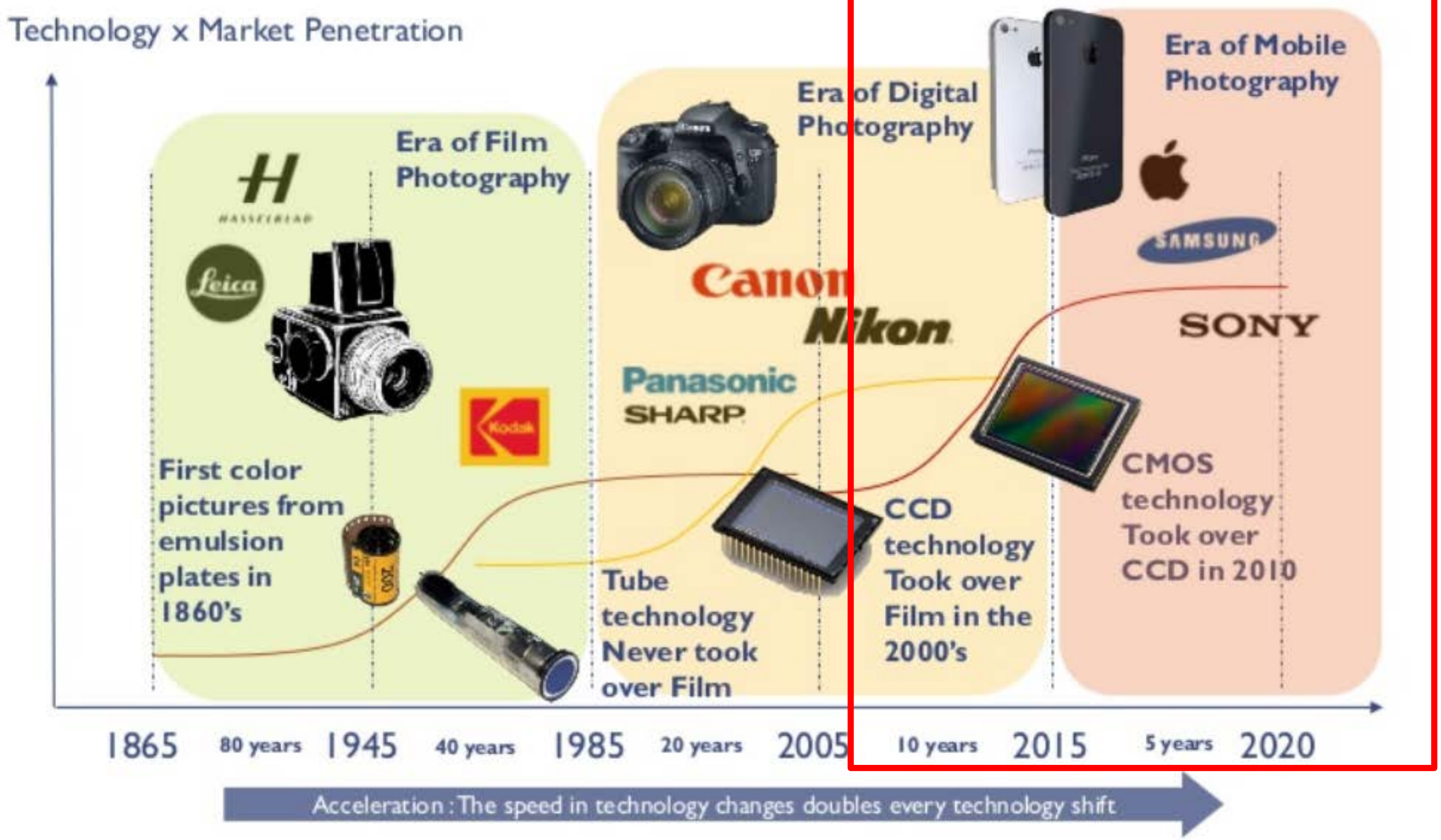
LV-MaxSonar-EZ (Typical sensor for altitude sensing and object avoidance for small UAVs)

Input: 2.5-5.5V
Update rate: 20Hz
Weight: 4 grams
Cost: $ 30

Advantages	Not affected by color, dust, dirt. Can be used in dark. Low cost.
Limitations	Accuracy depends on temperature, reflecting materials. Limited detection range.

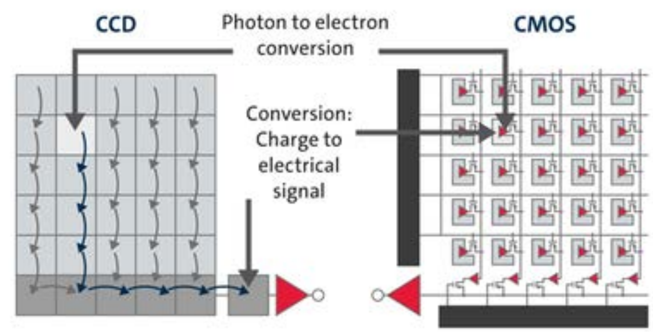
Cameras – Changing Markets

Advent of aerial imaging and autonomy on lightweight UAVs



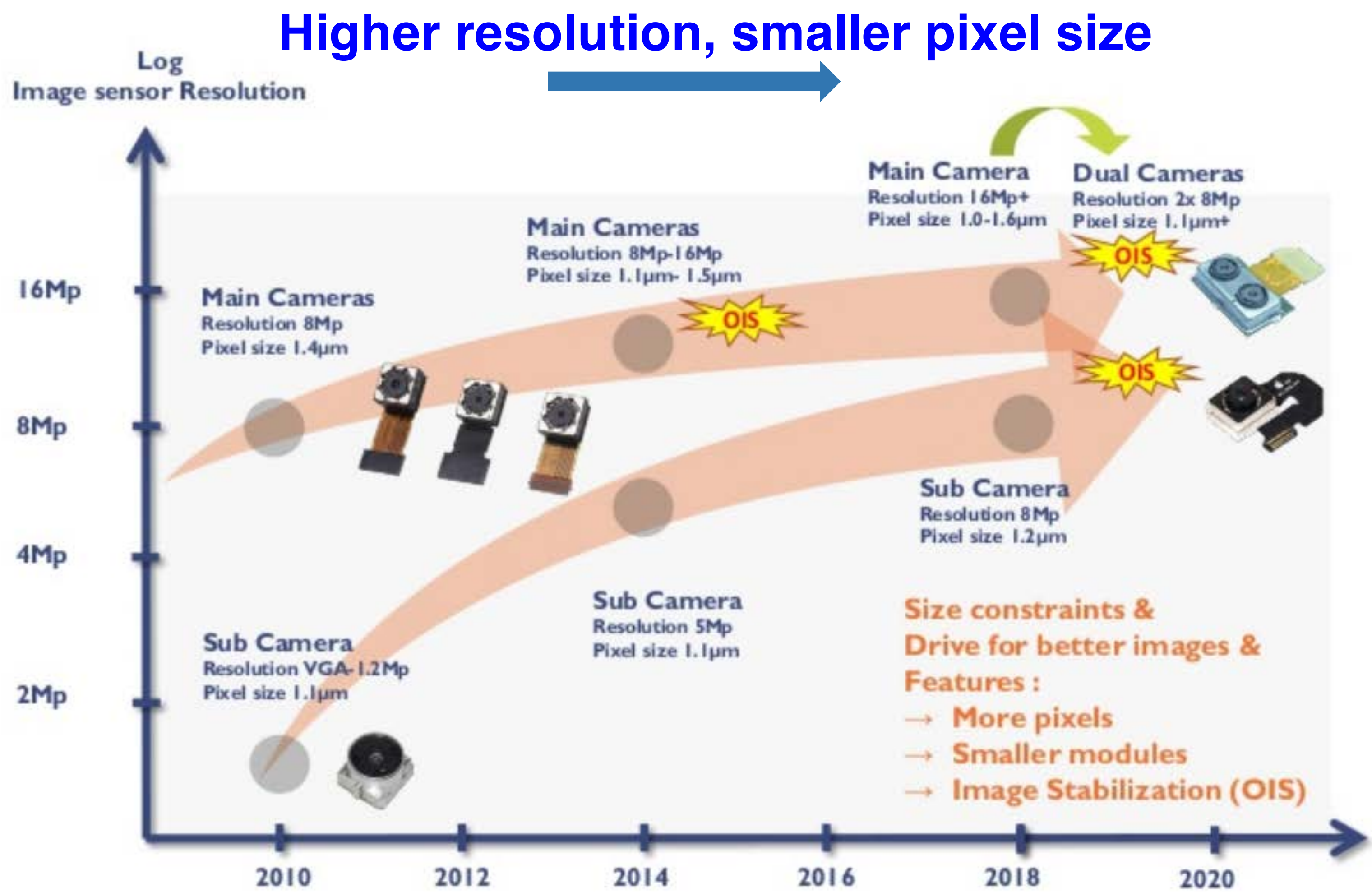
CMOS vs. CCD cameras

	CCD Camera (Charge coupled device)	CMOS Camera (Complementary metal oxide semiconductor)
Principle	Electron – voltage conversion at global level	Electron – voltage conversion at pixel level
Advantages	Low noise images, more and higher quality pixels, perform better in very dark, very bright conditions.	Less power consumption, fast image capture, continuous technology improvements.
Applicable to UAVs?	Yes, can be expensive	Yes. Widely available and cheap. Compact



Two different principles: CCD vs CMOS

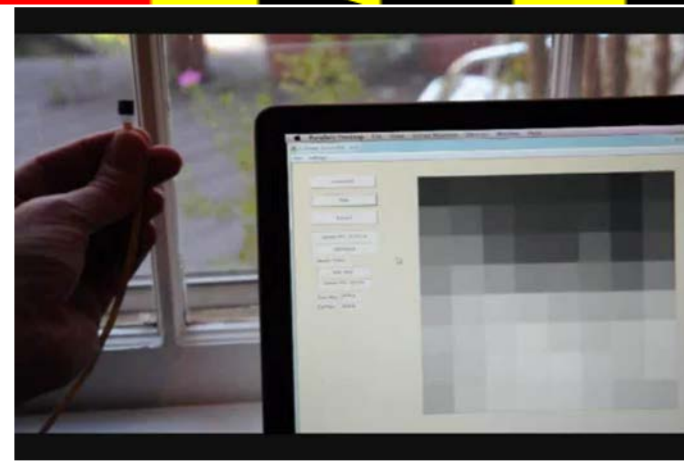
CMOS vs. CCD camera sensors



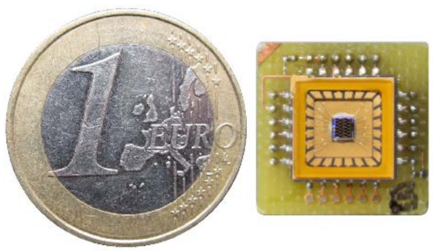
Market drivers for image sensors on cell phones
Needs for smaller, lighter; sharp imaging

Optic Flow Sensor

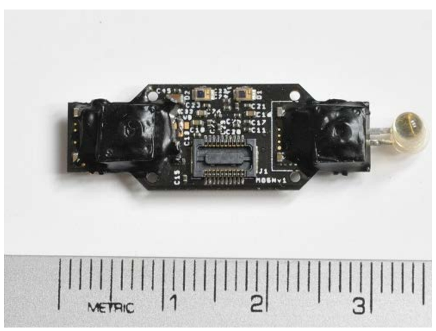
Optic flow is pattern of apparent motion of objects caused by relative motion between object and scene



Dedicated optic flow sensors



Auto-adaptive silicon retina (2016)



Centeye (2016)

Principle:

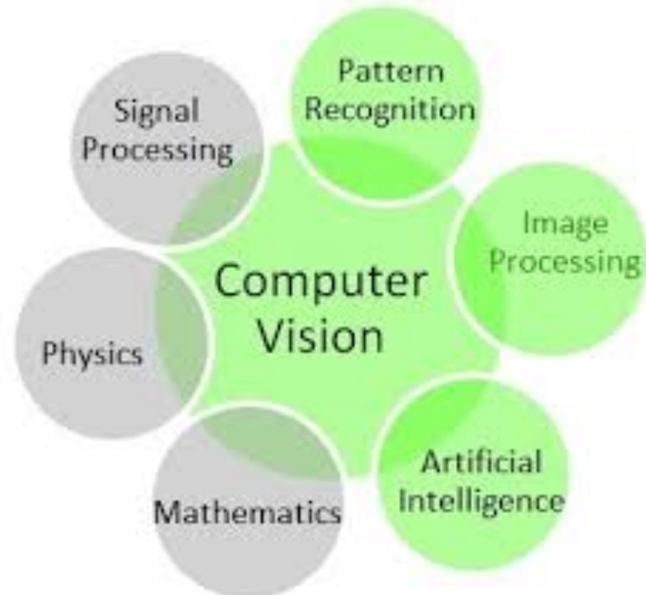
Detects relative visual motion of sensor by measuring intensity gradient changes

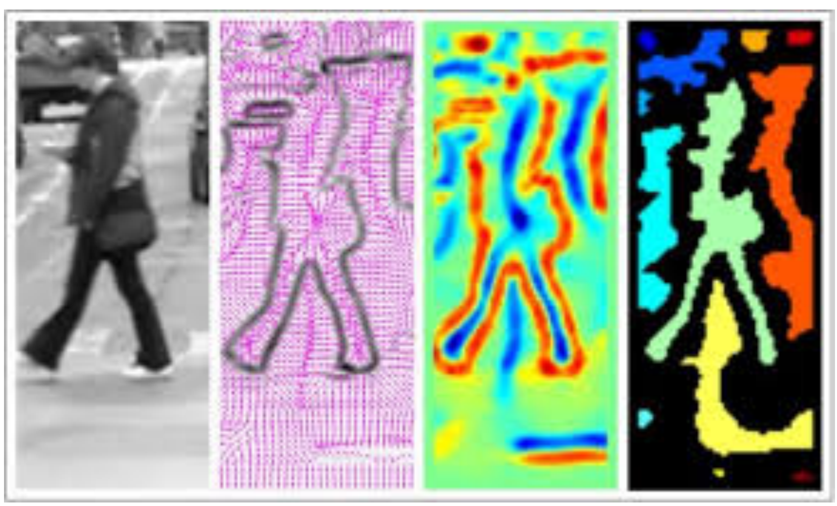
Advantages Optic Flow sensors

- Standard cameras have low dynamic range and high computational cost for image processing
- Superior frame rate (>300 Hz)
- Low weight (<1-2 gram)

Computer Vision

Computer vision:
Computer can achieve understanding from digital images or videos involves acquiring, processing and understanding digital images, and extraction of high-dimensional data in the form of symbolic information and object recognition



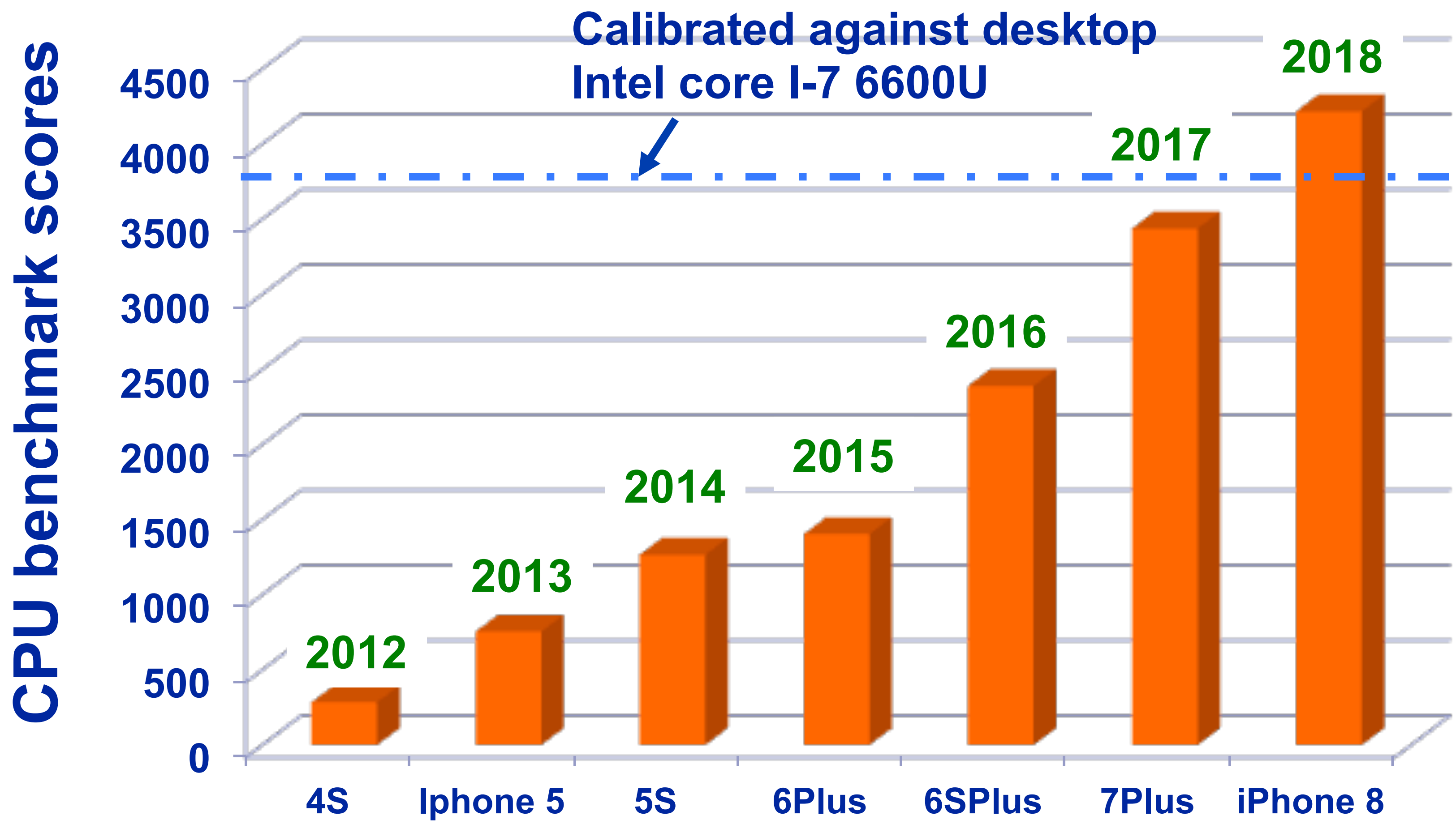


Microprocessor

Microprocessor is a computer processor with the function of central processing unit (CPU) on a single integrated circuit (IC). Contains: arithmetic, logic and control circuitry. Single-chip (multi-transistors) processor increases reliability and reduces cost

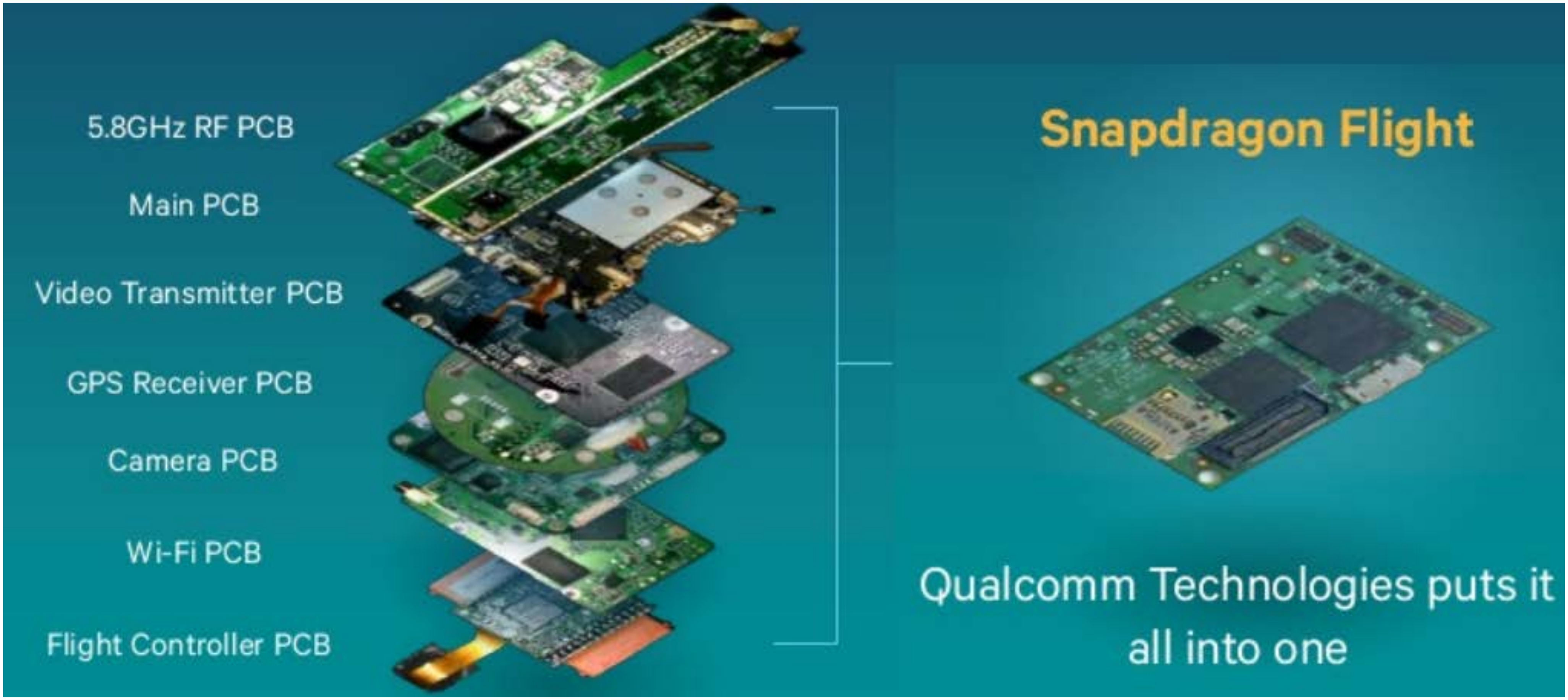
1973: First mobile phone
Mid 1990s: First camera phones
2007: iPhone (high-powered + built for people)
2015: Smartphone drone (Qualcomm + UPenn)
2018: Real-time pose tracking + augmented reality interfacing (Snapchat)

Evolution of processing ability of iPhones



Data extracted from Geekbench Browser

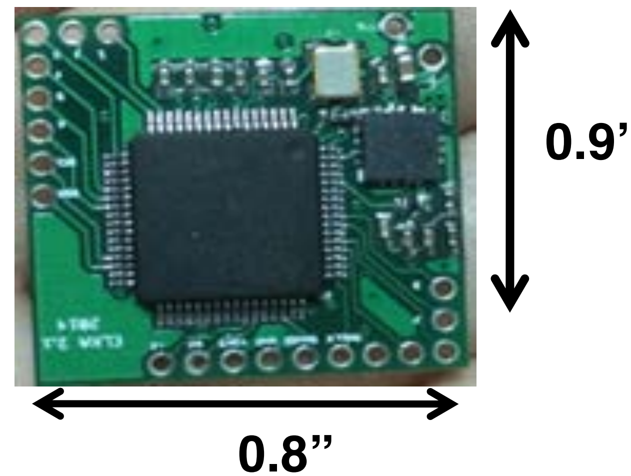
Snapdragon Flight™



Integrated Platform, Weight: 26 grams, Language: Linux

Embedded Lightweight Kinematic Autopilot (ELKA)

	Components
Processor	STM32 ARM Cortex M4
Sensors	Integrated 3-Axis Gyroscope, 3- axis Accelerometer, 3- axis Magnetometer
Radio	2.4 GHz Bi-directional Transciever, 50 m range

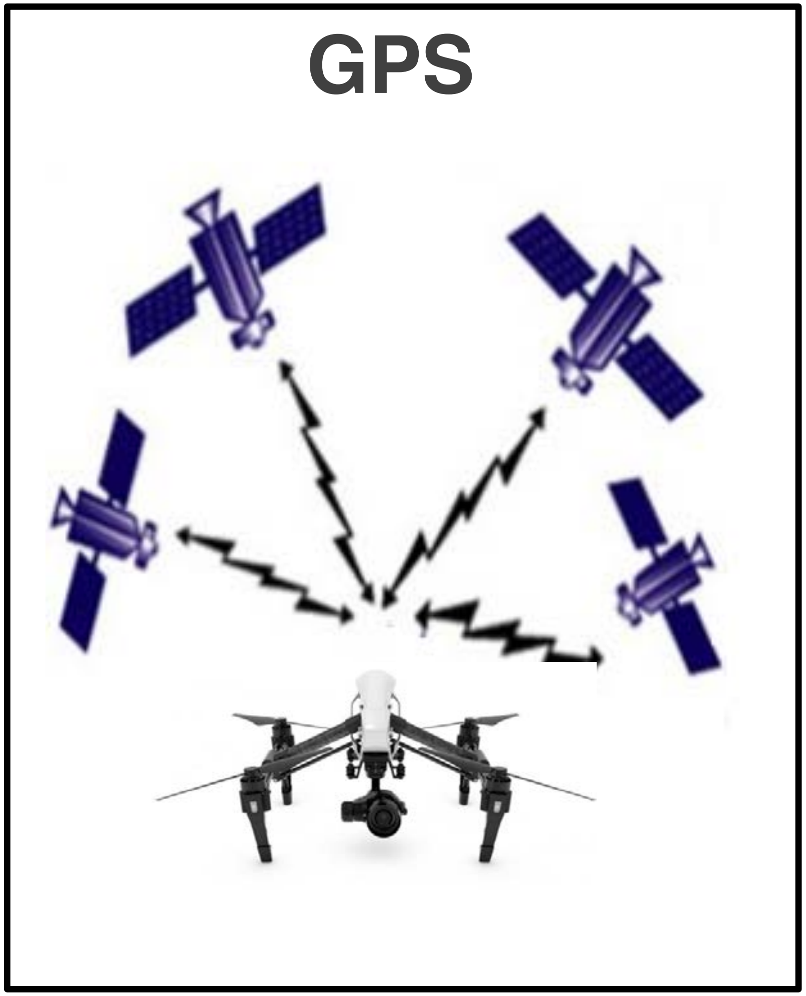


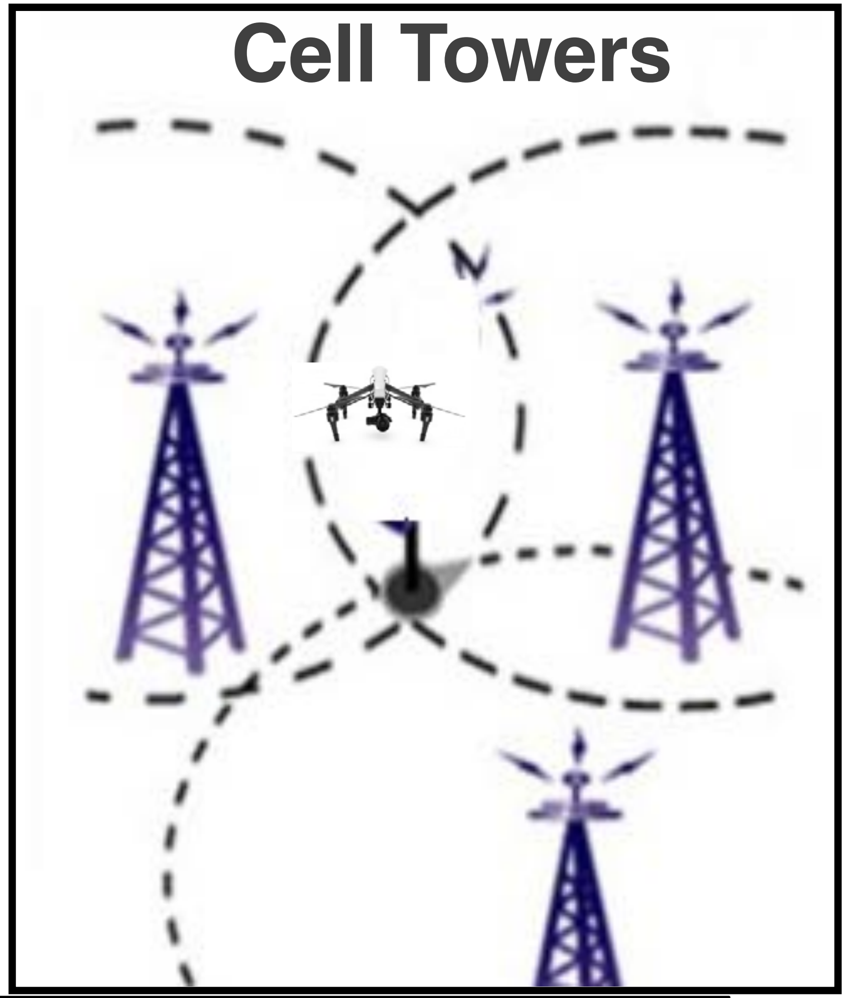
Comparison with Previous State of Art Micro Autopilot

	GINA (previous)	ELKA (Present)
CPU speed	16 MHz	168 Mhz
Stabilization rate	167-333Hz	1000 Hz
Weight	1.5 grams	1.6 grams
Actuator support	6 actuators	12 actuators

Navigation

Location Awareness/Navigation

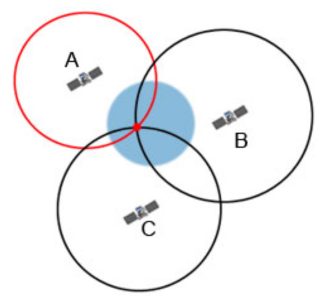


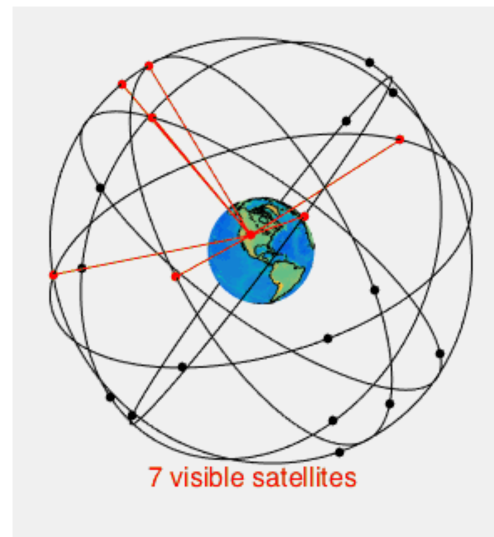


Similar to Localization on a Modern Smartphone

GPS: Global Positioning System

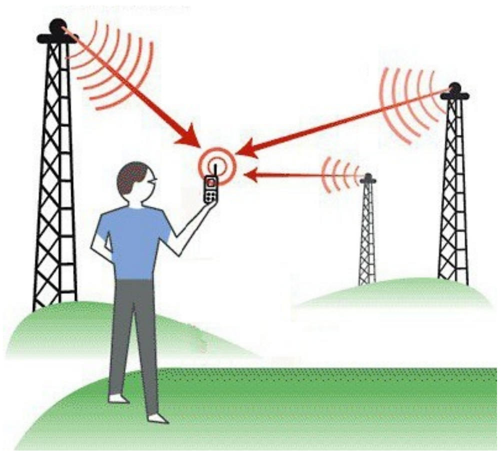
- Operated by US Air Force
- Provides geolocation and time information to GPS receiver with line of sight to 4 or more GPS satellite
- Initially 24 satellites (1995); 32 now (2016) dual use in 1996; mobile phone in 2004; 6 orbital planes with 6 satellites each
- Trilateration by receiver





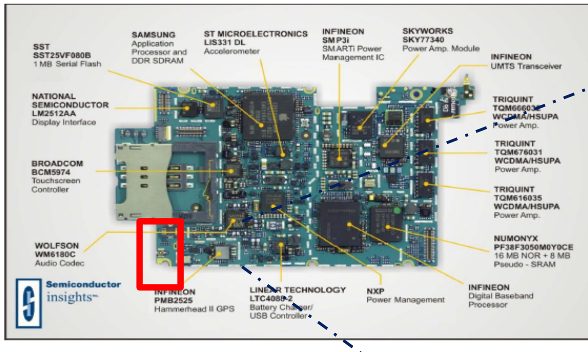
Cell Towers

- Cell Tower where antennae and electronic communication equipment are placed
- Line-of-sight propagation
- Range depends upon: height, power, signal frequency
- Overlap with other towers
- 30-45 miles for flat land; 3-5 miles in hilly area

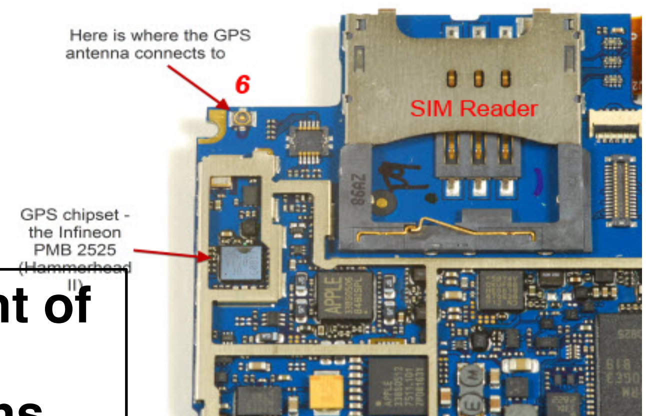


Cell tower triangulation and cell ID databases, wireless positioning systems

GPS on a Cell Phone

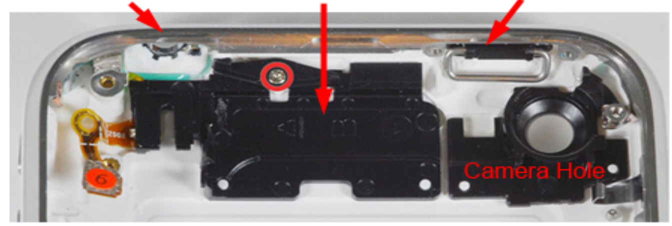


iPhone 3G GPS Chipset & Antenna



Estimated weight of GPS sensor and antenna <5 grams

Headset Jack - GPS Antenna Housing - Power Button

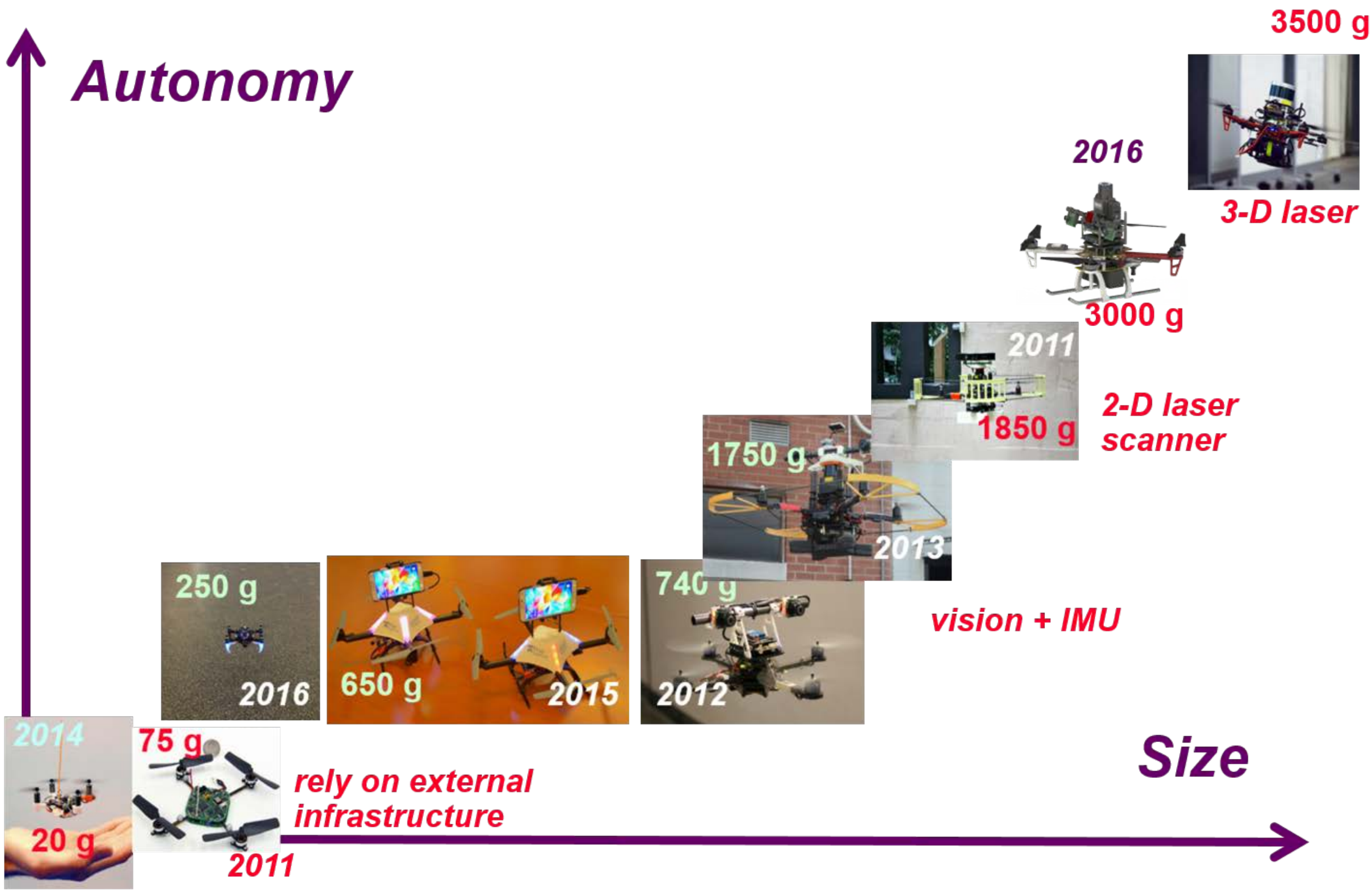


Latest projected accuracy of GPS systems in mobile phones in 2018 less than 1 foot

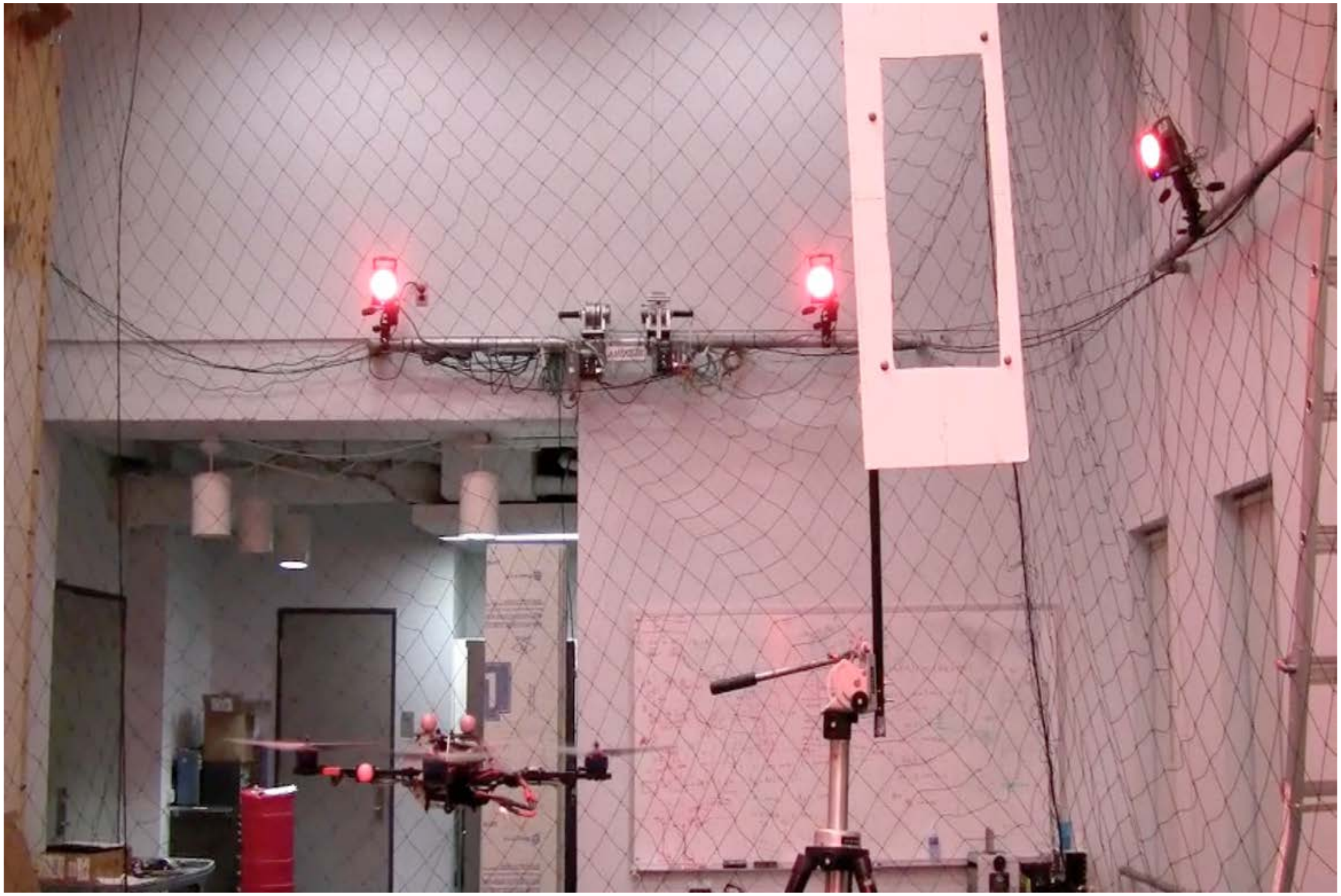
Autonomy

Autonomy

Onboard control estimation, trajectory planning & obstacle avoidance



Autonomous Control



Autonomous Navigation at High Speeds

(without external infrastructure)

Autonomous Navigation at High Speeds

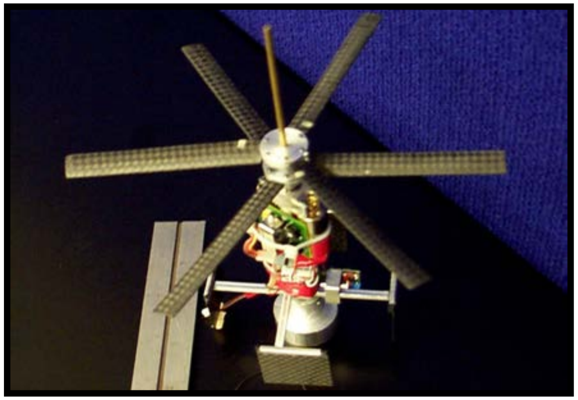
State Estimation (without GPS)

Upenn: (Ke, Liu, Mohta, Pfrommer, Watterson, Zhu, Taylor, Kumar, 2017)

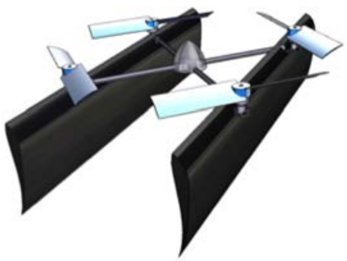
sUAS:
Small Unmanned Aircraft Systems
“Integrated Vehicles”

Small Unmanned Aircraft System (sUAS)

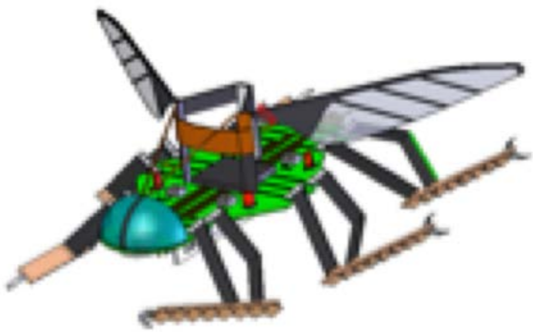
- Non-Hovering Vehicles: Fixed-wing based



- Hovering Vehicles: Rotor Based
  - Single main rotor (with & without tail rotor)
  - Co-axial rotor
  - Shrouded rotor
  - Quad-rotor and multi-rotors
  - Unconventional rotor-based designs



- Hovering & Long Range/Endurance: Compound
  - Tiltrotor, Tiltwing, Tail-Sitter such as Quad-biplane
- Hovering & Non-Hovering: Flapping-Wing
  - Insect-flight based kinematics (short distance)
  - Avian-flight based kinematics (long distance)



- Hovering Vehicles: Reaction Based
  (Power intensive)

sUAS: Rotor-Based

Hover: Index of Efficiency

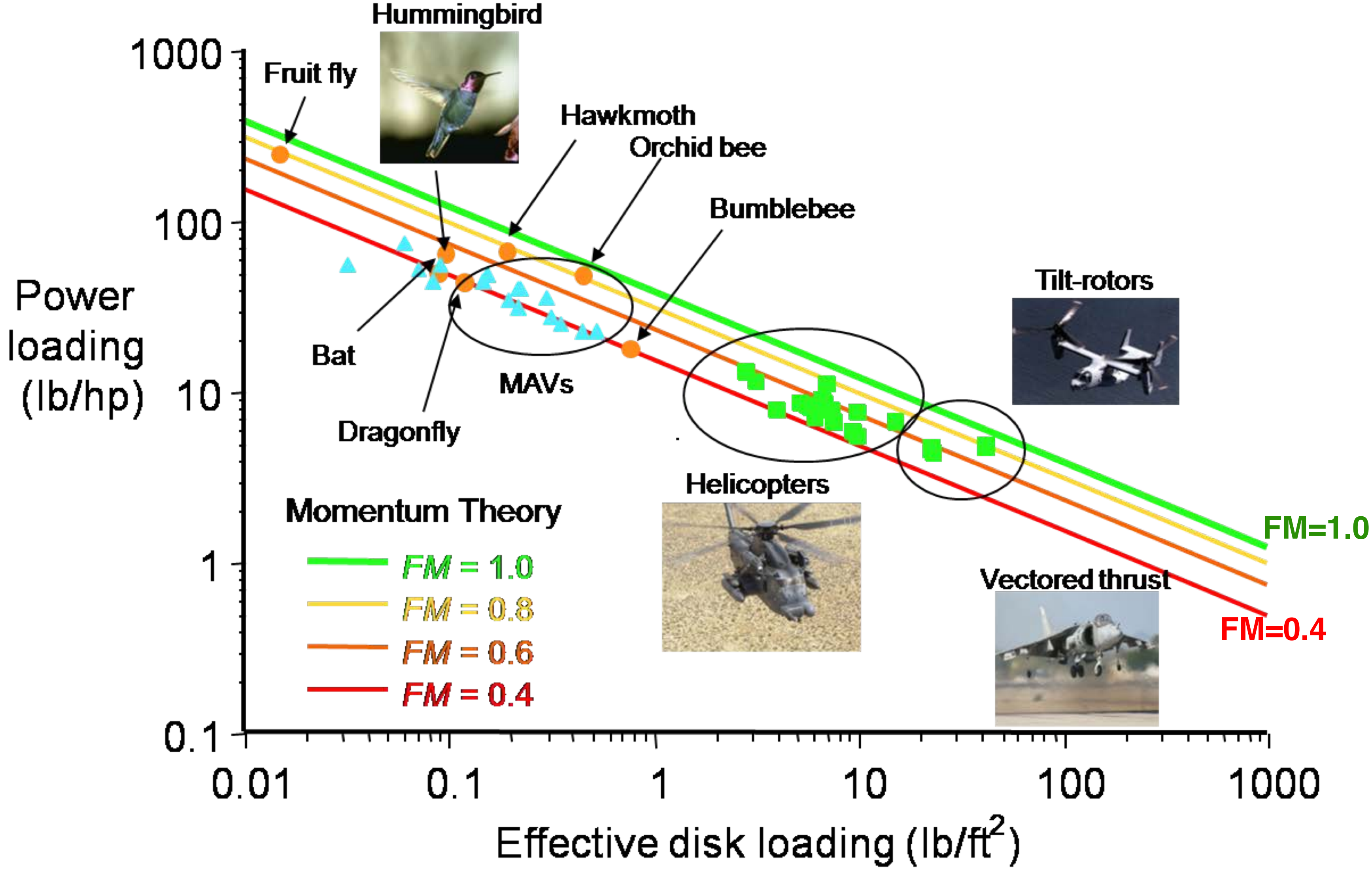
Figure of Merit

$$FM = \frac{\text{Ideal Power required to hover}}{\text{Actual Power required to hover}}$$

Power Loading

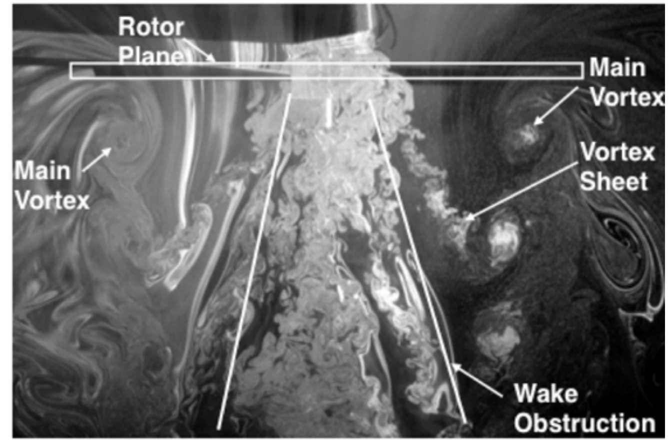
$$PL = \frac{\text{Thrust Produced}}{\text{Actual Power required}}$$

Power Loading (Thrust/Power)



Comparison of Rotor Efficiencies

	Full Scale	MAV scale
Figure of Merit	0.75-0.85	0.45-0.6
Power Loading (lb/HP)	7.5 (DL ~ 6 lb/ft²)	20.0 (DL ~ 0.2 lb/ft²)
C_{P_0}/C_{P_I}	10-15%	30-50%



MAV vs. Full Scale		Value
Profile Power	$\dfrac{(C_{P_0})_{MAV}}{(C_{P_0})_{FS}}$	5-8
Induced Power	$\dfrac{(C_{P_I})_{MAV}}{(C_{P_I})_{FS}}$	1.5

Hover power = Profile power + Induced power

Low Re aerodynamics dominates profile power losses

sUAS: Single Main Rotor

Commercial Single Rotor MAVs

ProxDynamics Black Hornet
18 grams

Mini Spark
46 grams

Walkera 4G-3B
69 grams

Walkera Sub-Micro
140 grams

Hurricane 200 V2
300 grams

Falcon 40
350 grams

Prox Dynamics (Norway)
Single Rotor MAV

Acquired by FLIR in 2016

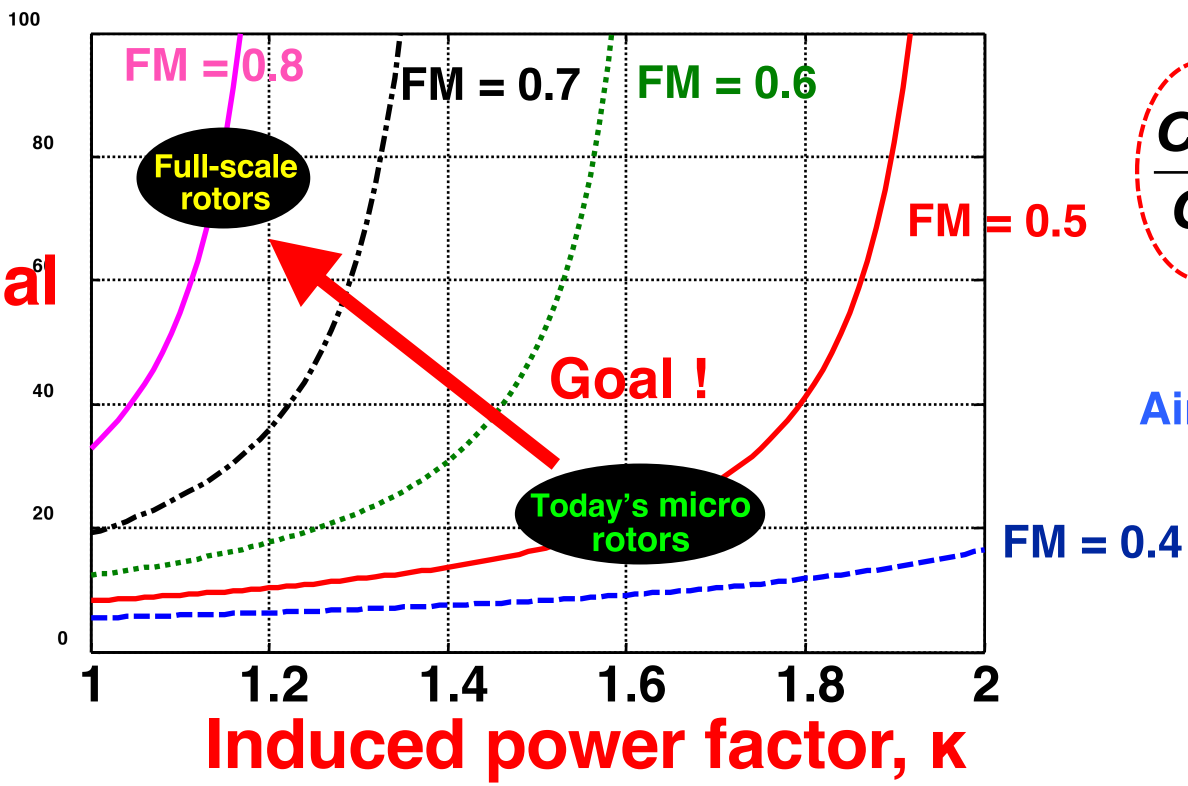
Rotor diameter 12 cm
Total weight 18 gram
Max speed 5 m/s
Endurance 25 minutes

GPS Navigation
Steerable Camera
Digital data link 1.6 KM
System weight 2 copters 1.3 Kg

Improvements in Aerodynamic Efficiency

Understand/Improve small-rotor hover efficiency through systematic experimental/ CFD studies

Sectional $C_l^{3/2}/C_d$



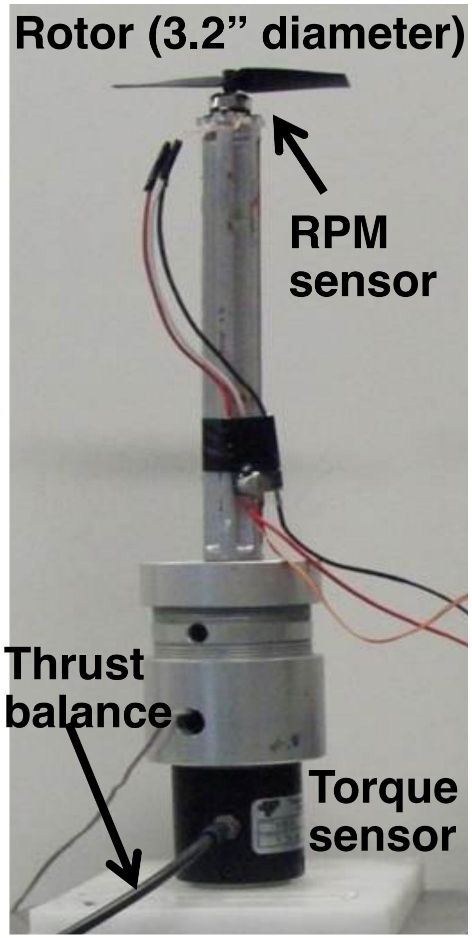
$$\frac{C_l^{3/2}}{C_d}\uparrow,\ \kappa\downarrow\ \Rightarrow\ FM\uparrow$$

Airfoil efficiency

Induced losses

Need to improve sectional aerodynamics + reduce induced losses

Experimental Parametric Study

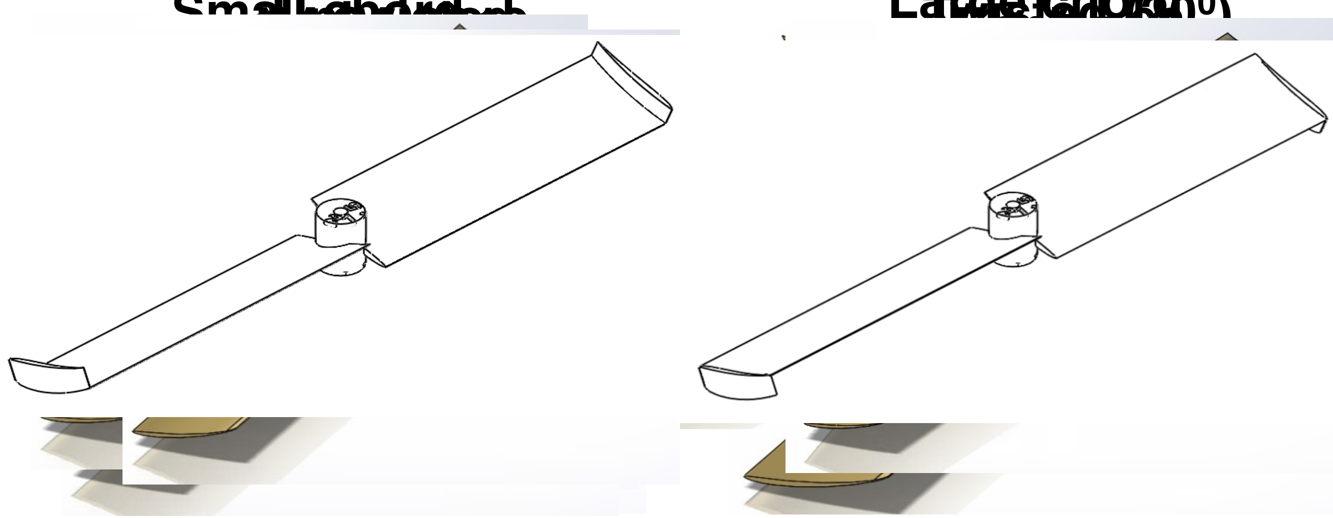


Parameters varied

Effect of winglets

Small chord

Large chord



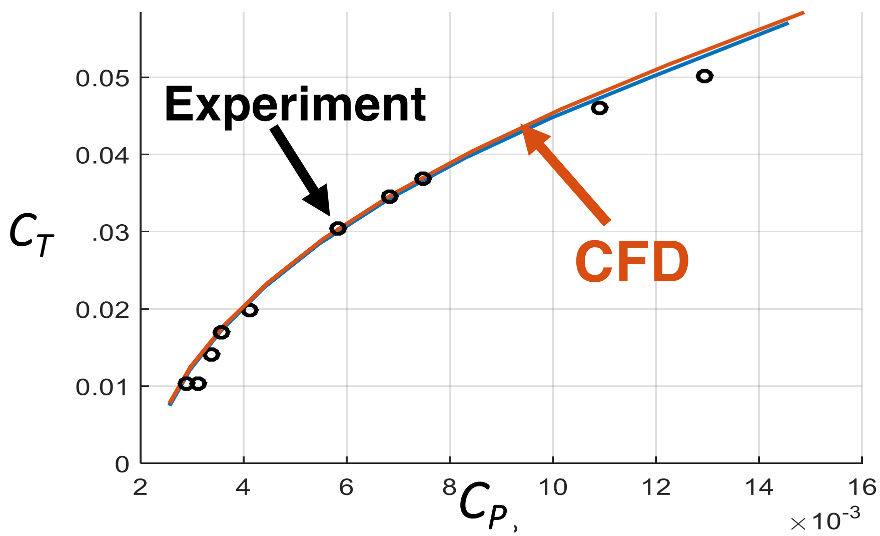
Each parameter tested over a range of blade collective pitch angles

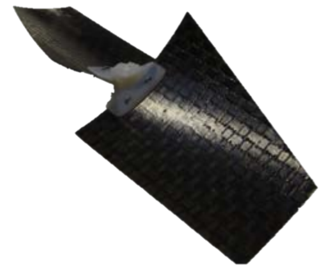
Power = Torque X rpm

More than 500 rotor designs tested

Baseline rotor: 2-bladed, R=1.6", solidity=0.17, untwisted, untapered

BEMT/CFD Validation





Optimum Micro-Rotor

- 6% Cambered Plate
- 2% t/c Ratio
- 0.32 Solidity
- 0.5 Chord Taper
- -11° Twist

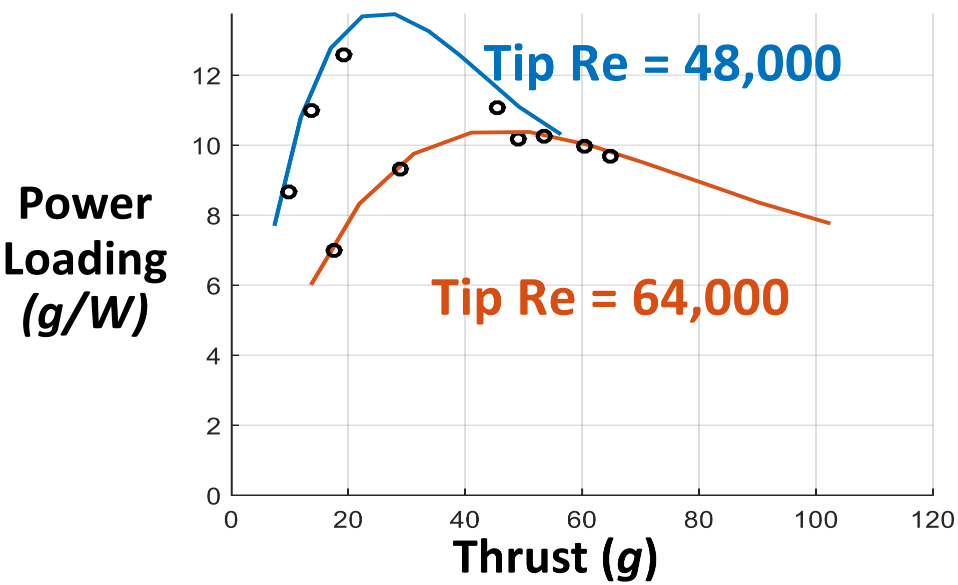
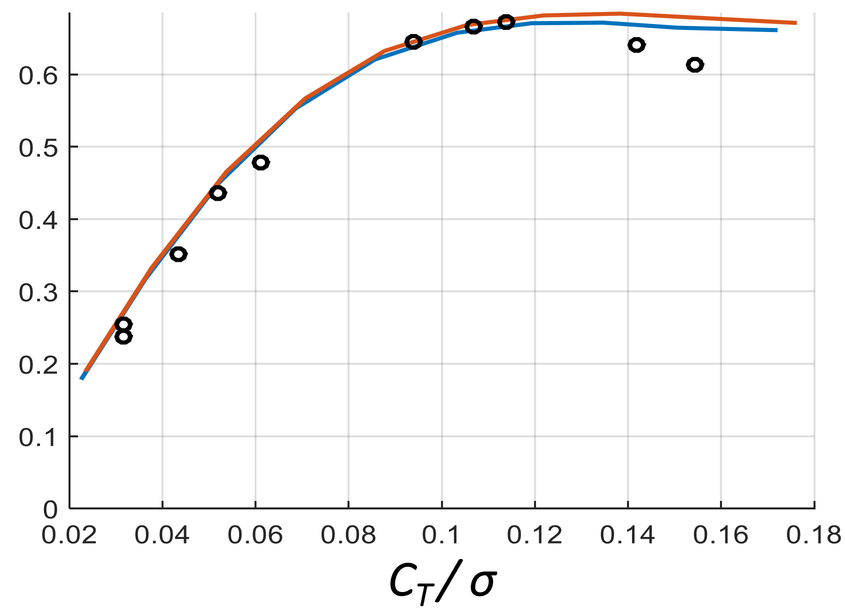
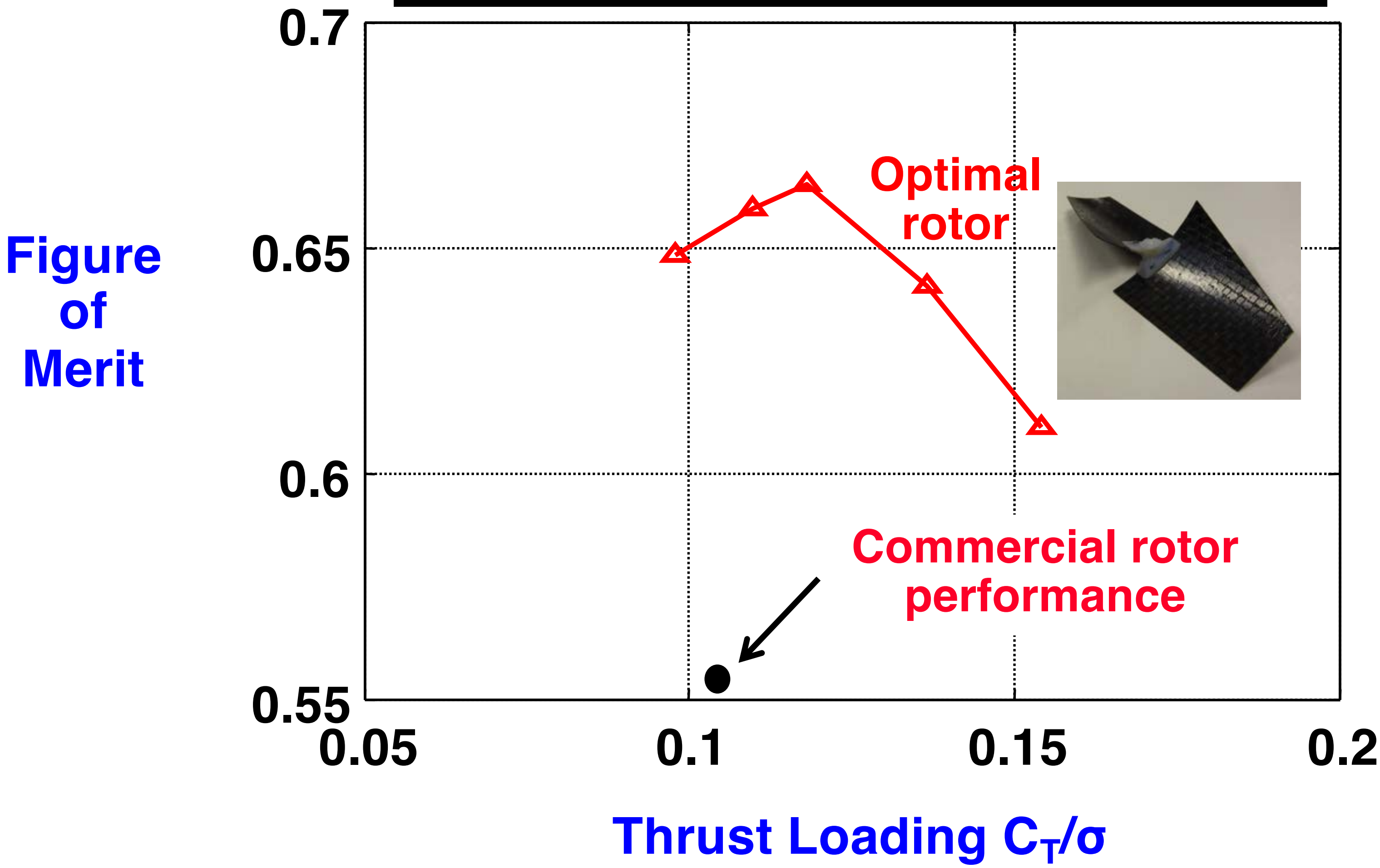


Figure of Merit



Optimal Rotor Performance

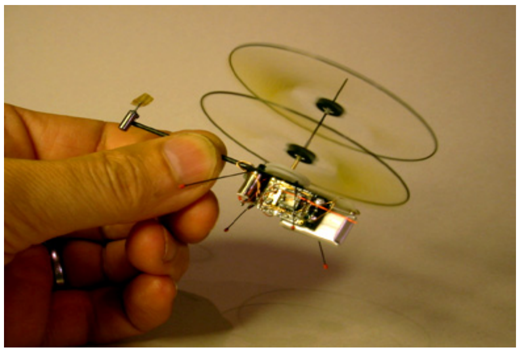
FM = 0.67; Highest ever reported at MAV-scale Reynolds numbers



sUAS: Coaxial Rotor

Commercial Coaxial Rotor MAVs

ProxDynamics Pico Flyer
3.3 grams



Micro Mosquito
28 grams

Walkera DragonFly
68 grams

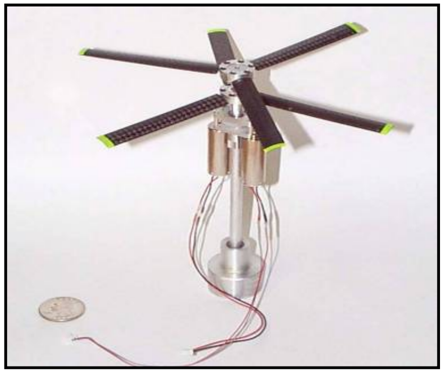
Walkera 5#10
195 grams

Blade CX
227 grams

SkyBotix
280 grams

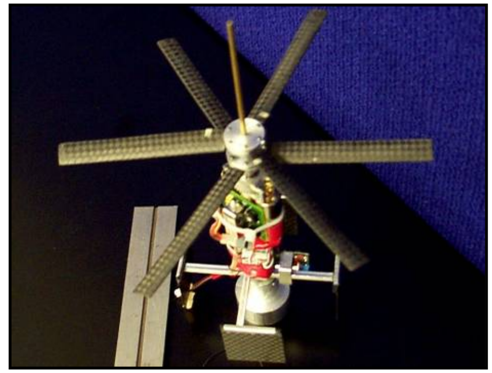
Coaxial Rotor MAV Development at UM

Evolution of MICRO MAV

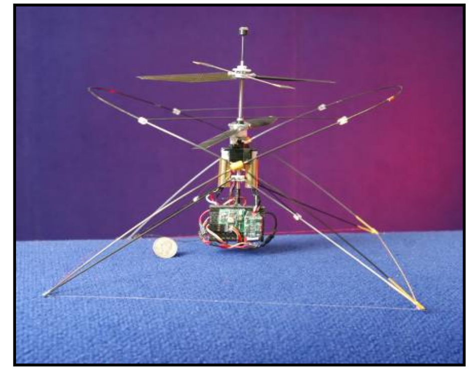


1st Gen.

2nd Gen.



3nd Gen.



4nd Gen.

1st Generation

- 100 g Weight
- Maximum Single Rotor FM ~ 0.4
- No Payload Capacity
- No Lateral Control - Unstable
- 3 Minute Hover Endurance

4th Generation

- Two bladed teetering rotors
- 135 gr. Single rotor max FM ~ 0.65
- Swashplate for cyclic control
- 20 minute hover endurance
- 25 g payload

Coaxial Rotors: Pros & Cons

Pros

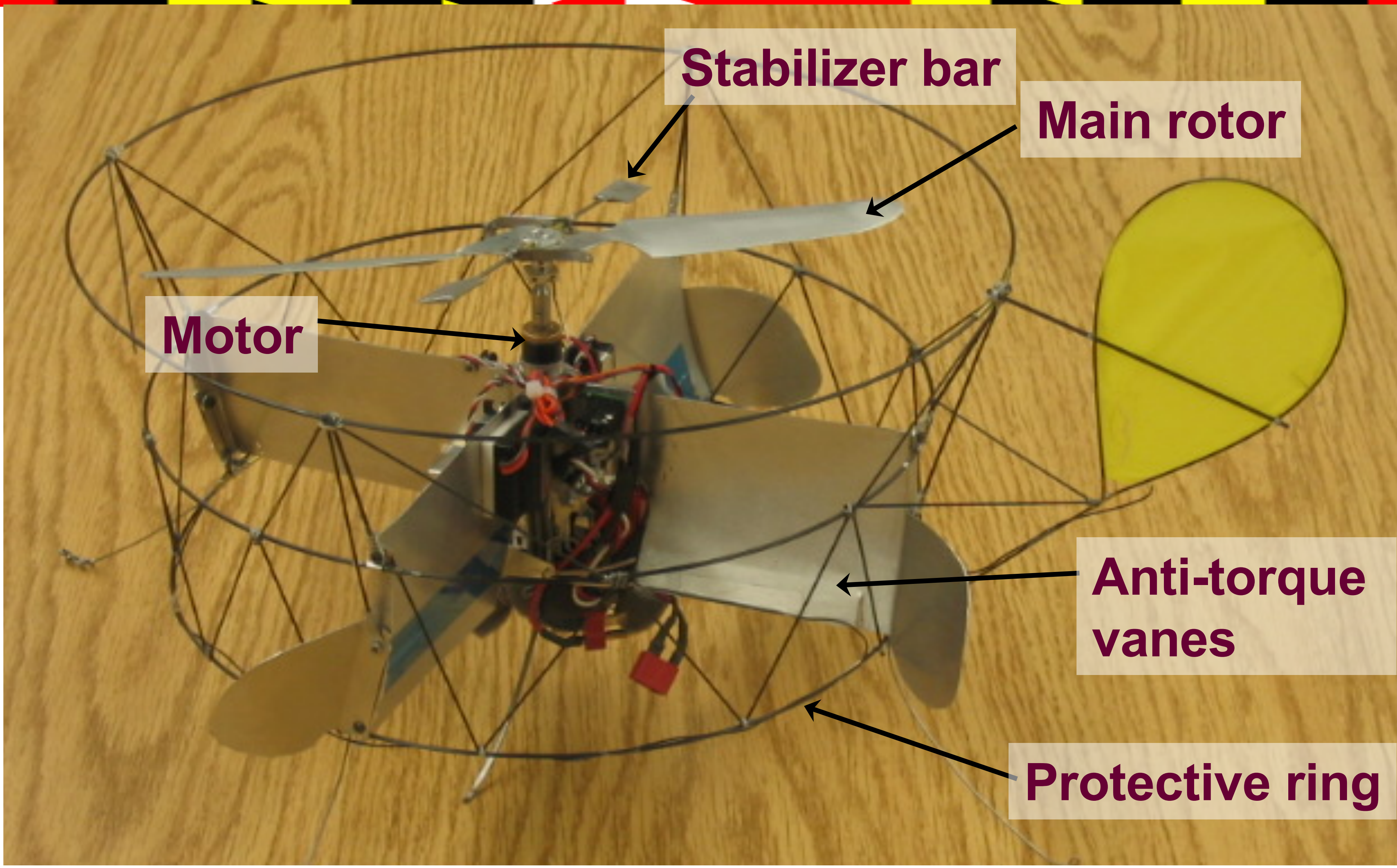
- Compact design (no tail rotor)

Cons

- Mechanical complexity of hub design
- Poor yaw flight stability
- Aerodynamic efficiency (interference on lower rotor especially in hover)
- Needs significant rotor-separation in high speed (more hub drag)

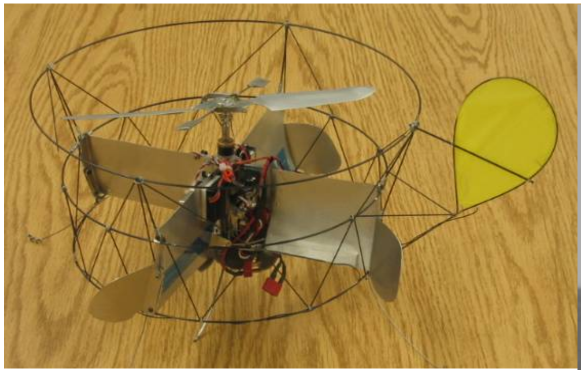
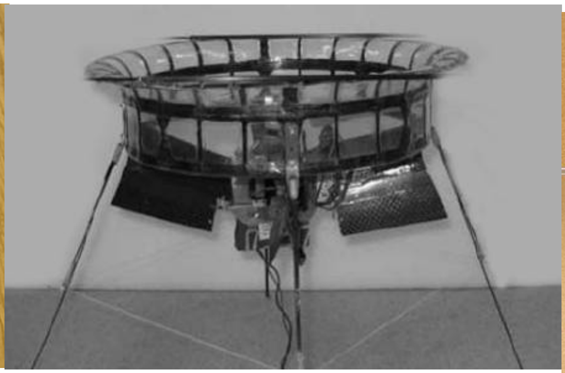
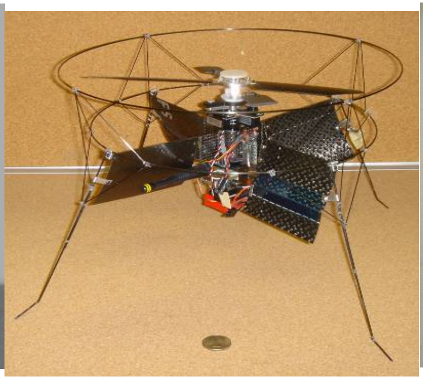
sUAS: Single Main Rotor with Anti-Torque Vanes

MAV: Single Rotor & Anti-Torque Vanes



MAV: Single Rotor & Anti-Torque Vanes

Evolution of the Giant MAV

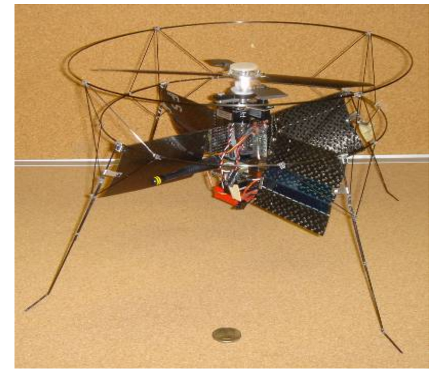





1st Gen. 2nd Gen. 3nd Gen. 4nd Gen.

1st Generation
- 27 cm diameter
- 310 gm gross weight
- Aluminum construction
- Basic RC Components
- Endurance 4 minutes

4th Generation
- 20 cm rotor diameter
- 200 gm gross weight
- Carbon fiber construction
- Refined spider-type swashplate
- On-board stability augmentation
- Endurance 15 minutes

Single Main Rotor with Antitorque Vanes Pros & Cons



Pros

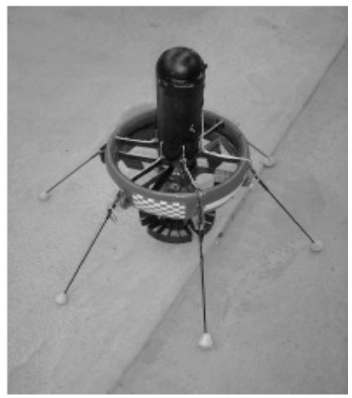
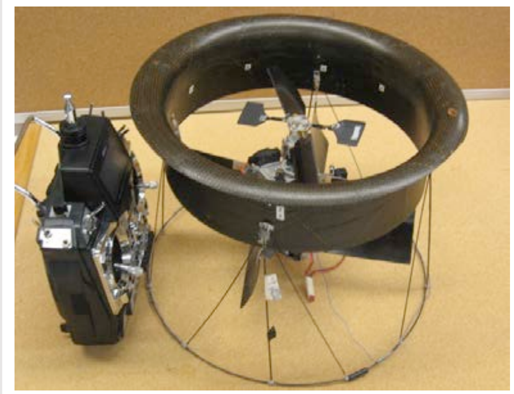
- Compact and simple design (no tail rotor)

Cons

- Flight stability issues near ground
- Limited control authority
- Needed additional power because of hub & vanes interference (same level as tail rotor)

sUAS: Shrouded Rotor

Shrouded rotor vehicles

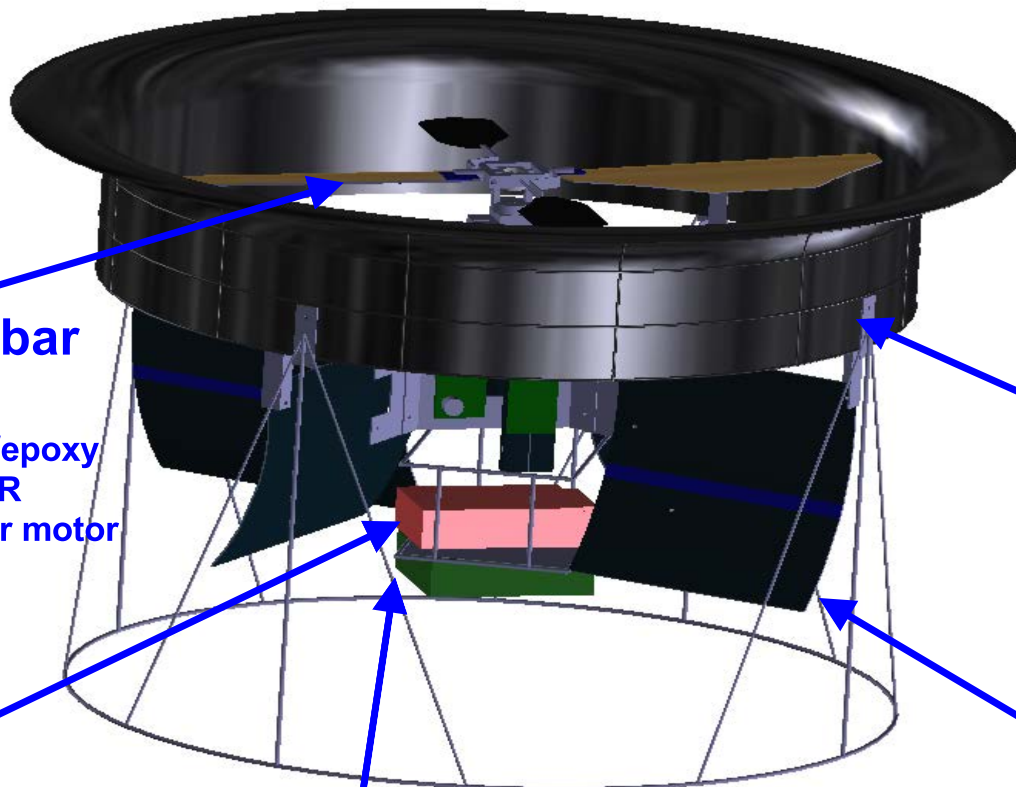
Cypher	GTSpy	ISTAR	TiShrov
			

115 Kg → 2 Kg → 1.8 Kg → 0.28 Kg
Weight

2.2 m → 0.25 m
Rotor diameter

Shrouded Rotor TiShrov

Gross Weight
257 g



Hingeless rotor-Hiller bar (245 mm dia)
Circular camber, sharp LE carbon/epoxy
2:1 Linear taper blade @ 80%R
Driven by 75 W brushless outrunner motor

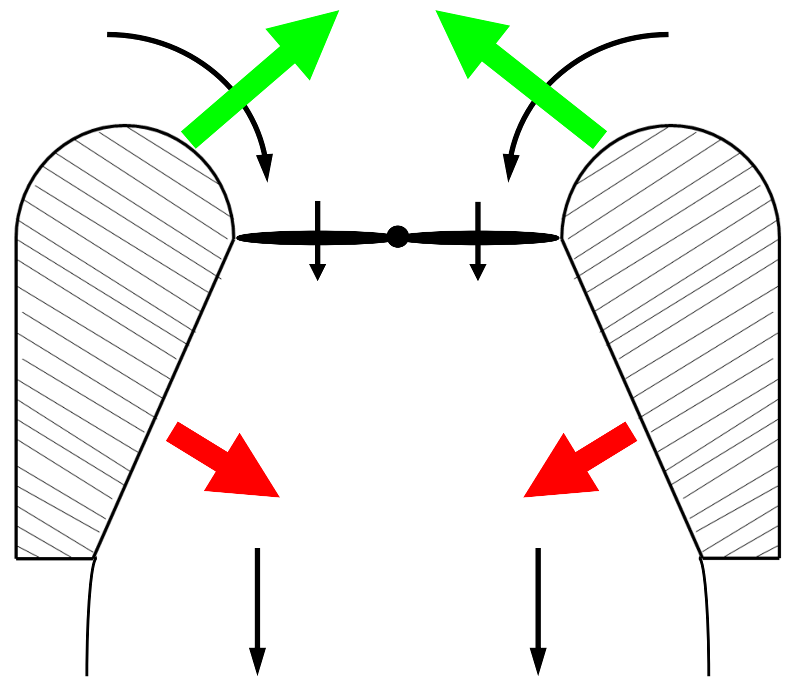
Shroud
Carbon /epoxy

Battery
3 cell 800mAH 20C LiPo
~ 50 g

IMU
Complimentary filter gyro and acc input
for pitch and roll attitude (~ 30 g)

Vanes for anti-torque
Two deflectable flaps for yaw control

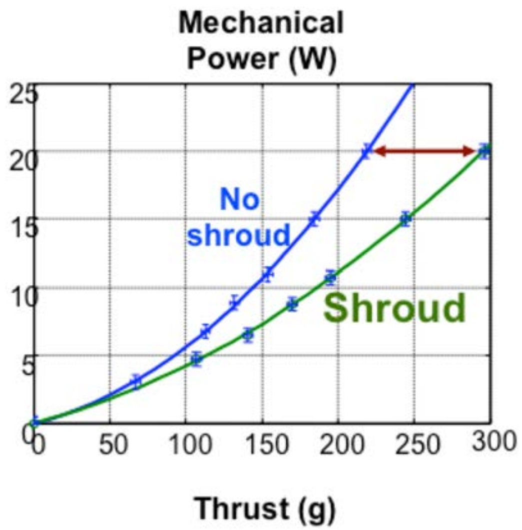
Shrouded-Rotor: Increase Hover Performance

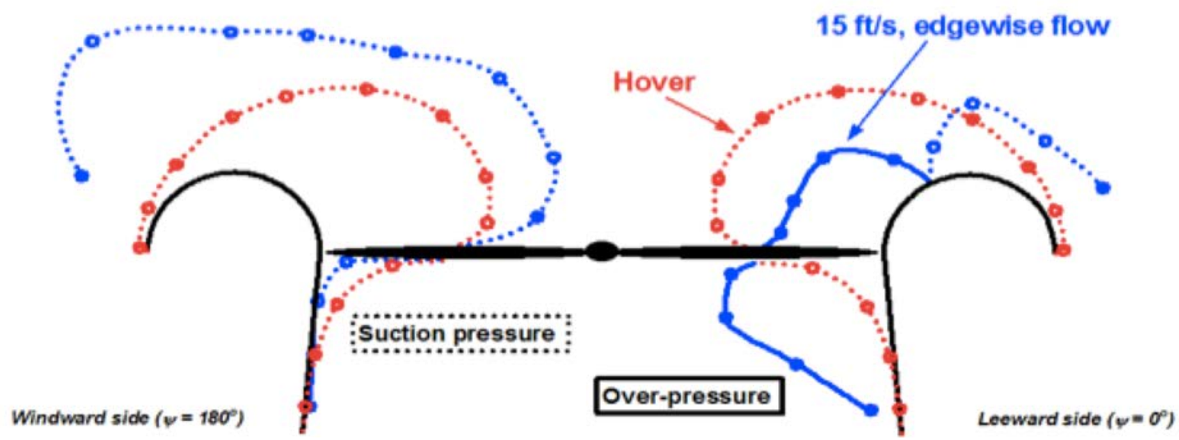


Optimized Configuration: Lip radius 13%R, 10^0 diffuser angle and 72%R diffuser length results in 95% increase in thrust for same power

Challenges: Structural weight of shroud must be less than lift augmentation plus possible performance degradation in forward flight (increase of drag and pitching moment), Susceptibility to gust

Shrouded Rotors

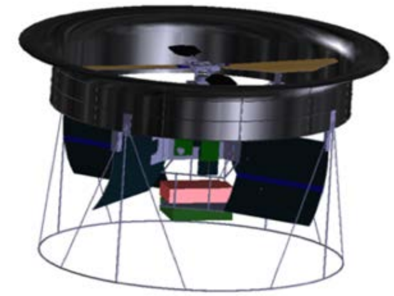




- **Shrouded rotor**
  - **- 30% higher power loading**
  - **- Stall delay: Can accept higher cyclic pitch range**
  - **- 300% higher adverse pitching moment**

Shrouded rotor MAV viable platform for low gust environments

Shrouded Rotors: Pros & Cons



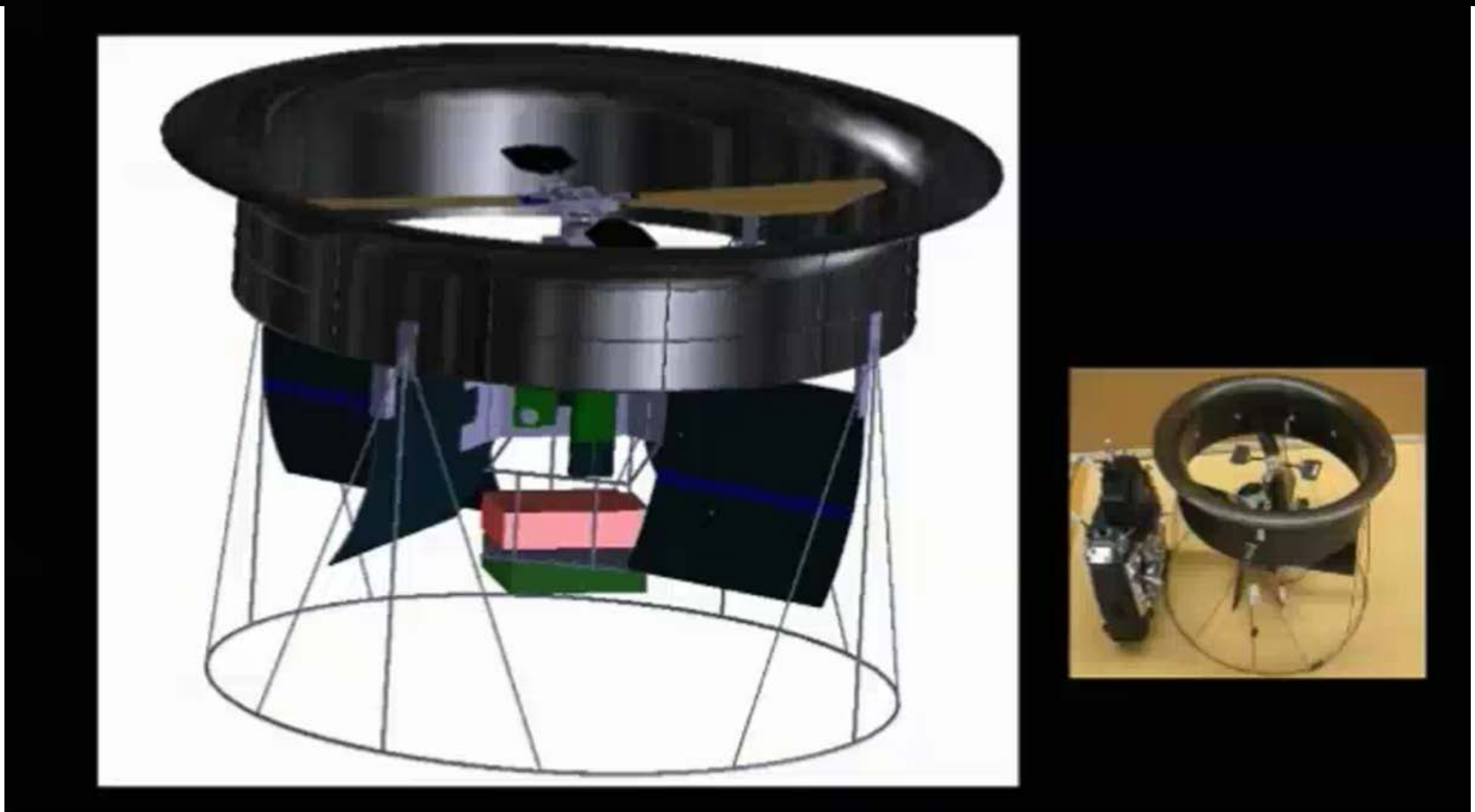
Pros:

- Shroud protects rotor
- Improved hover efficiency
- Delay stall

Cons:

- Challenging to design shroud (lightweight but stiff)
- Degrading forward flight performance (drag)
- High hub pitching moment in forward flight (flight stability issue)
- More susceptible to gust

Shrouded Rotor Flight Video



Shrouded Single Rotor with Anti-Torque Vanes
Weight: 260 g
Rotor Diameter: 9.5"

sUAS: Quad-Rotor

Commercial Quad-Rotors

UDI-RC (38 grams)

UDI-RC (42 grams)

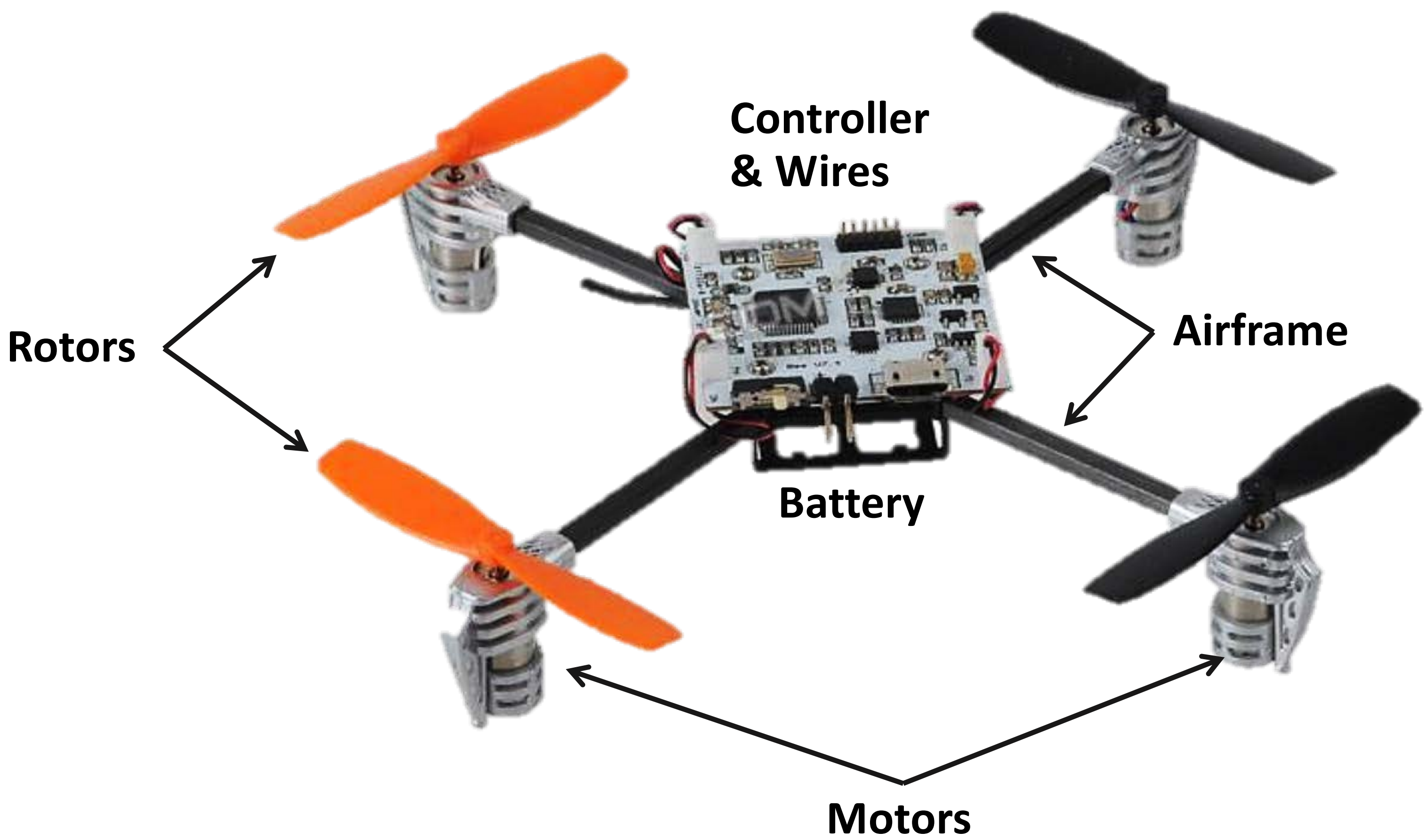
Syma X5 (64 grams)

Syma X5 (108 grams)

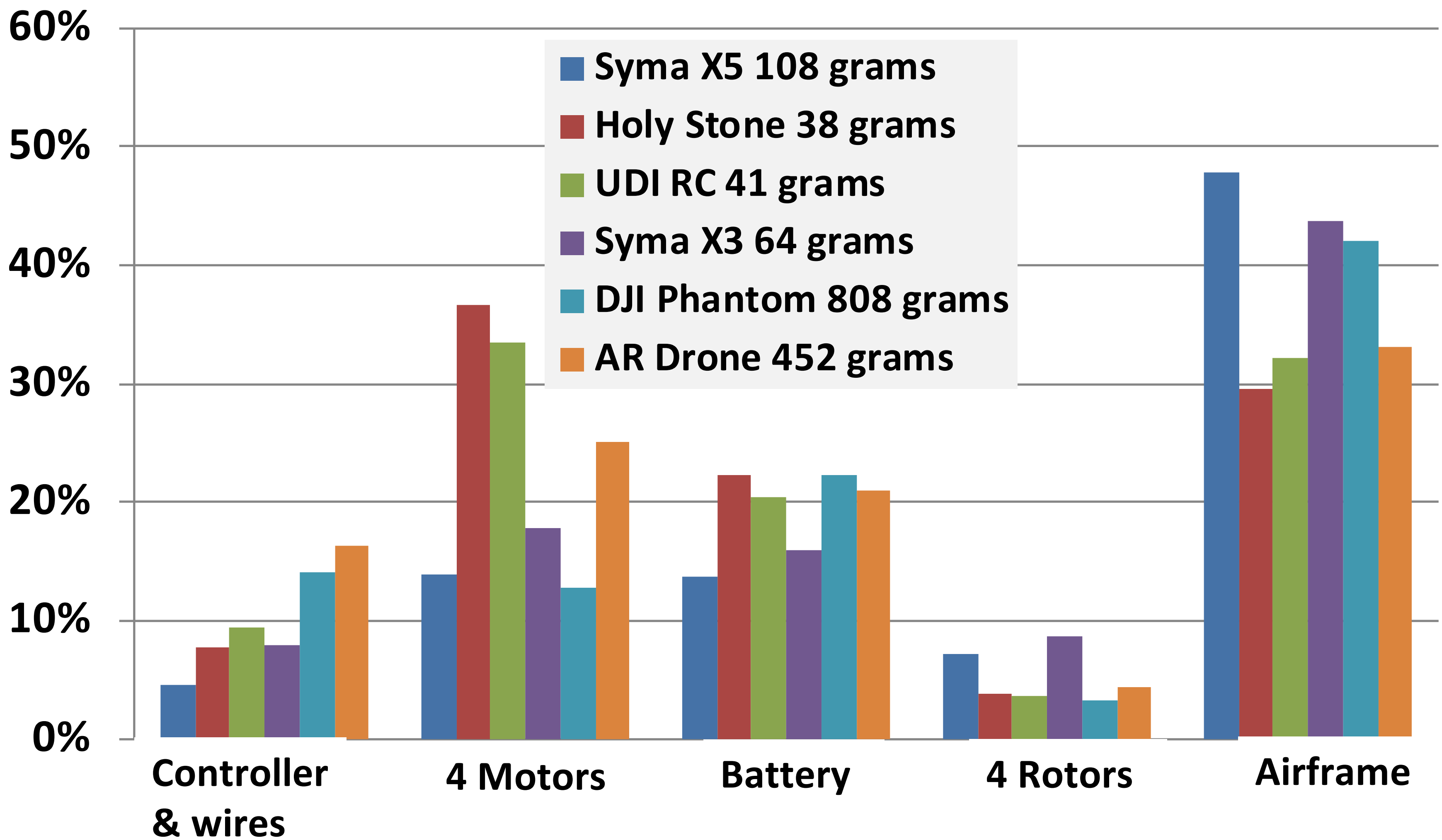
Parront AR Drone 2.0
450 grams

DJI Phantom 2.0
(800 grams)

Basic Quad-Rotor Weight Breakdown



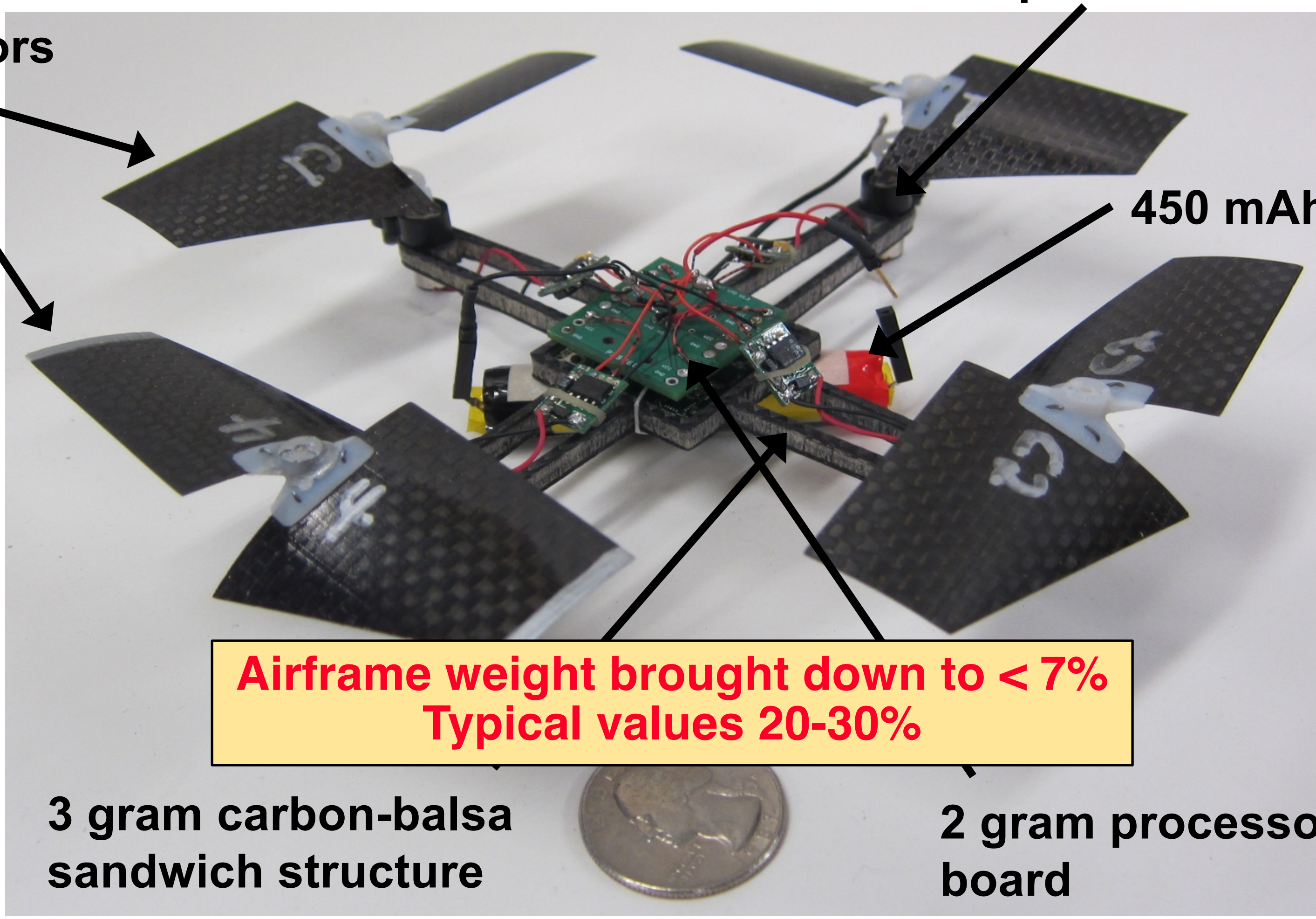
Comparison of Weight Groups



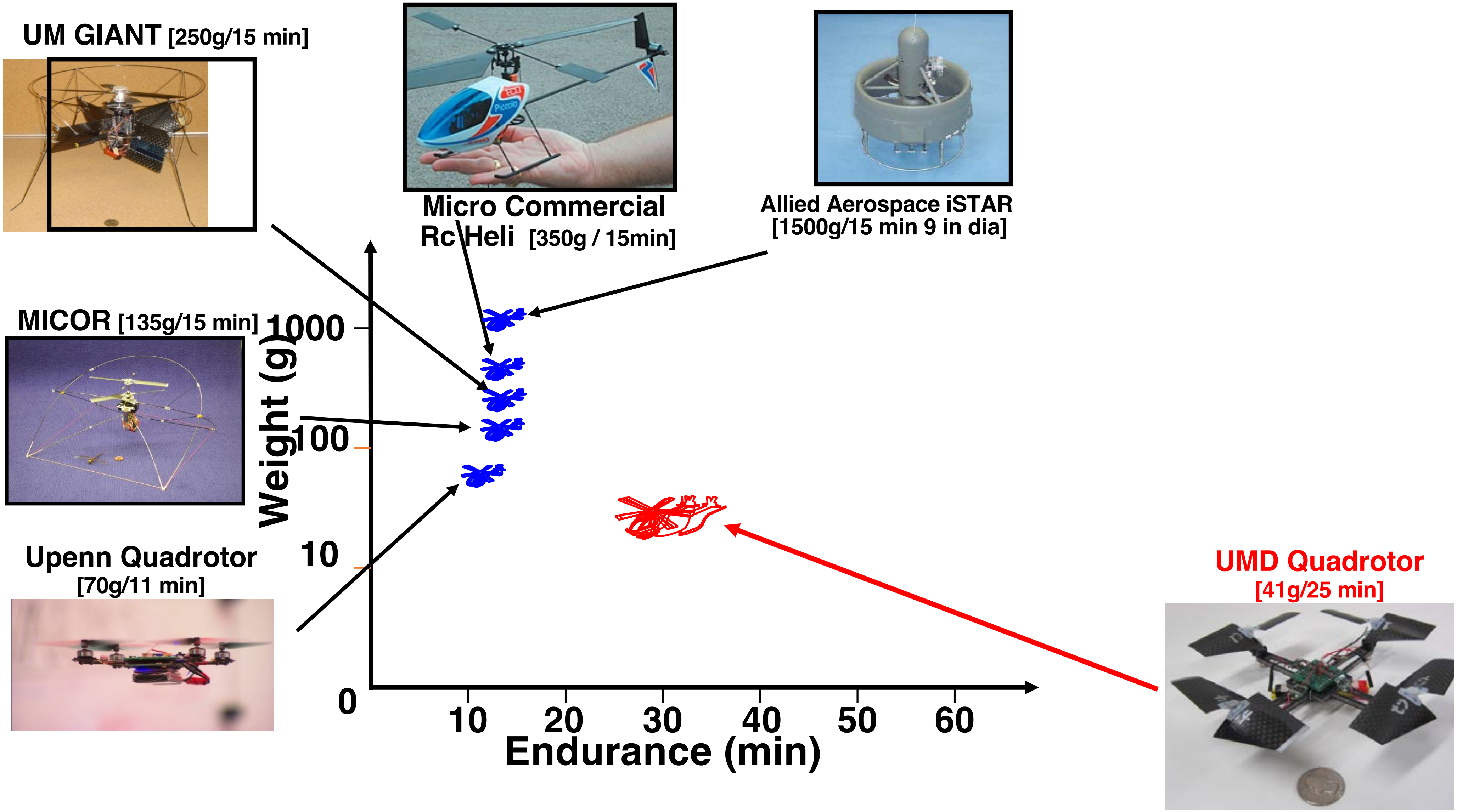
Lack of consistency among commercial quad-rotors

45-grams Quad-Rotor MAV Using Optimal Rotors

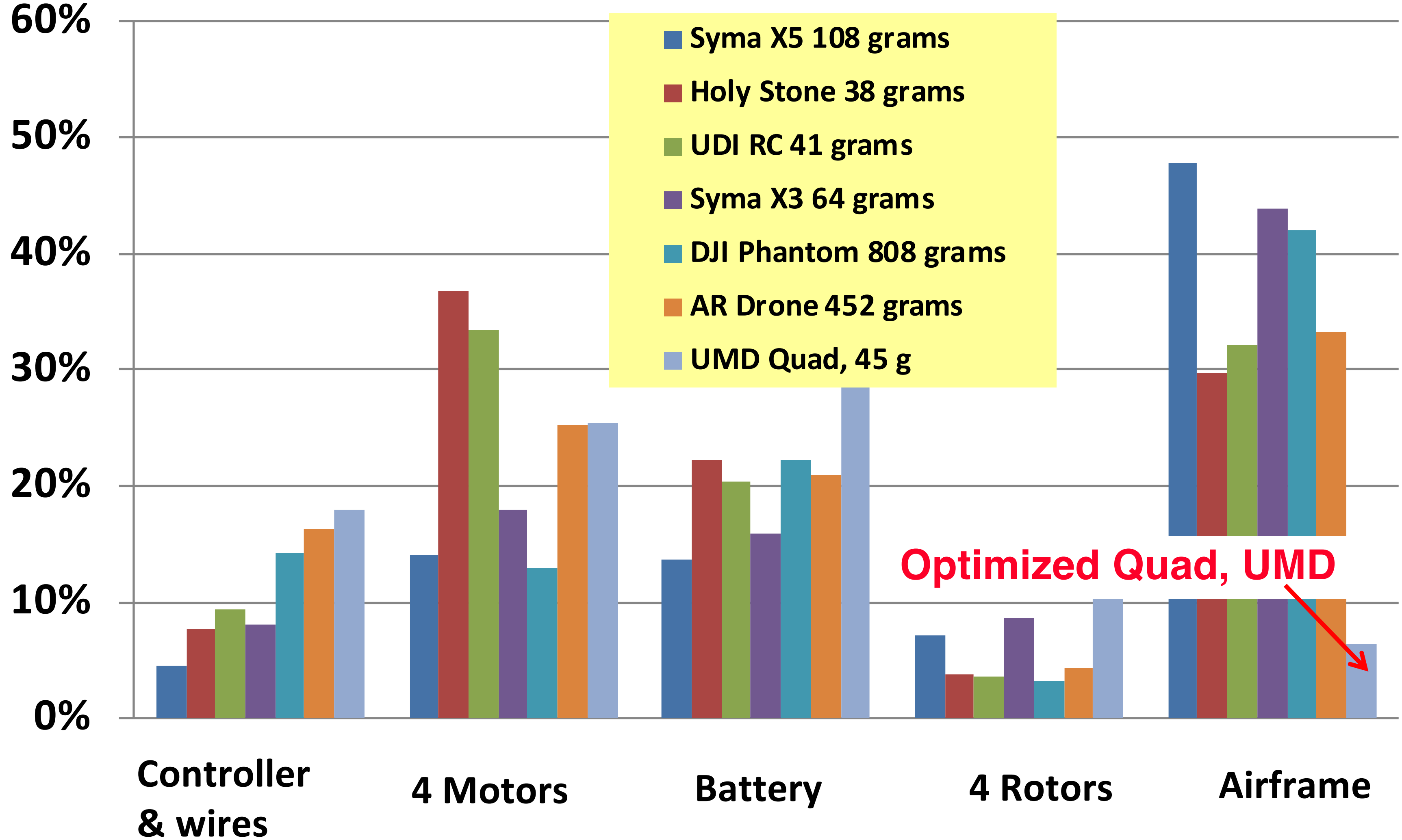
Weight = 41 grams including battery



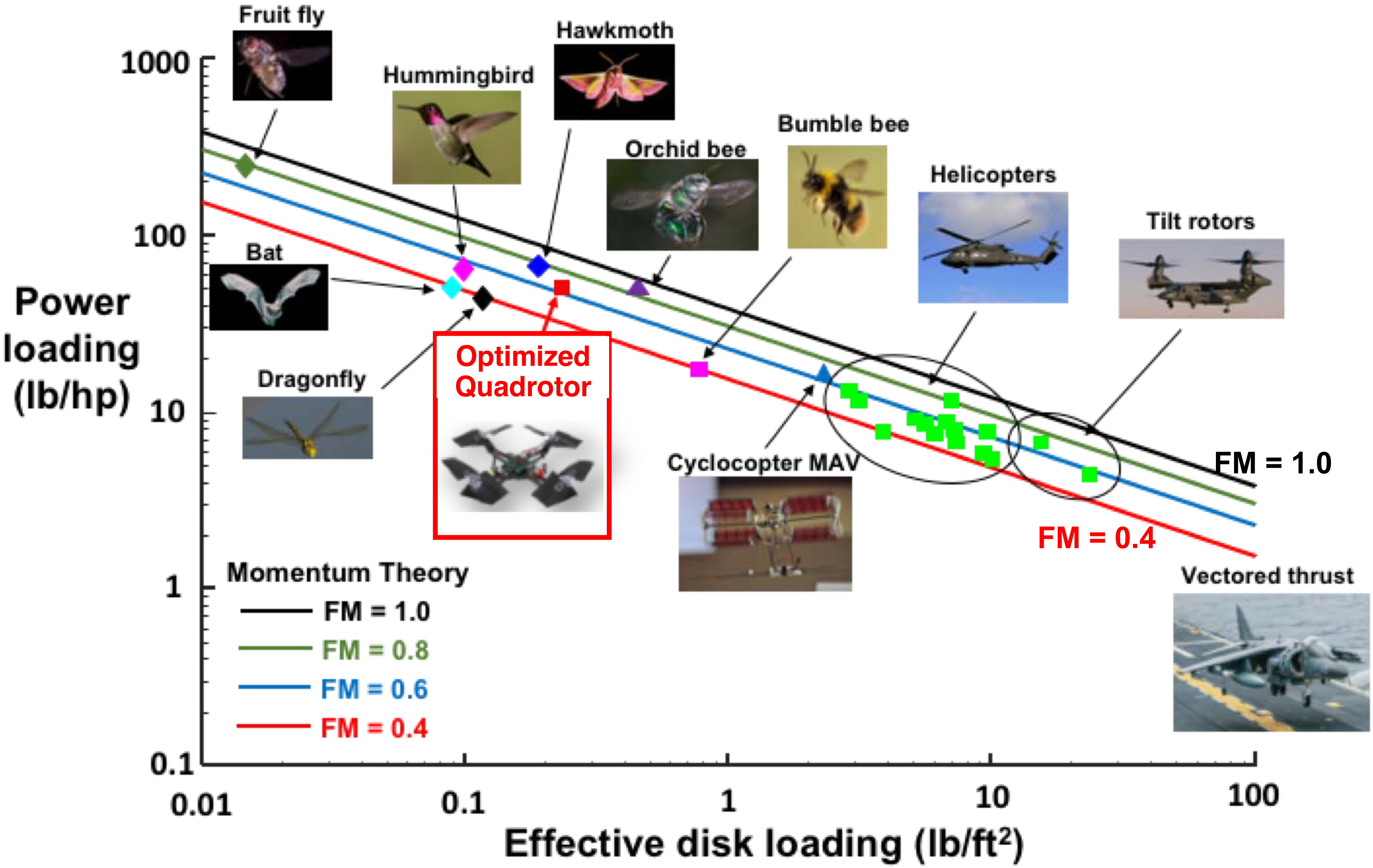
Existing Micro Air Vehicles (MAVs)



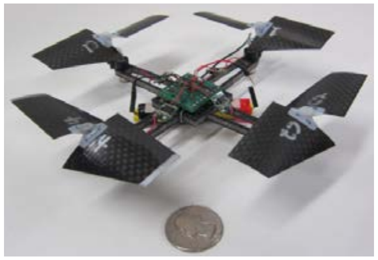
Comparison of Weight Groups Quad Rotors



Power Loading (Thrust/Power)



Quad-Rotors: Pros & Cons



Pros:

- Mechanical simple design (no tail rotor)
- Flight dynamics simple (fixed pitch RPM control), stable platform
- Large cg travel possible (large control authority)

Cons:

- Multi-rotors
- Airframe drag in forward flight

Rotor-Based sUAS Challenges

- Improve hover Figure of Merit, power loading and L/D (Lift/Drag)
  FM: 0.5 ⟶ 0.75
- Increase range/endurance/payload (based on specific flight mission)
- Improve susceptibility to gust (Lateral gust of 5 m/s)
- Optimize propulsion (motors, batteries) for specific flight mission

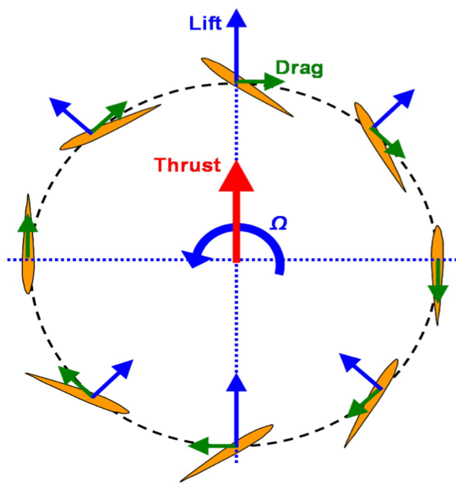
sUAS:
Unconventional Rotor-Based Configurations

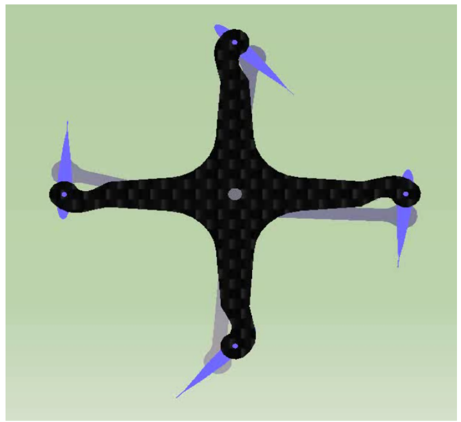
sUAS: Cyclocopter

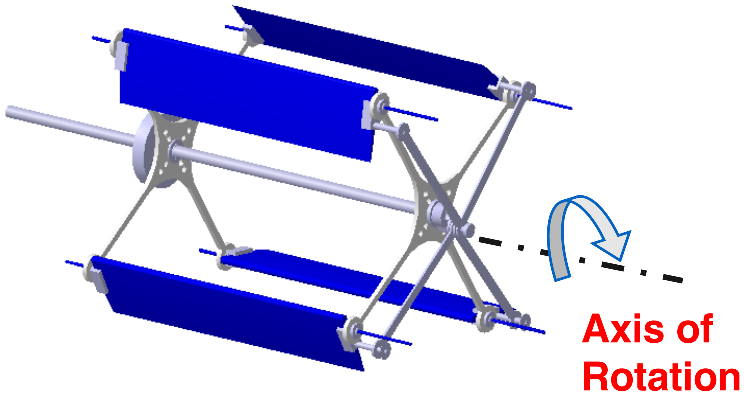
Cycloidal Rotor

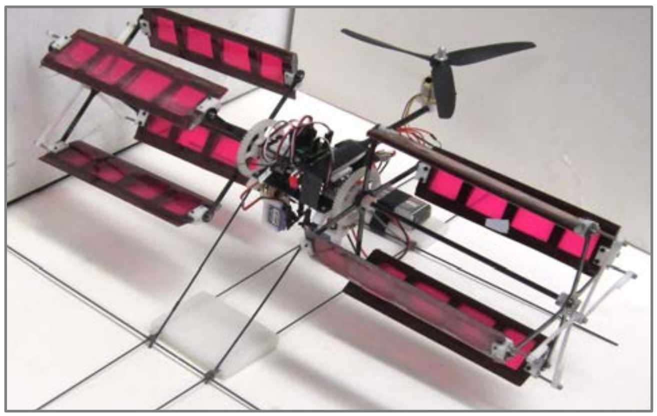
- **Blade span parallel to horizontal axis of rotation**
- **Blade pitch angle changes periodically as it rotates around rotor azimuth**
- **Identical environment spanwise**

Passive Blade Pitching



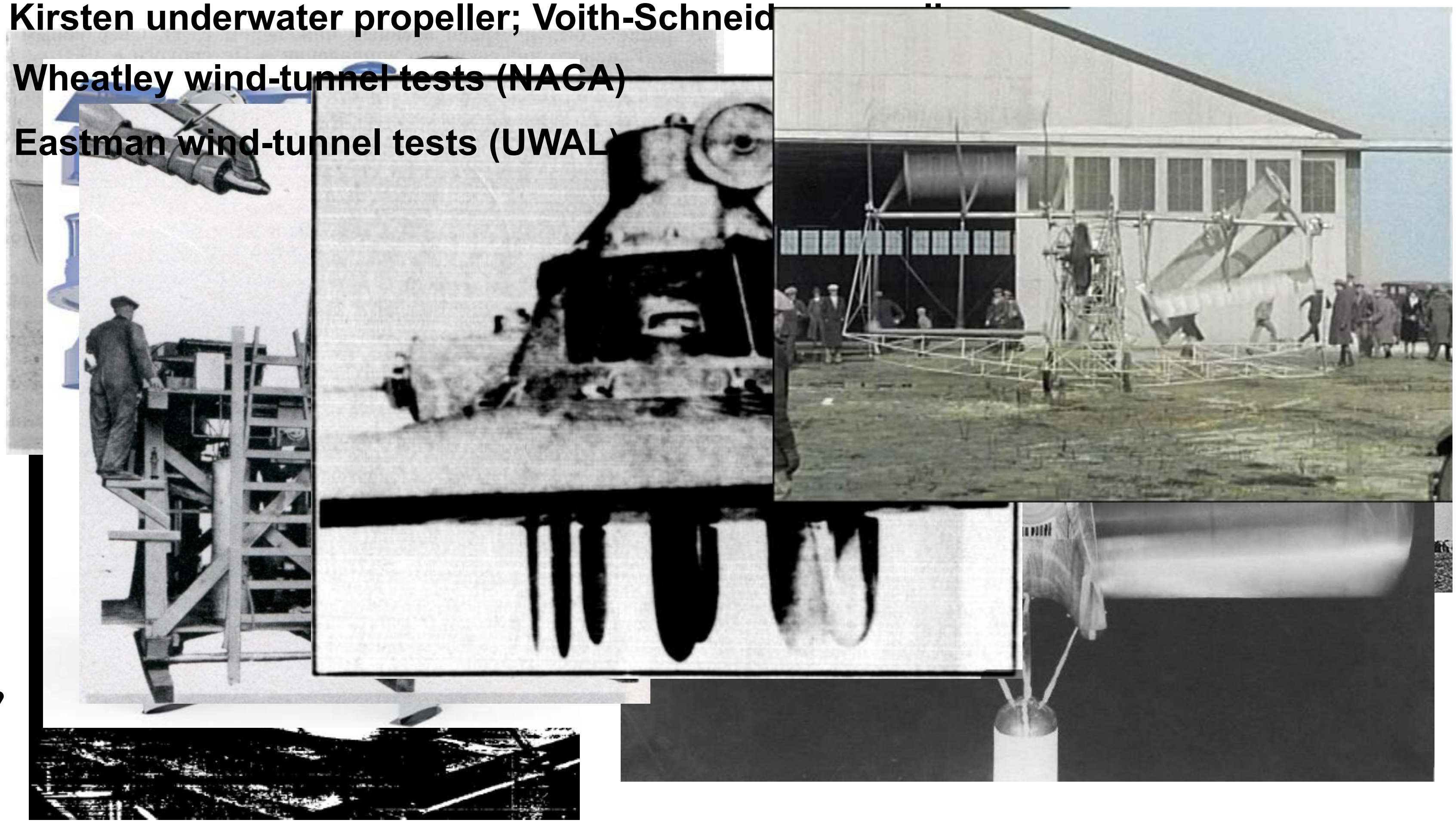






Cyclorotor History: Timeline

- 1909 - 1914 ‘Samiolot’; unknown French cyclogiro
- 1926 - 1931 F. K. Kirsten, ‘Kirsten-Boeing’ propeller
- Kirsten underwater propeller; Voith-Schneid
- 1935 Wheatley wind-tunnel tests (NACA)
- 1943 Eastman wind-tunnel tests (UWAL)



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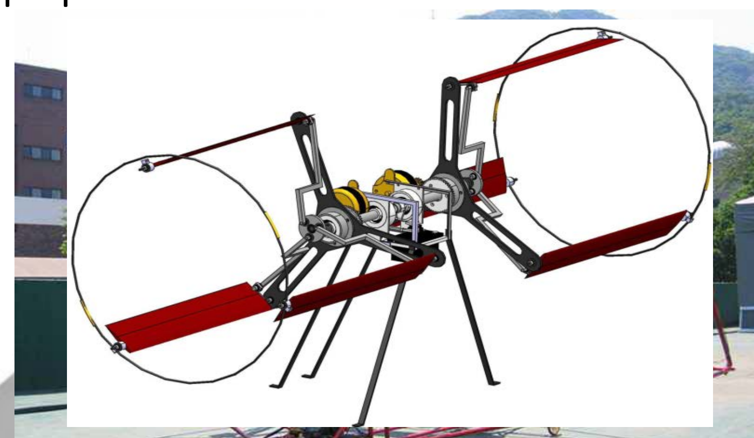
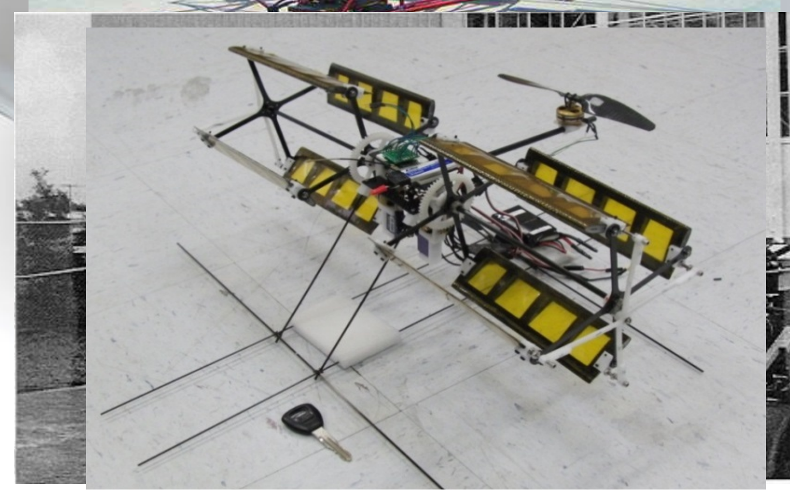
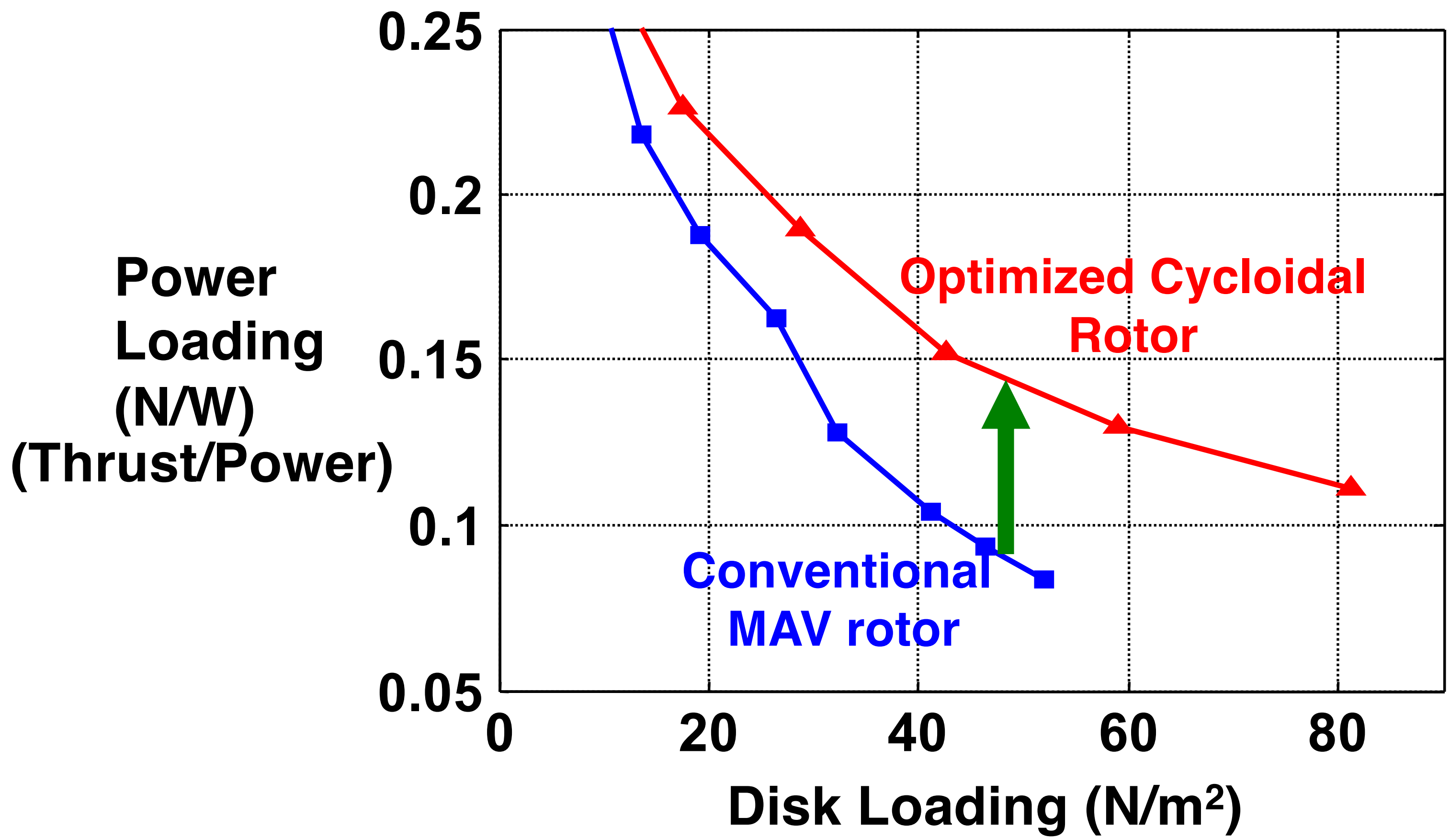
- Kirsten underwater propeller; Voith-Schneider propeller
- 1935 — Wheatley wind-tunnel tests (NACA)
- 1943 — Eastman wind-tunnel tests (UWAL)
- Lapse in cyclorotor research for aviation applications (research continued for wind turbine & ship propeller applications)
- 1998 — **Bosch Aerospace UAV Cycloidal r**
- 2003 - 2015 — **Seoul National University**
- 2006 - Present — **University of Maryland**
- 2012-2013 — **D-Dalus UAV**



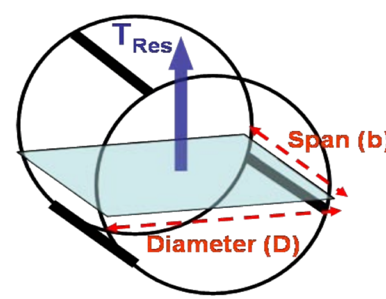


Aerodynamic Efficiency
Cyclorotor vs. Conventional Rotor



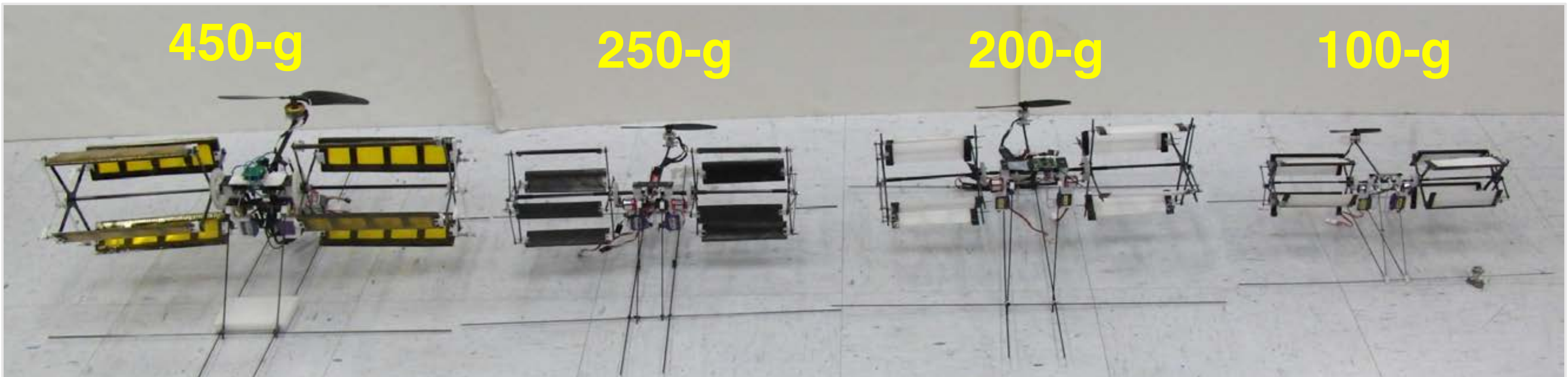
Parameters Varied

- Rotational speed
- Blade airfoil profile
- Blade flexibility
- Blade pitching kinematics
- Pitching axis location
- Number of blades

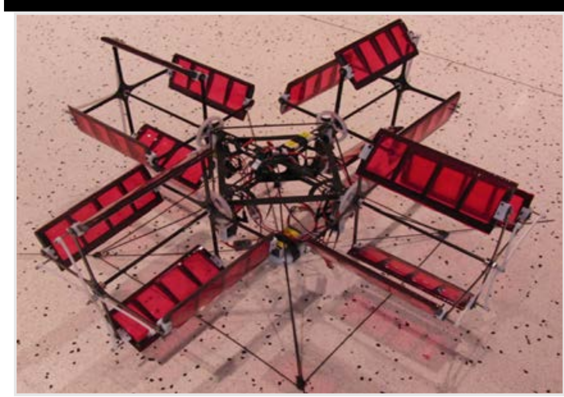


Higher Aerodynamic Efficiency (identical flow in spanwise direction

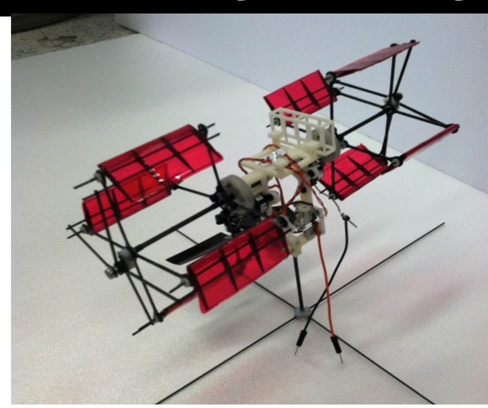
Cyclocopter



Flight-Capable Cyclocopters Developed at the University of Maryland



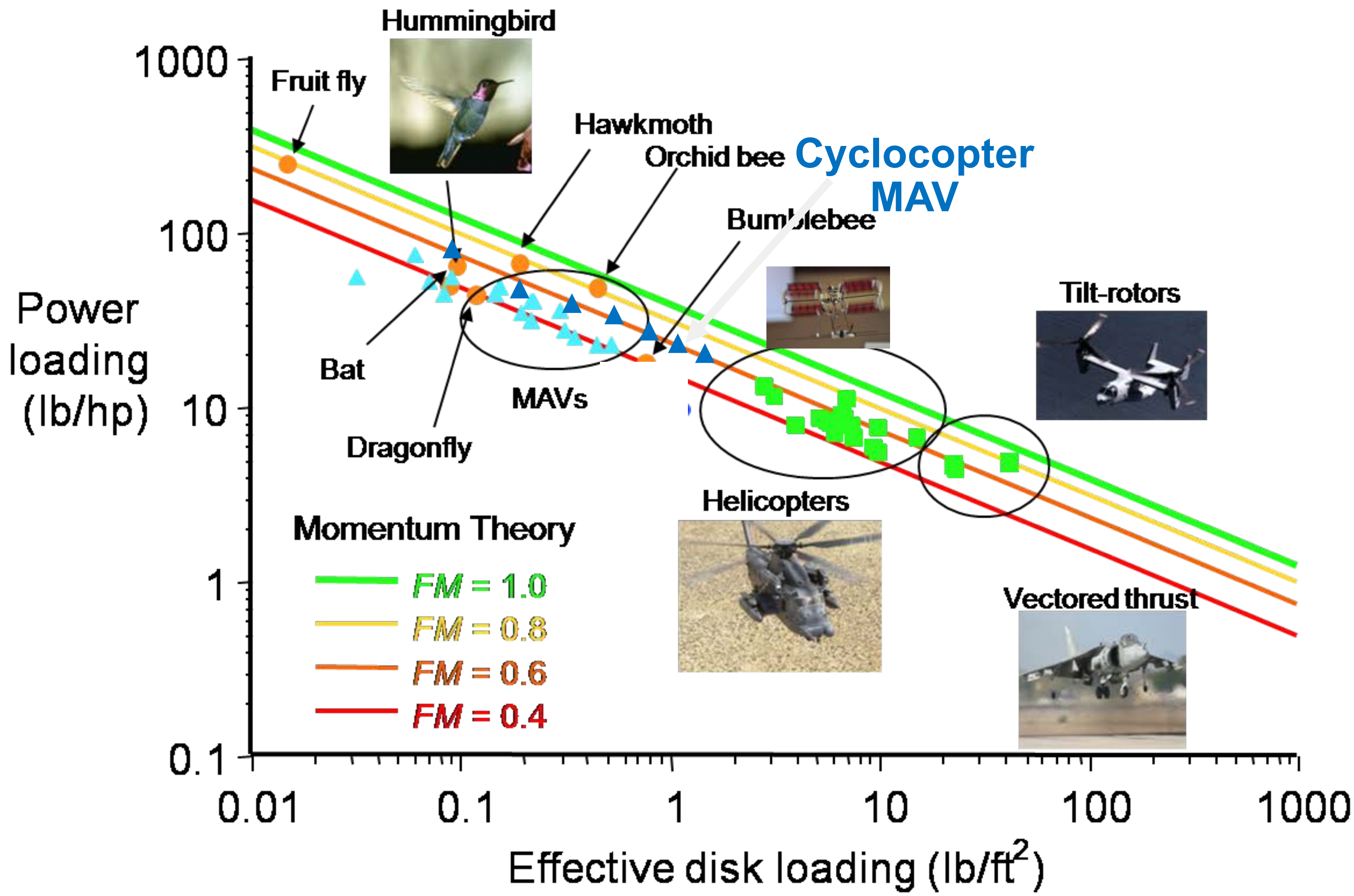
800-g



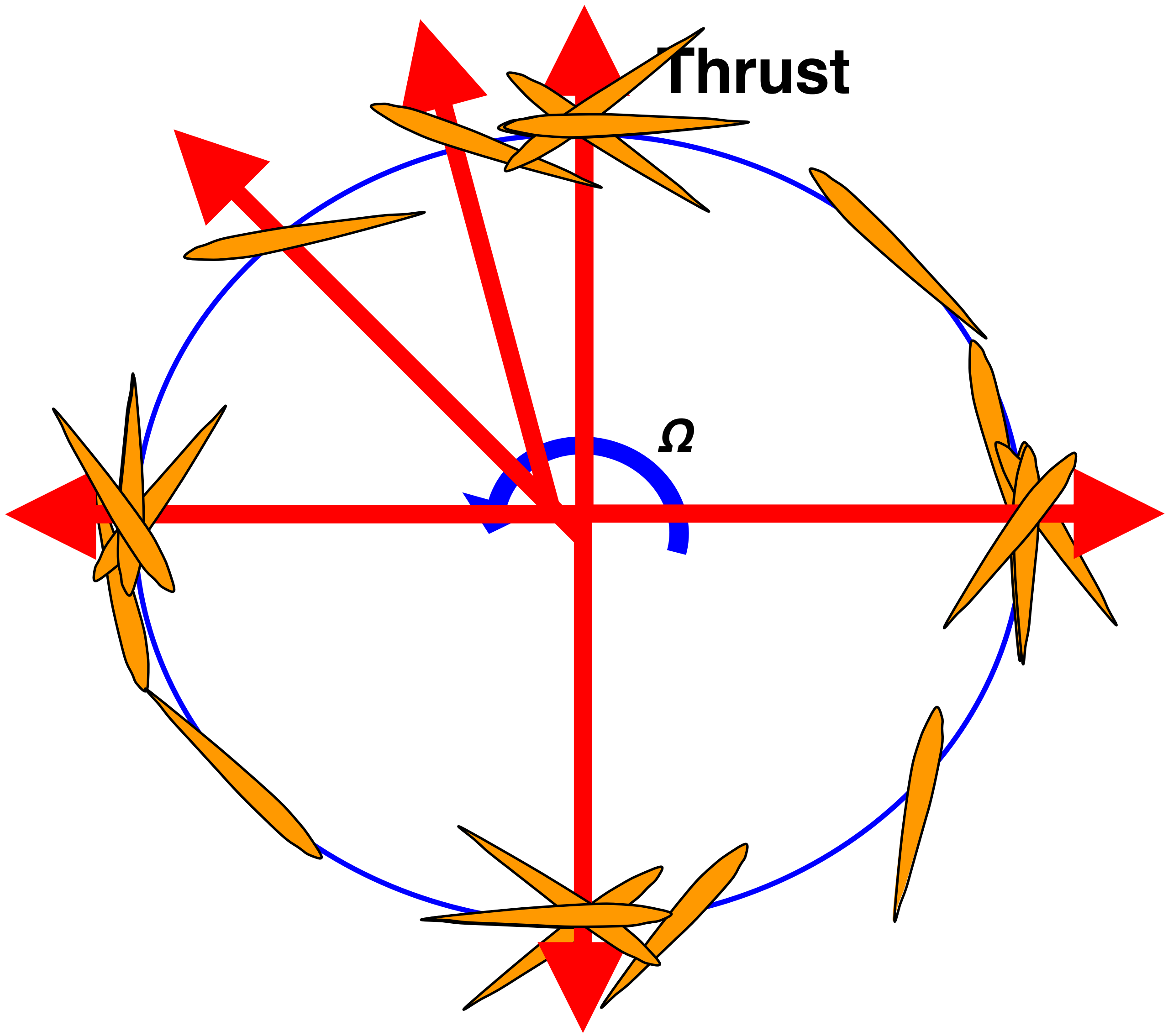
50-g

500-g

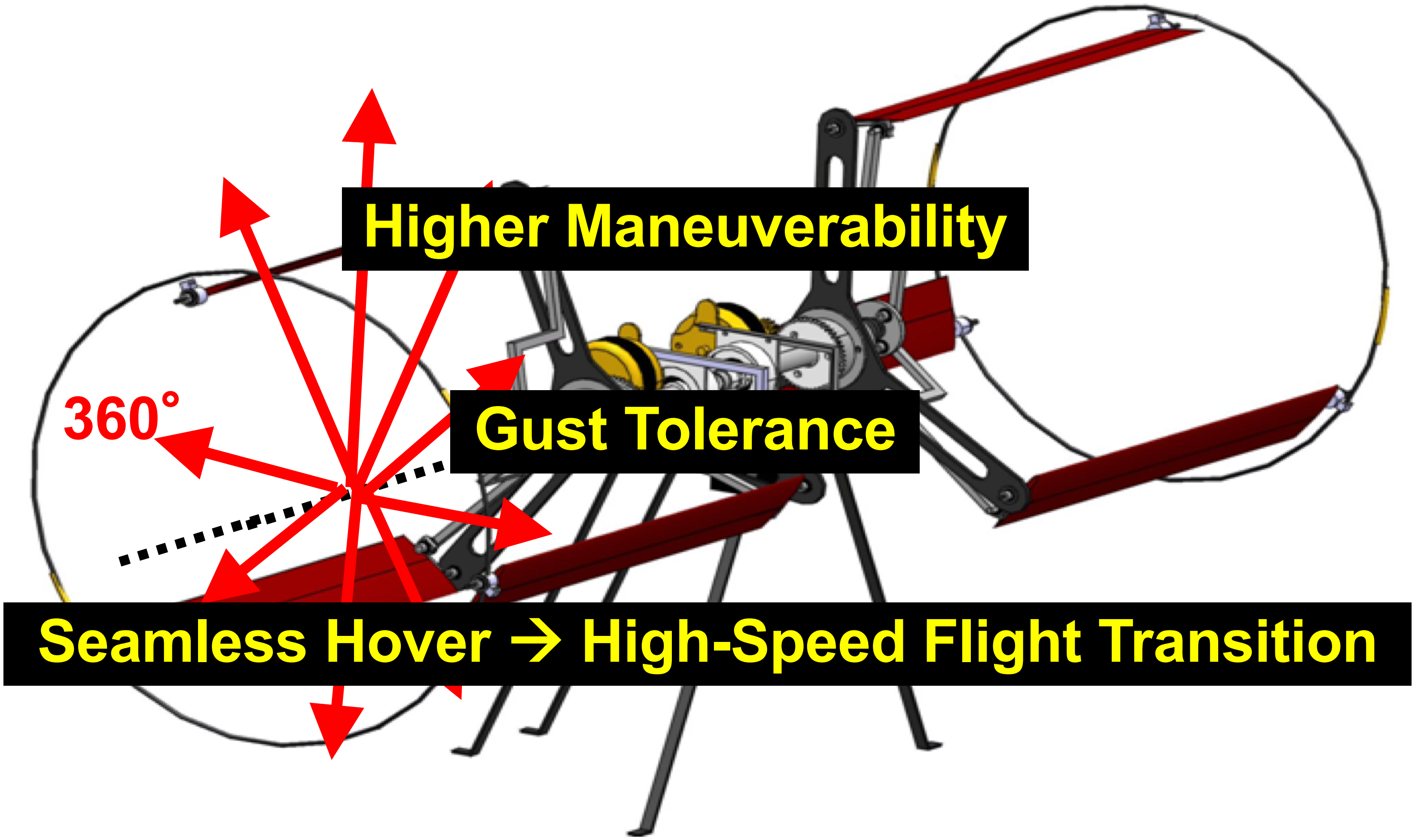
Power Loading (Thrust/Power)



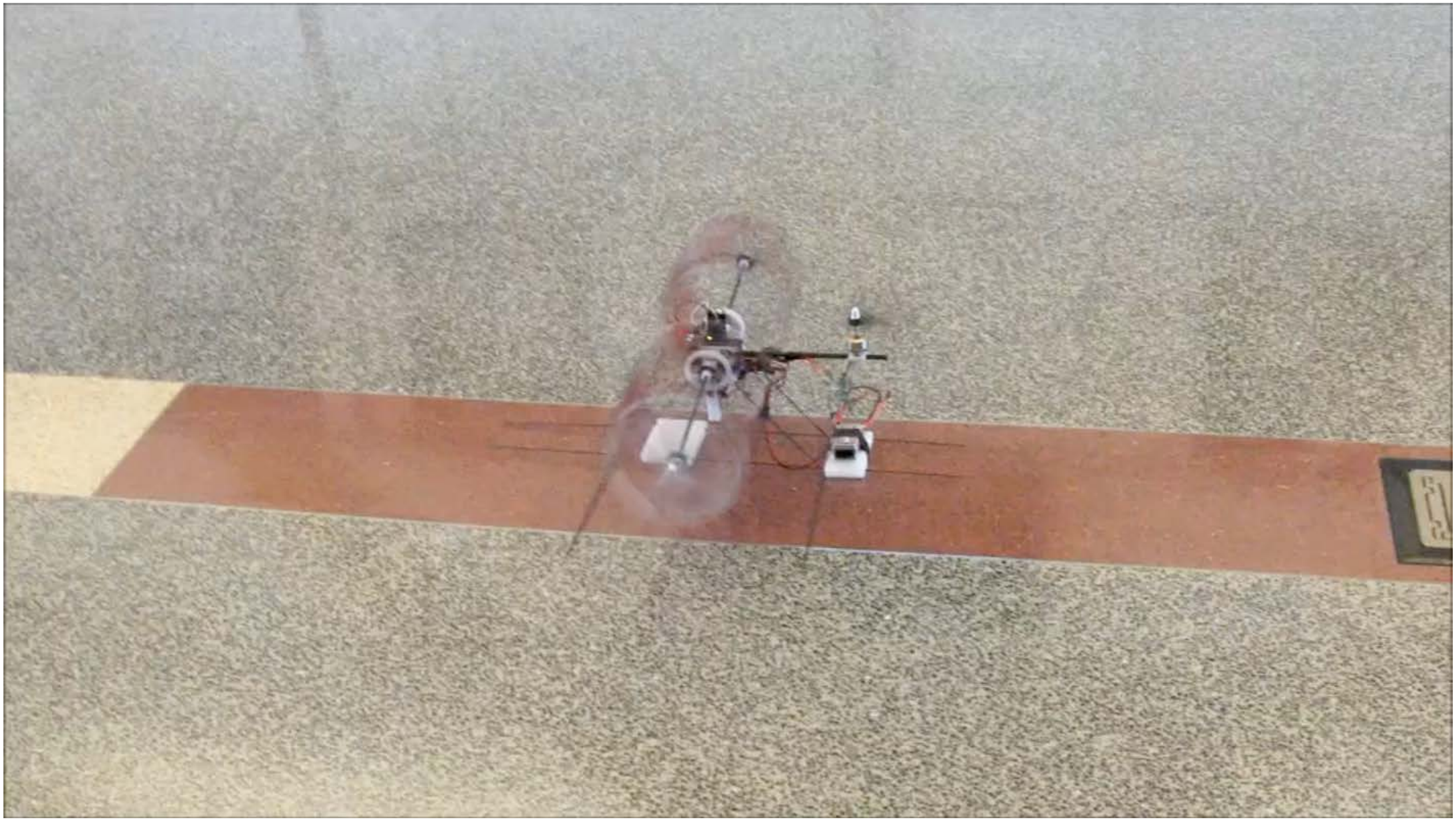
360°Thrust Vectoring Capability



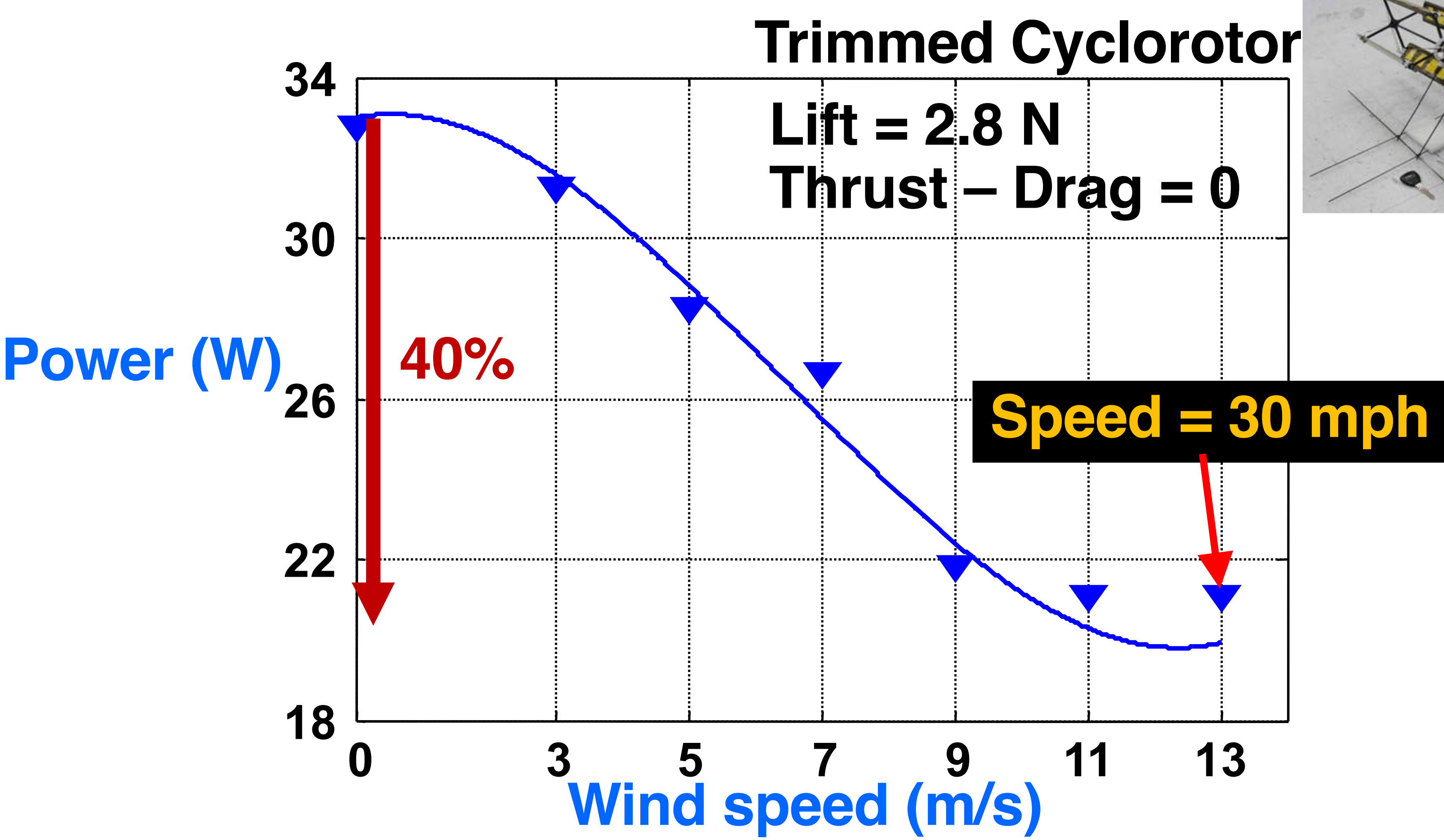
Thrust Vectoring Capability

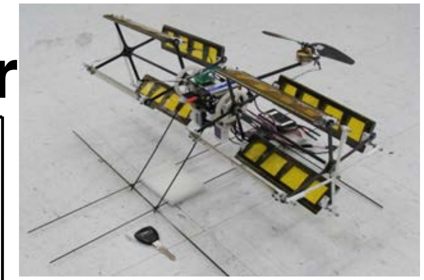


Cyclocopter in Hover Flight



High Speed Flight Capability

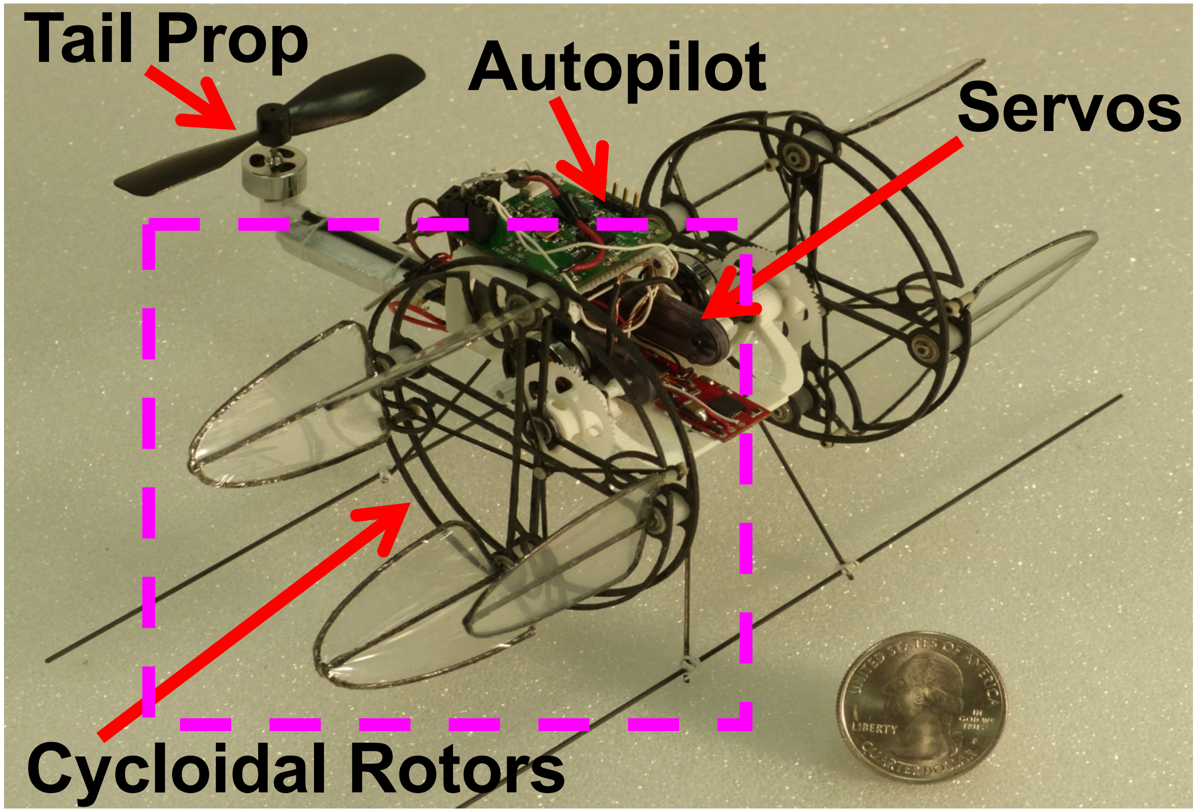




Cyclocopter in Forward Flight

Micro Cyclocopter

Dimensions: 5” X 5” X 3”

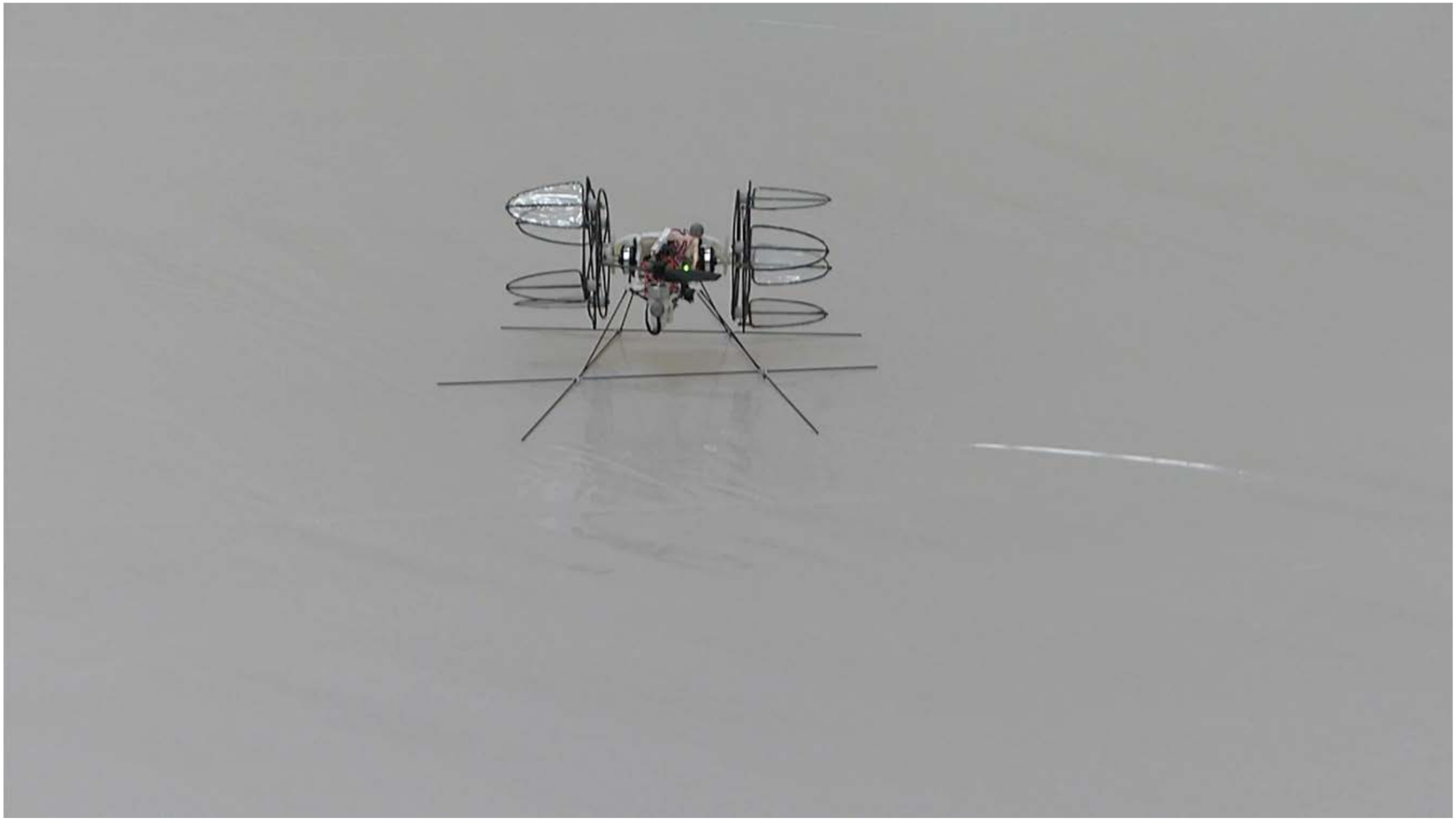


Weight: 29 grams

Rotor RPM: 4000

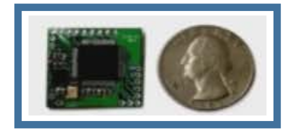
Rotor radius: 1”
Span: 1.3”
Chord: 0.8”

29-g Cyclocopter: Flight Testing

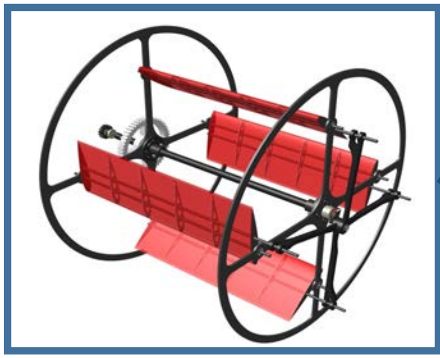


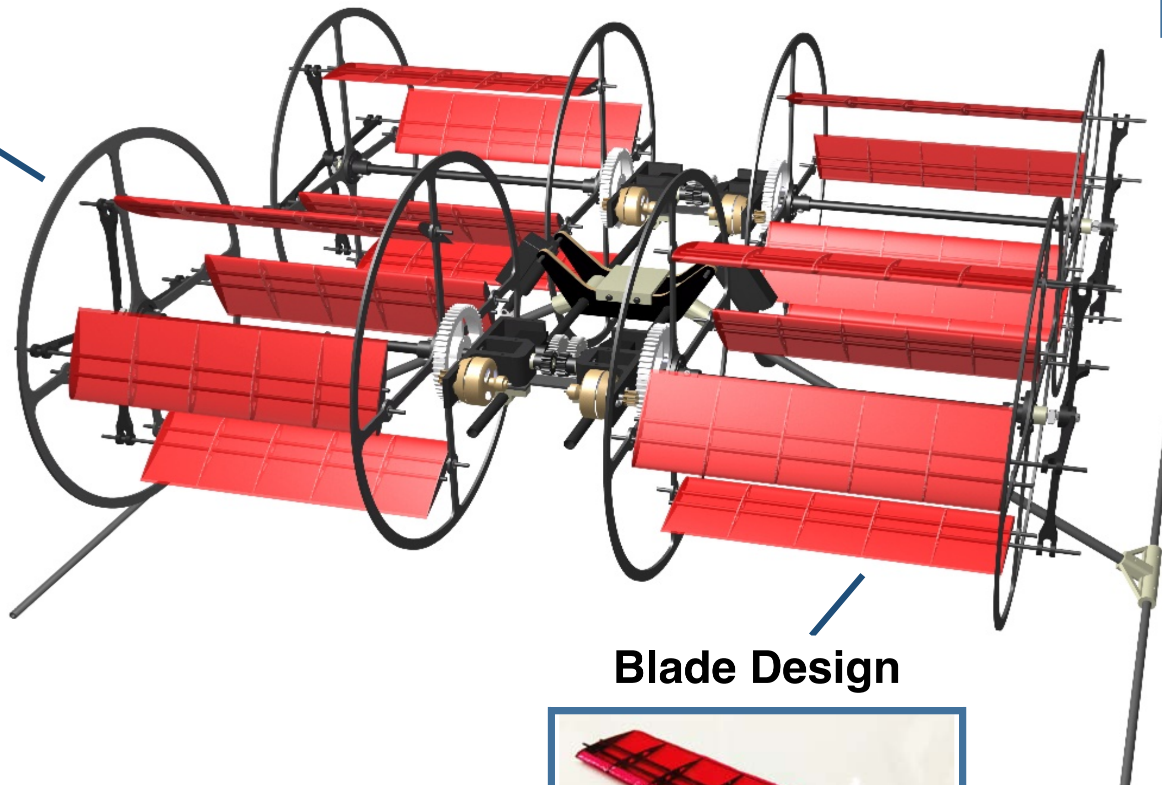
All-Terrain Cyclocopter

Auto-pilot

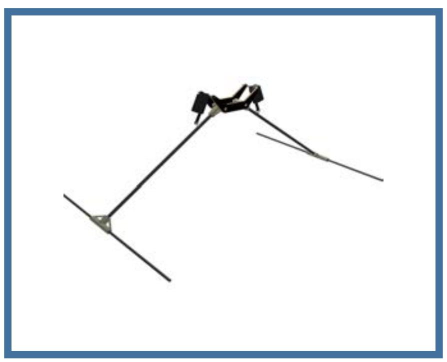


Wheel Design





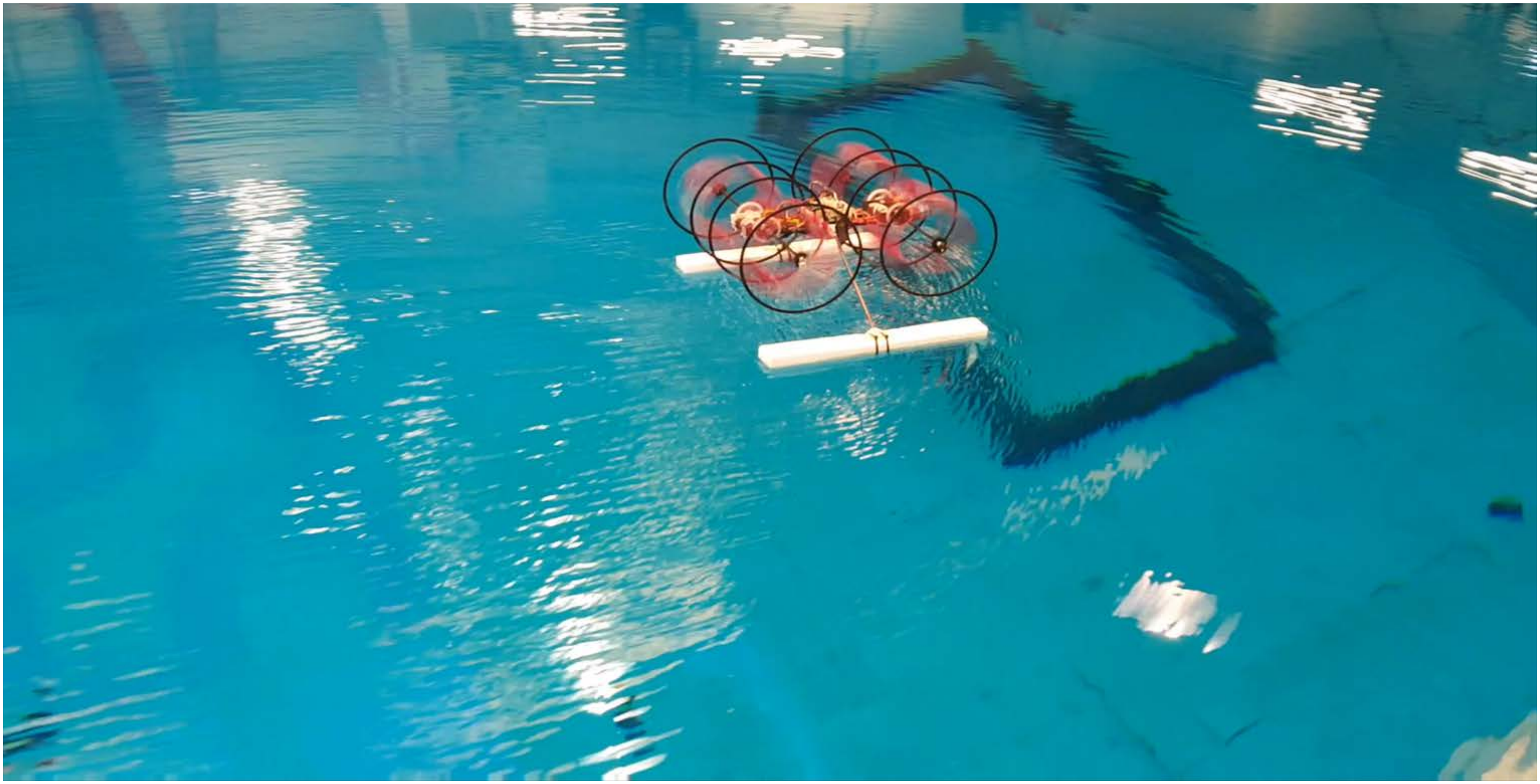
Landing Gear



Blade Design

Aerial-Terrestrial Demonstration

Aquatic Locomotion



Cyclocopters: Conclusions

- Power loading better than a conventional rotor

- Absence of blade stall at high pitching amplitudes (45^0) – high induced velocities in wake

- Requires: 12% of hover power in terrestrial mode (at 2 m/s)
  8% of hover power in aquatic mode

Future: Development of high-speed gust-tolerant autonomous cyclocopter

Cyclocopters: Pros & Cons

Pros:

- Aerodynamic efficient at small scale (unsteady aero forces)
- 360^0 Thrust vector capability (vehicle orientation unchanged in forward flight)
- Highly maneuverable (gust alleviation potential)

Cons:

- Mechanical complex (Pitch change)
- Airframe drag in forward flight

sUAS Compound Configurations

sUAS: Compound Configurations

Goal: Achieve flight mission with vertical takeoff/landing and large speed/range/endurance

Rotorcraft: Hover efficiency

Fixed-wing: Cruise efficiency

Possible configurations:

Tail Sitter (Quad-rotor biplane)

Tiltrotor

Tiltwing

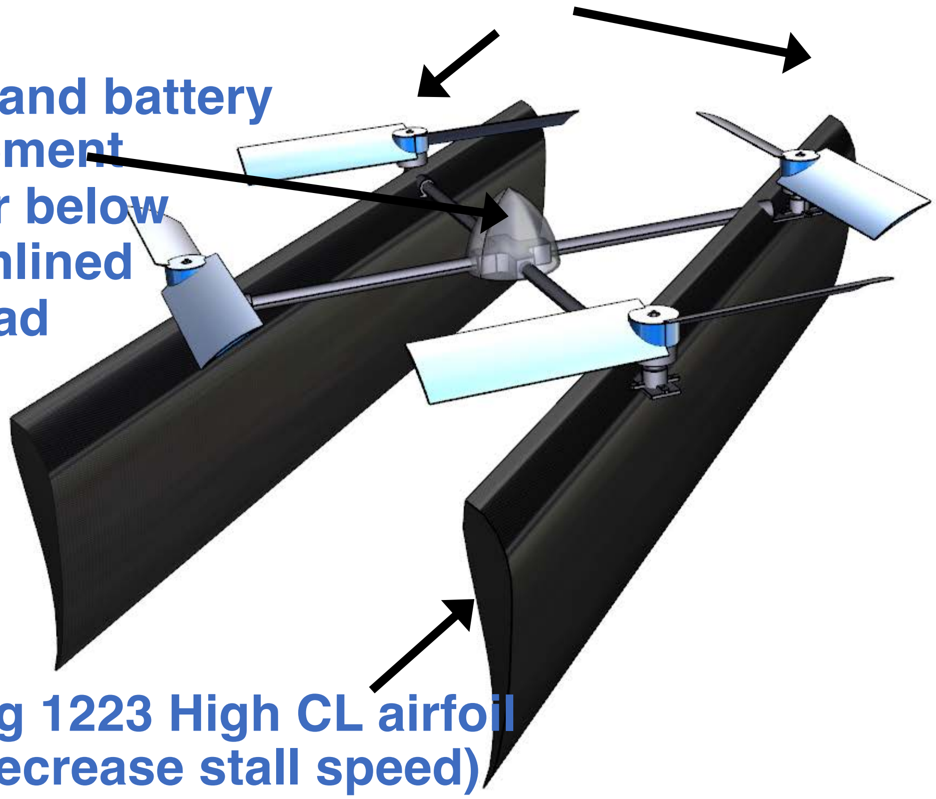
Major Challenges:

Transition flight (helicopter to fixed wing and vice versa)

Blade twist compromise (requirements quite different)

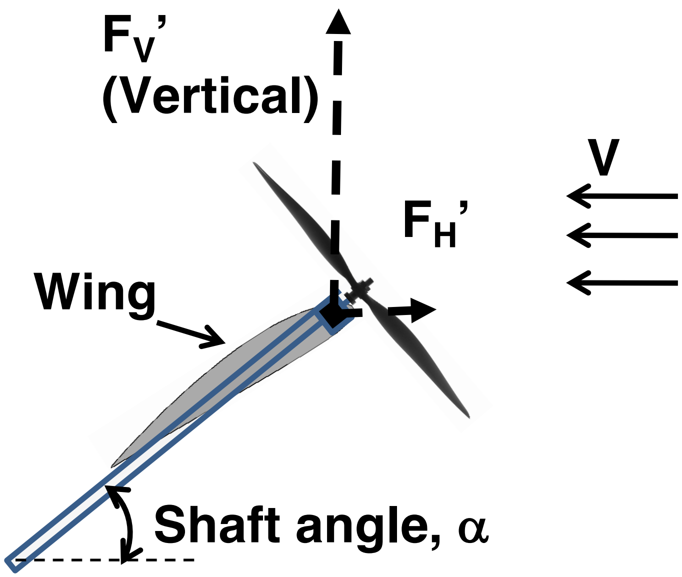
Quad Rotor Biplane

230 grams Quad Rotor Bi-Plane: Takes off as quad-rotor and transition into bi-plane in forward flight

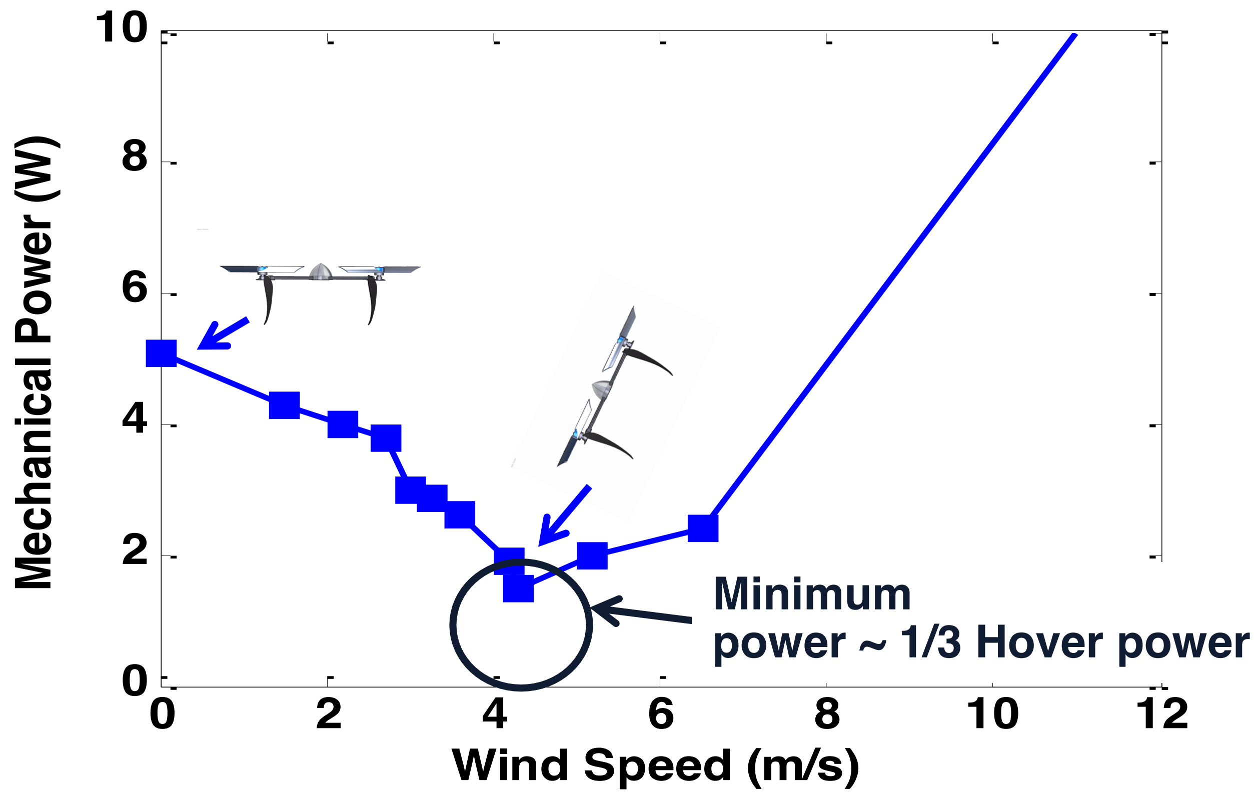


Component	Weight (grams)
4 Rotors	8
4 Motors (with speed controllers)	70
Sensor-processor with aux.battery	8
Structure, wings and motor mounts	74
Battery	70
Total	230

Quad Rotor Biplane: Wind tunnel tests

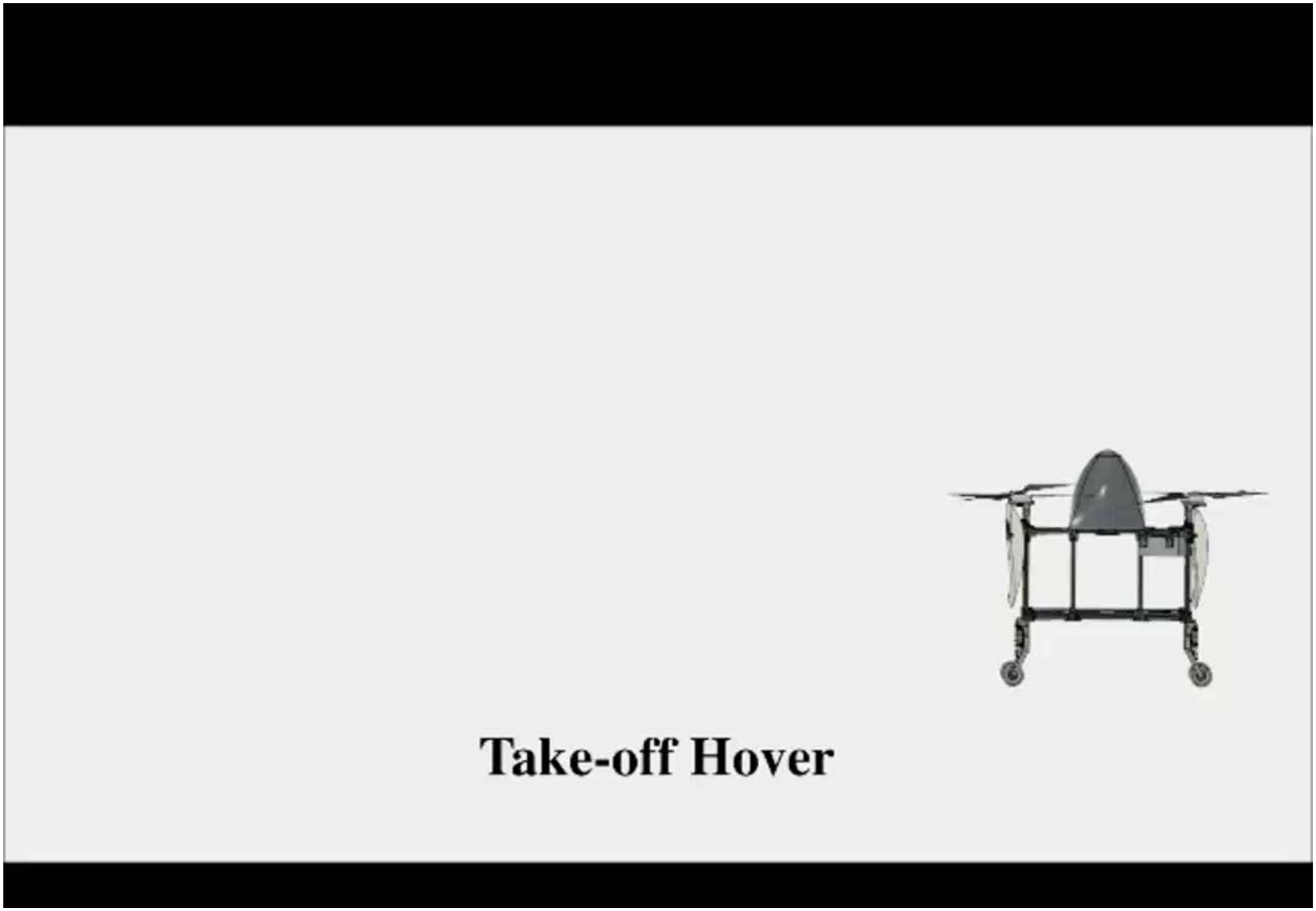


Propeller with wing



Speed at minimum power: 4-4.5 m/s
Maximum speed with hover power: 8 m/s
Significant reduction in power reqd in cruise

Quad Rotor Biplane



Quad-Biplane: Pros & Cons

Pros:

- Adaptable from widely popular quad-rotor
- Simple design without control surfaces (RPM control)
- Scalable concept

Cons:

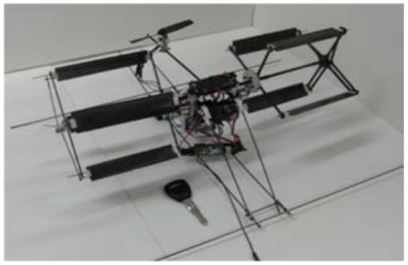
- Compromise performance (non-ideal pitch setting)
- More sensitive to gust

Conclusions: Rotor-Based sUAS

Conventional Rotors: Single, coaxial, quad
- Design principles for simple missions mature
- Susceptibility to gust (> 3m/s)
- Limited forward speed (5-10 m/s) and low range/endurance

Unconventional Rotors: Cyclocopter
- Design principles for hover acceptable
- More maneuverability and better tolerance to gust
- Potential for superior forward speed (>25 m/s) and range

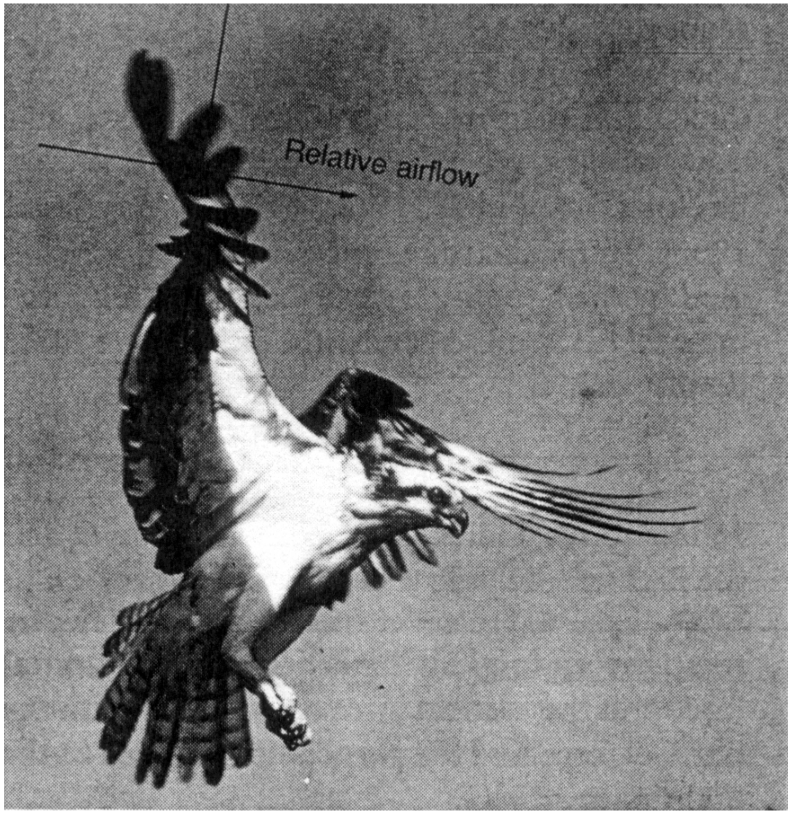
Compound Rotors: Tiltrotor, Tiltwing, Quad-Biplane
- Design principles adequate
- Challenge: transition mechanism & Control
- Susceptibility to gust
- High forward speed (>25 m/s) and range/endurance



Future Research: Rotor-Based sUAS for specific mission
- Conventional Rotors: Increase gust tolerance
- Unconventional Rotors: Expand forward flight & gust tolerance
- Compound Rotors: Validate design tools for long range/endurance and apply simple mechanism for transition

sUAS: Flapping-Wing-Based

Mechanism of Flapping-Wing Flight
Insects vs Birds



Natural Flyers – Kinematics

Avian flight

Flapping in vertical plane

- Moderate variation in wing pitch
  - Twisted down on down-stroke; twisted up on up-stroke
- Complex wing structure: Morphing

Insect flight

Flapping in horizontal plane

- Large variation in wing pitch
- Hover capable
- Complex unsteady aerodynamics

Birds vs Insects

Function	Bird	Insect
Weight	20g to 15 kg	Less than .2g
Size	0.15 to 3m	5 cm and less
Aerodynamics	Quasi-steady Drag-reduction	Unsteady Lift enhancement
Morphing	Active wing morphing	Rigid wing, base motion
Wing frequency	Modest <10 Hz	High >50Hz
Hovering	Very rare	Quite common
Speed	High, wing morphing	Modest, tilting body and stroke plane
Reynolds No.	>10,000	<10,000

Natural Flyers

Honeybee subject to wind gust

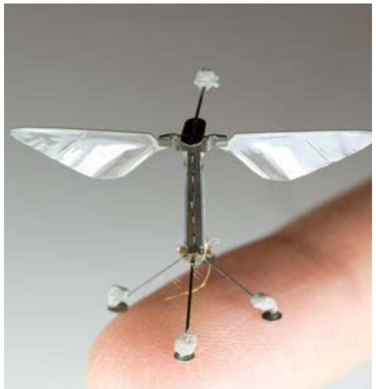
Hummingbird in free flight

Flapping-wing Flyers: Insect kinematics

– Good gust tolerance; hover-capable, high flight endurance

– Mechanical design quite difficult to build

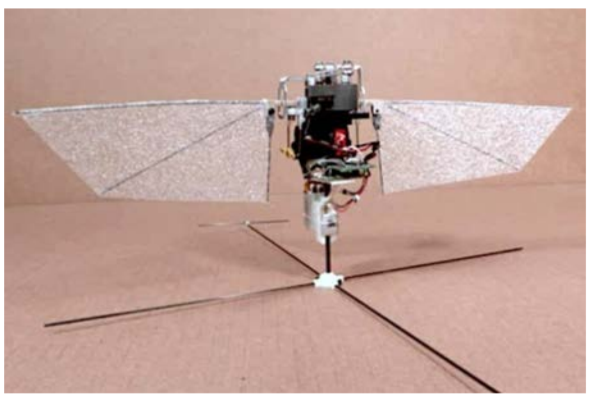
Status of Flapping-Wing MAVs: Insect-Based (Hover-capable)



RoboBee (80mg)
Harvard

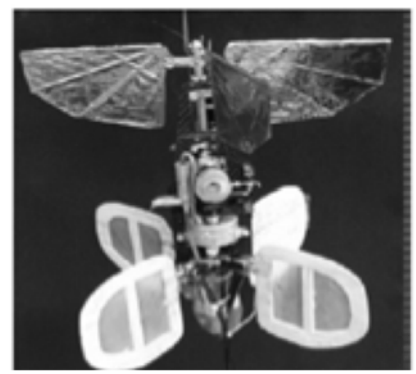
DelFly II;16g, 9 min)
Delft

Hummingbird 19g, 4 min
AeroVironment



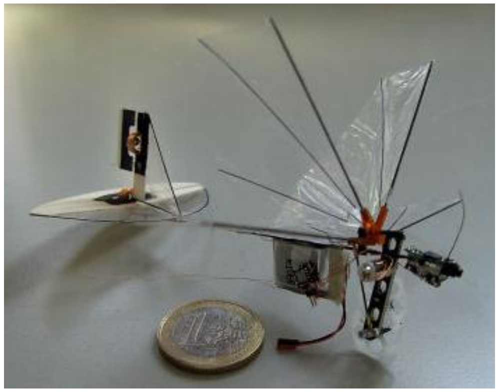
Robotic Hummingbird
62g, 1 min; TAMU

BionicOpter 175g
FASTO

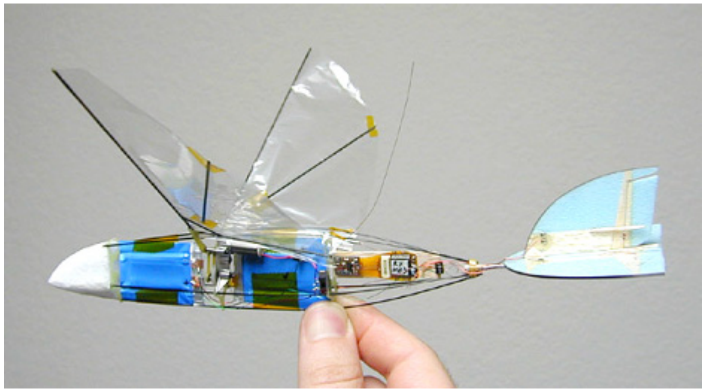


Mentor 580g, 6 min
SRI

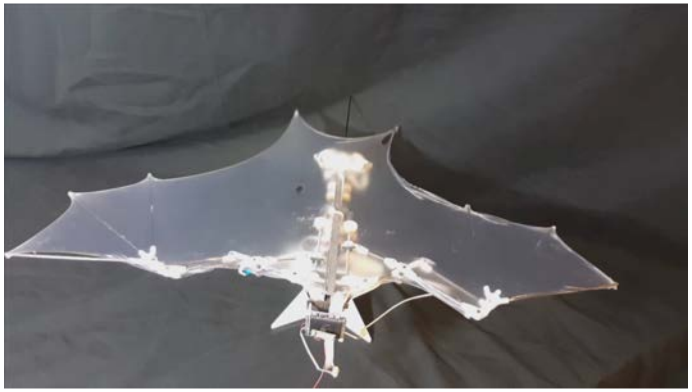
Status of Flapping-Wing MAVs: Avian-Based



Delfly 3g, 3 min
Delft



Microbat 12.5g, <1 min
AeroVironment



Bat Bot 93g, <1 min
Caltech

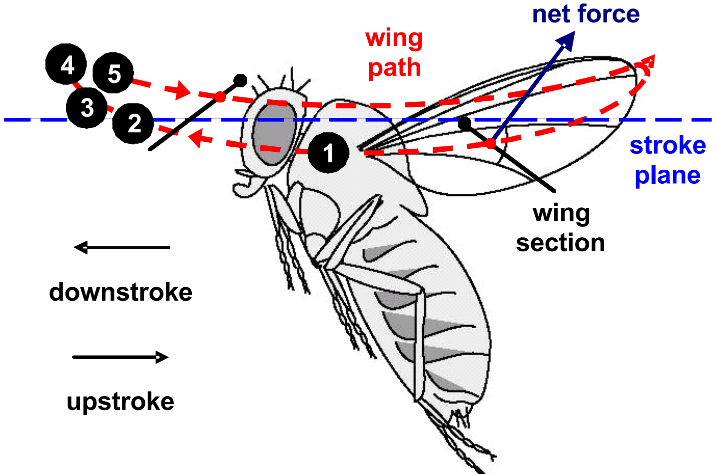
CYBIRD 200g,10 min
Univ. Arizona

Robo Raven 290g, 5 min
UMD

Odyssey 450g, 25 min
Odyssey

Insect-Based Flapping

Wing stroke of an insect is divided into four kinematic stages



1. **Upstroke**
2. **Downstroke**

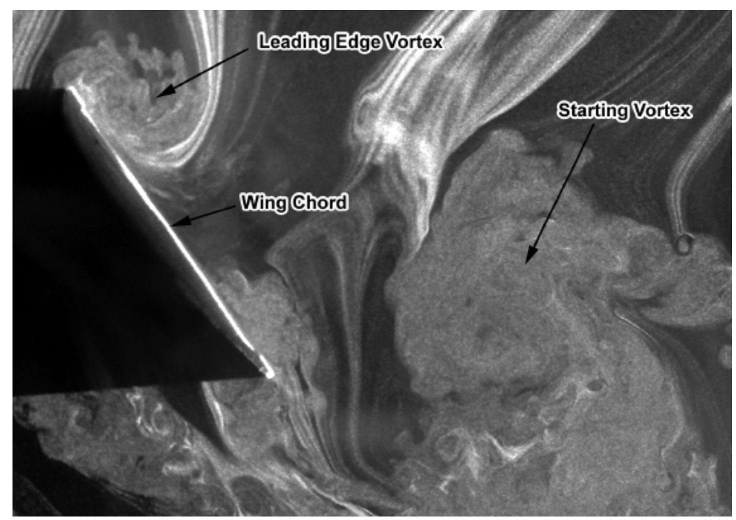
TRANSLATIONAL phase

sweep at high pitch angle

3. **Pronation**
4. **Supination**

ROTATIONAL phase –

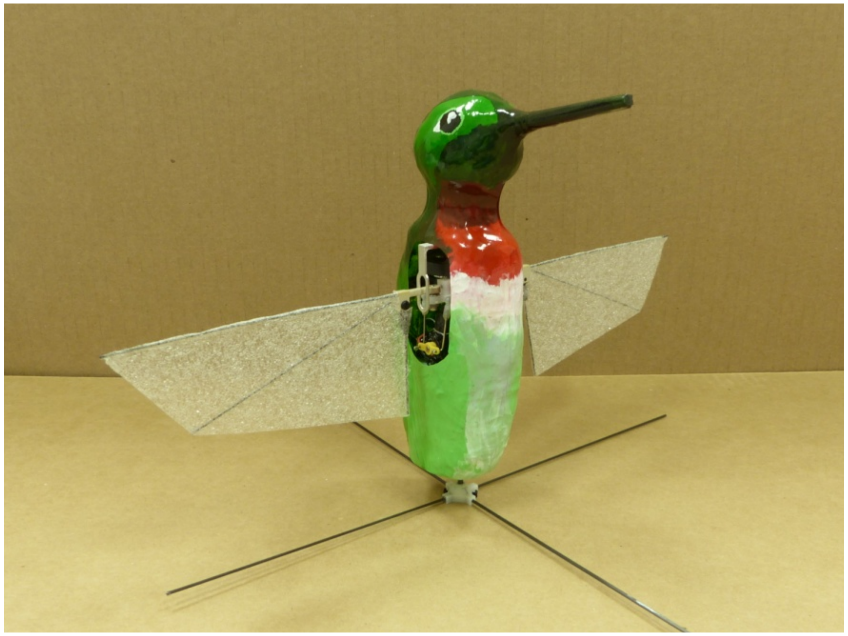
wings rapidly rotate and reverse direction: Magnus



- **Flapping causes delayed dynamic stall, rotational circulation and wake capture**
- **A folded wake with the presence of multiple vortices**

➢ **Key Parameters : wing frequency, flap amplitude, pitch angle, aeroelastic couplings (flexibility)**

Challenges – Flapping-Wing MAVs



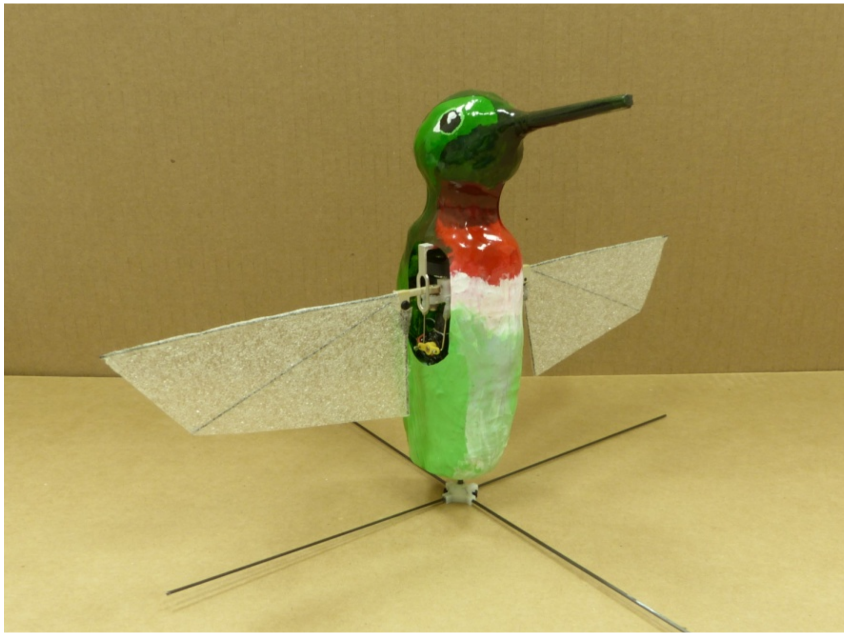
Nano Hummingbird Test Flight

AeroVironment (2011)

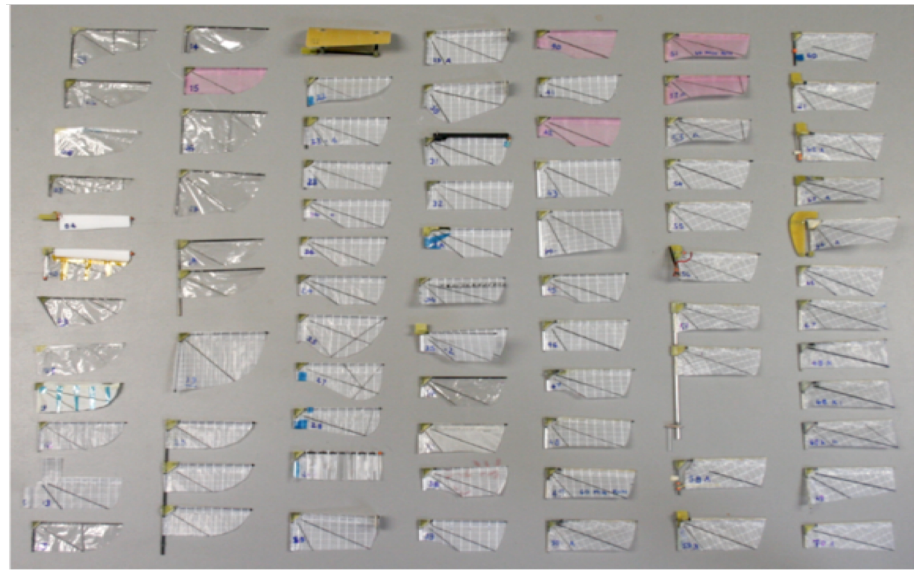
Unsteady Wing Motion
- Vortex Shedding
- Wing-Wake Interactions

Lightweight Wing Structure
- Large Deformations
- Aeroelastic Effects

Challenges – Flapping-Wing MAVs



Sample Set of Test Wings



Unsteady Wing Motion
- Vortex Shedding
- Wing-Wake Interactions

Lightweight Wing Structure
- Large, Nonlinear Deformations
- Aeroelastic Effects

Limited understanding of flow physics and expected performance for flapping wings in flight

Flapping-Wing: Experiment Challenges

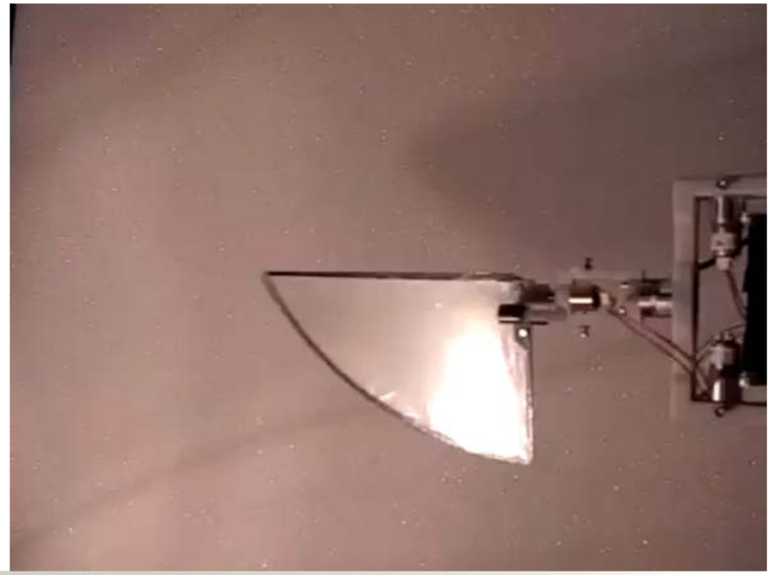
Wing size (ultra-light)
Flap amplitude (large, $\pm 60^0$)
Flap frequency (high, 5-20+ Hz)
Pitch angle (large, time varying, $\pm 30^0$)

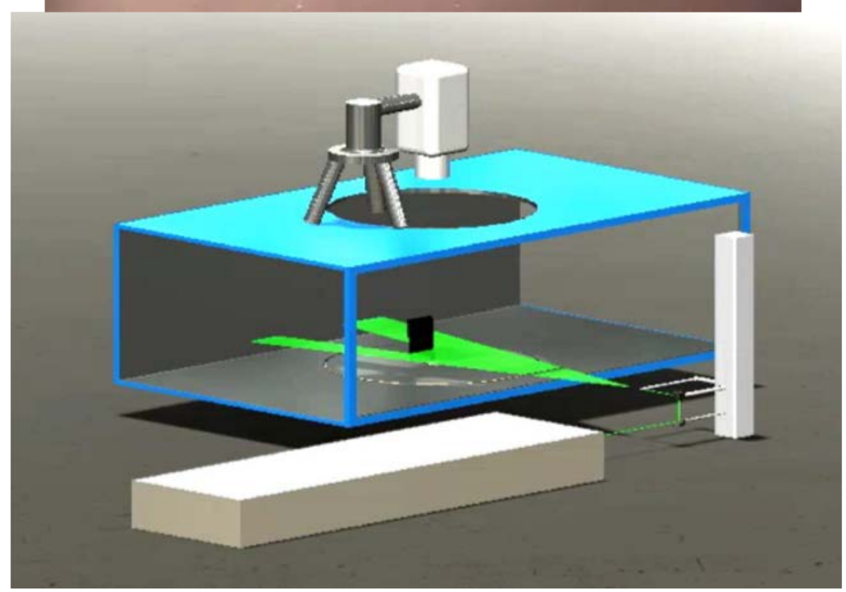
Inertial forces dominant (aerodynamic forces small, filtering, dynamic calibration)

Time varying flow

PIV challenging

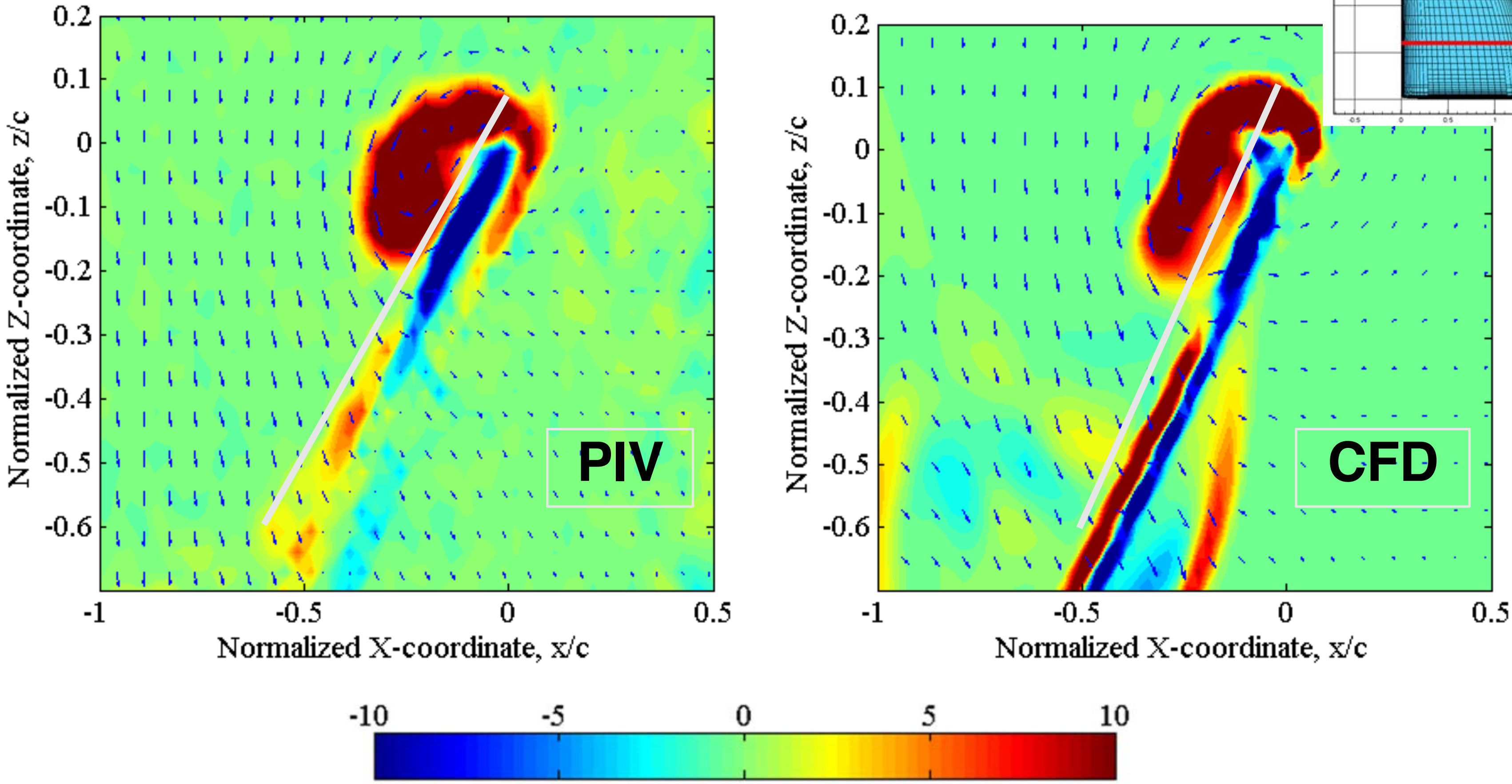
Seeding particles; Reflections from wing and background; Optical access

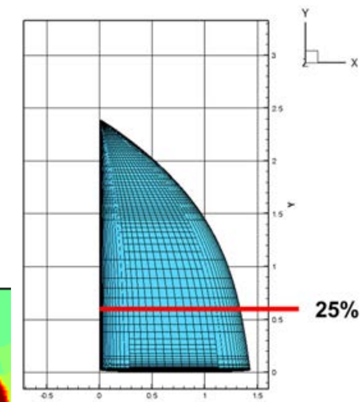




Vorticity Contours: Midstroke, 50° pitch case

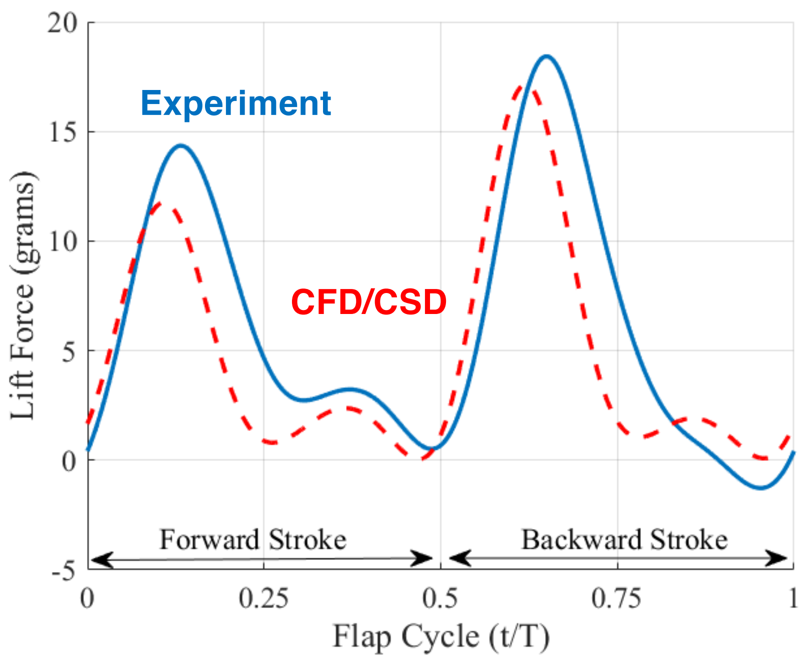
Location: One-Quarter Span



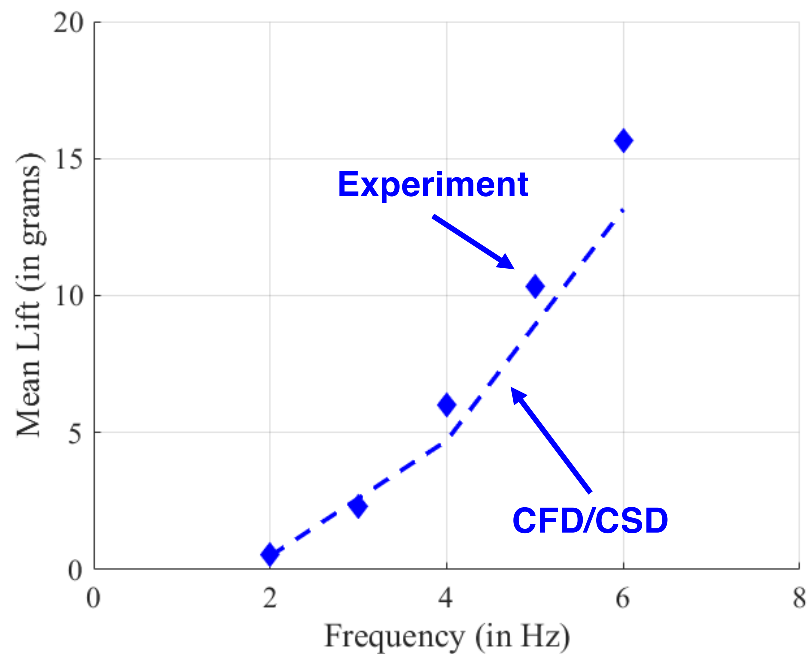


Force-time History Comparison: Lift vs Time

Lift vs Time (ω = 4 Hz)

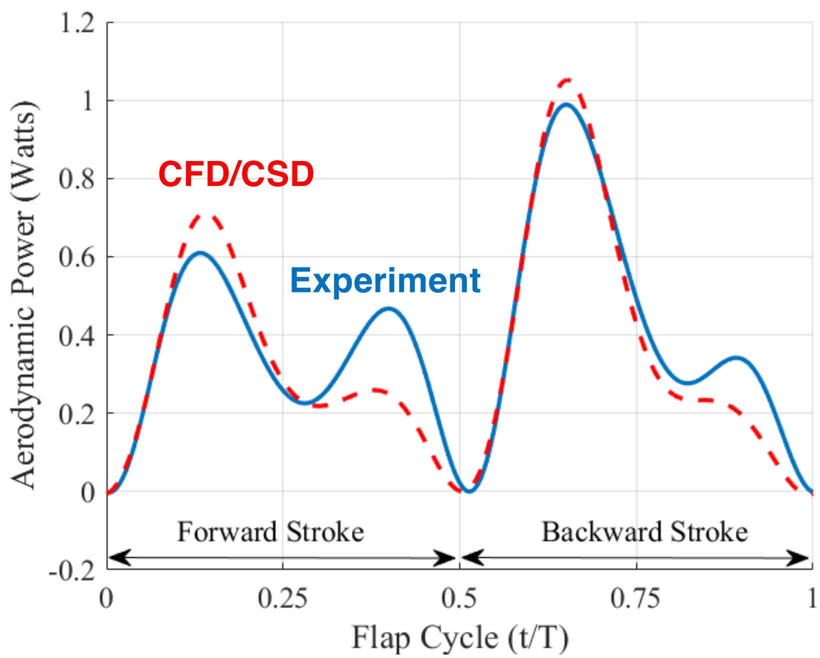


Mean Lift vs Frequency

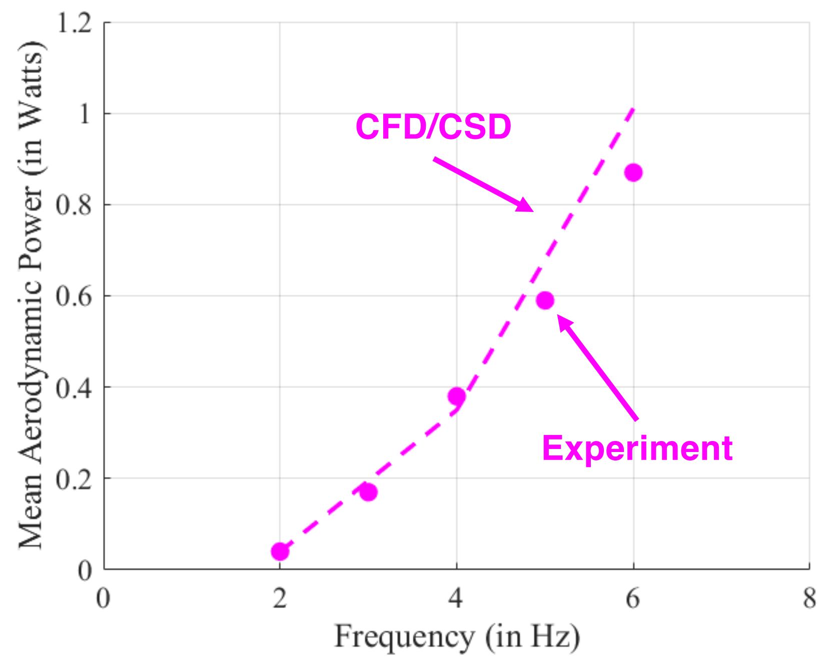


Force-time History Comparison: Aerodynamic Power vs Time

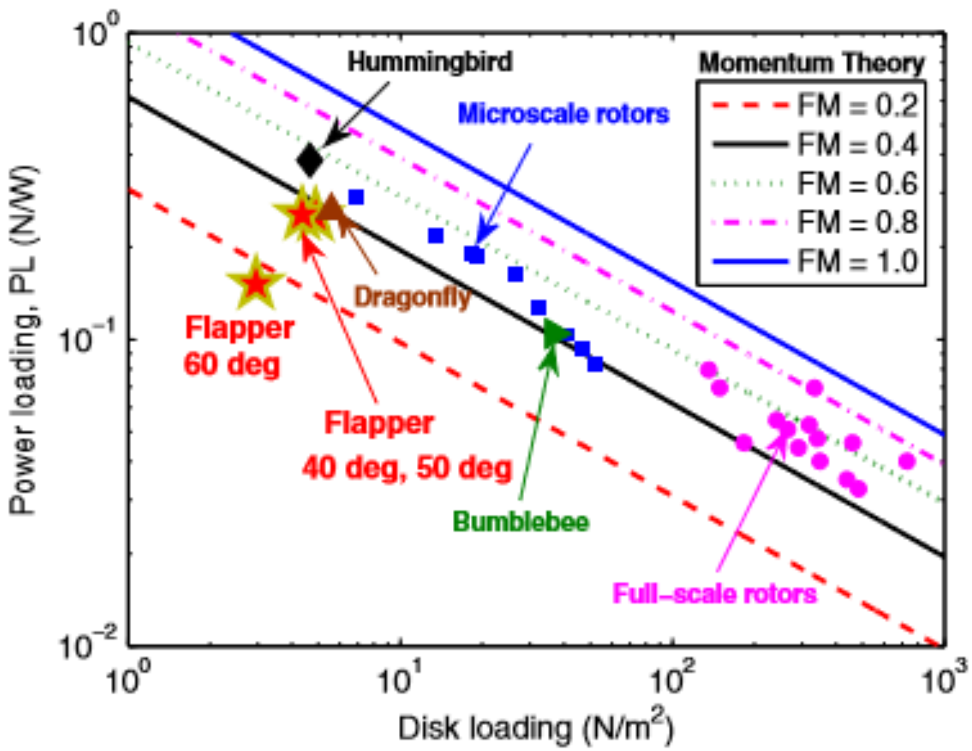
Aero. Power vs Time (ω = 4 Hz)



Mean Aero. Power vs Frequency



Power Loading vs Disk Loading

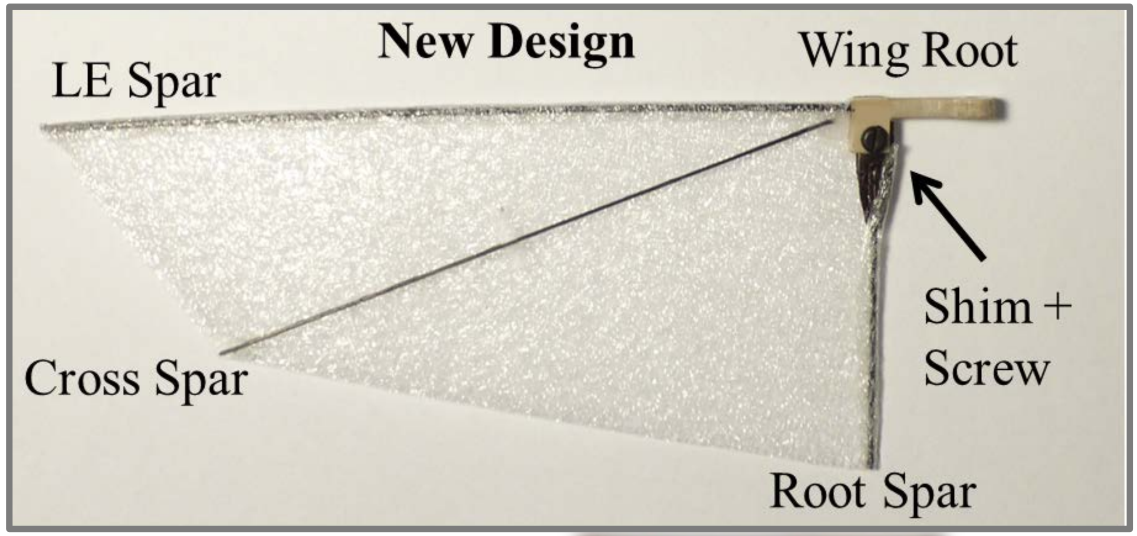


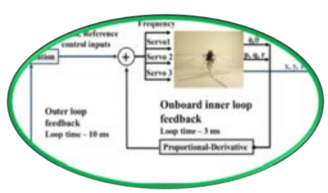
Configuration	Figure of Merit
Full-Scale Rotor	0.65 – 0.75
MAV-Scale Rotor	0.40 – 0.50
Flapping Wing	0.20 – 0.40

Flapping Wing Vehicle Development

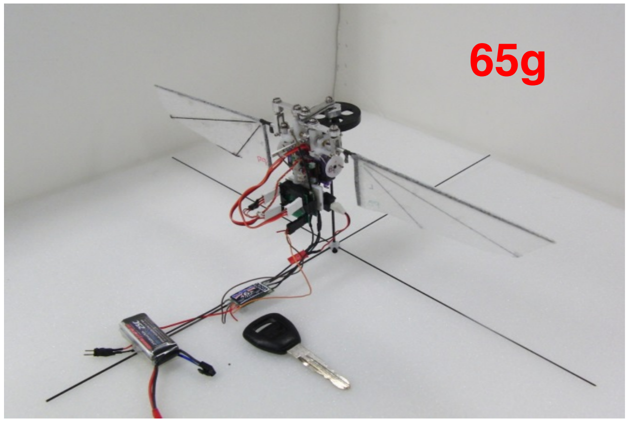
Ultralight wing design that sustains over 20 Hz flap frequency

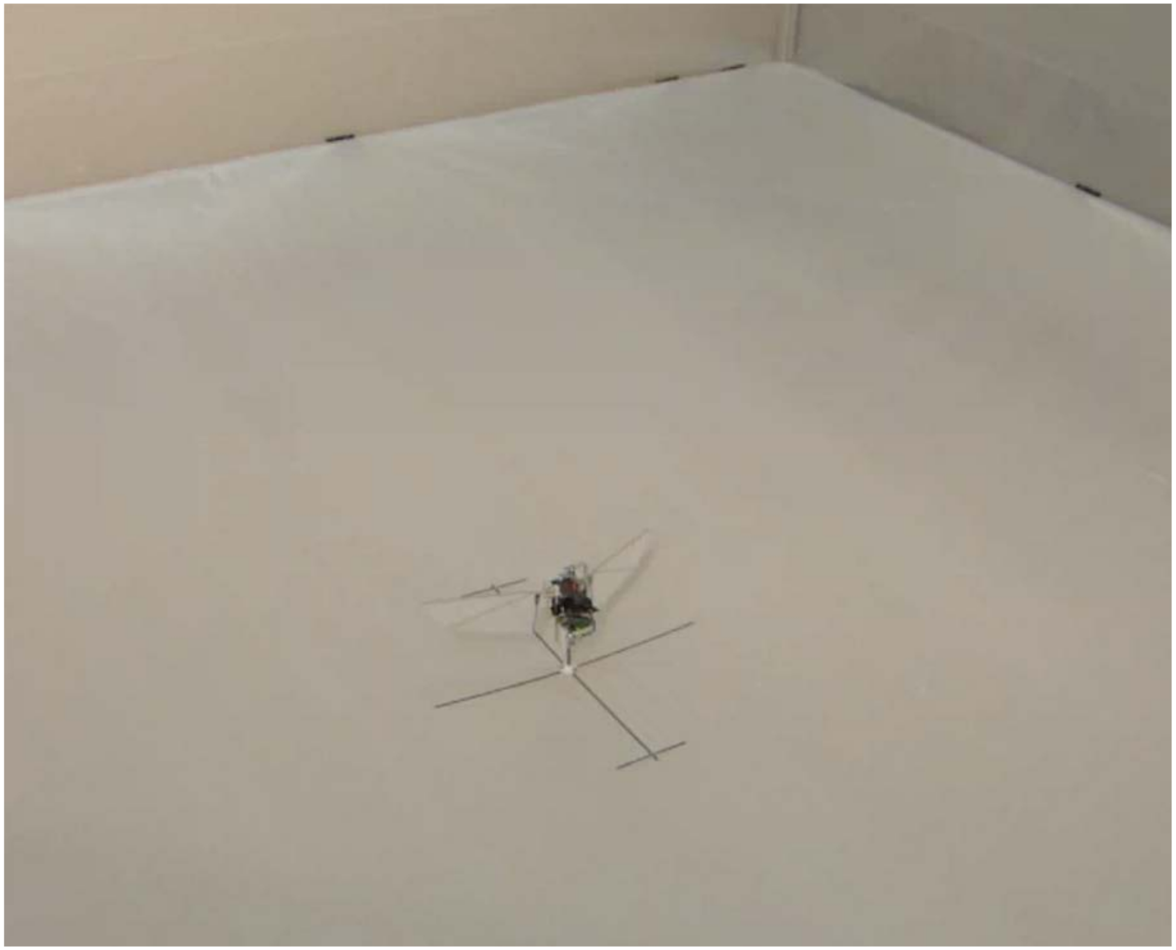
Control implementation





Flapping Wing 65-g sUAS



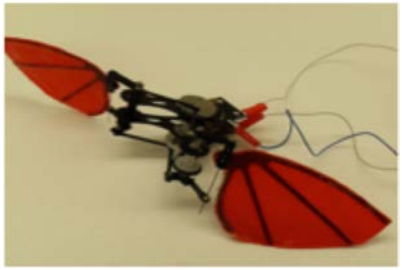


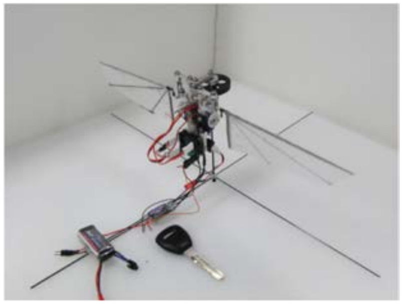
- Insect-based flap mechanism
- Flapping frequency: 22 Hz

Conclusions: Flapping-Wing MAVs

Insect-Based Flapping Systems

- Wing kinematics complex
- Basic principles of flight becoming more clear
- Design principles rudimentary
- Controllable integrated vehicles not ready





Avian-Based Flapping Systems

- Wing kinematics simple, but requires wing morphing
- Design principles not ready
- Controllable autonomous vehicles with payload not ready

Future Research: Flapping-Wing MAVs

- Insect-Based Kinematics: refined design tools, controllable vehicles
- Avian-Based Kinematics: Basic flight physics understanding with wing morphing, Controllable vehicles
- Hybrid: Development of vehicles for specific missions

sUAS Development Roadmap

	10 Years ago	Today	5 Years Later
Vehicles	Mostly fixed-wings	Quadrotor/ Multi-rotor	Multi-rotor/hybrid; some flapping-wings Mission-based designs
Payload	Zero to Small	Modest	Mission-based payload
Speed/Range	Low	Modest	Higher speed/range
Navigation	In-sight	Mostly in-sight	Out-of-sight
Propulsion	Battery	Battery	Battery/Fuel Cell/IC
Flight Robustness	Low	Modest	High in gusty and obstacles-rich
Autonomy	None	Semi-autonomous	Full autonomy

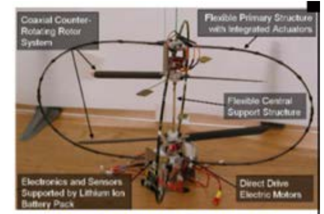
Conclusions

sUAS & Delivery Drones are a multidisciplinary systems and require synthesis of:

- **Aeromechanics (low Re) Micropropulsion**
- **Microelectronics**
- **Microprocessing**
- **Microfabrication**
- **Navigation**


250g MAV with Single Rotor & Anti-torque Vanes

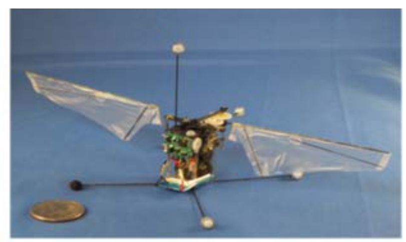

100g MAV with Coaxial Rotor


50-g Active Structures Coaxial MAV


UM: 800-g Quad-Cyclocopter


35-g Quadrotor MAV


500-g AscTec Quadrotor


10-g Flapper


100-g Insect-Based Flapping-wing system


25-g Avian-Based Flapping-Wing MAV


25-g Bio-inspired Aerial and Terrestrial Vehicle

Many Challenges:

- Increase in hover figure of merit and power loading (towards full-scale)
- Increase in payload/range/endurance
- Major increase in autonomy
- Significant Increase in flight robustness and integrity

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A Wonderful World of sUAS?