SWARM

A Reconfigurable Rotor for 24 Hour Hovering

AHS 34th Annual Student Design Competition

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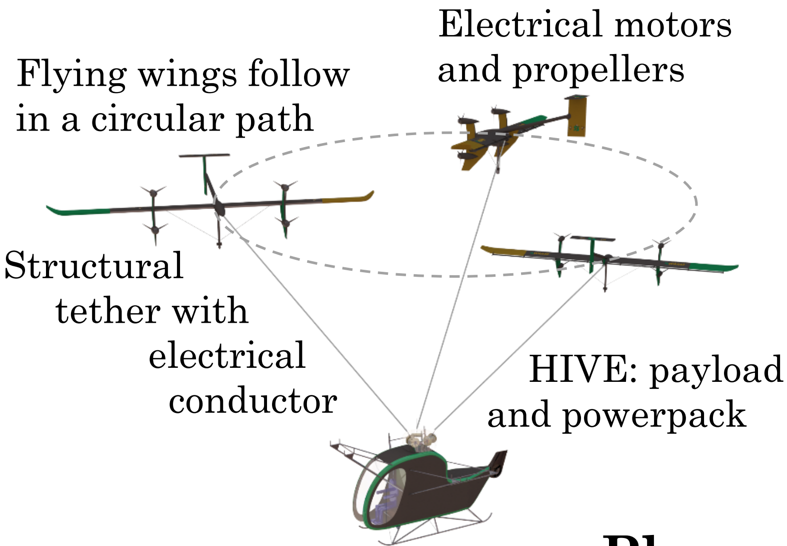
Introducing the Reconfigurable Rotor

System Decomposition

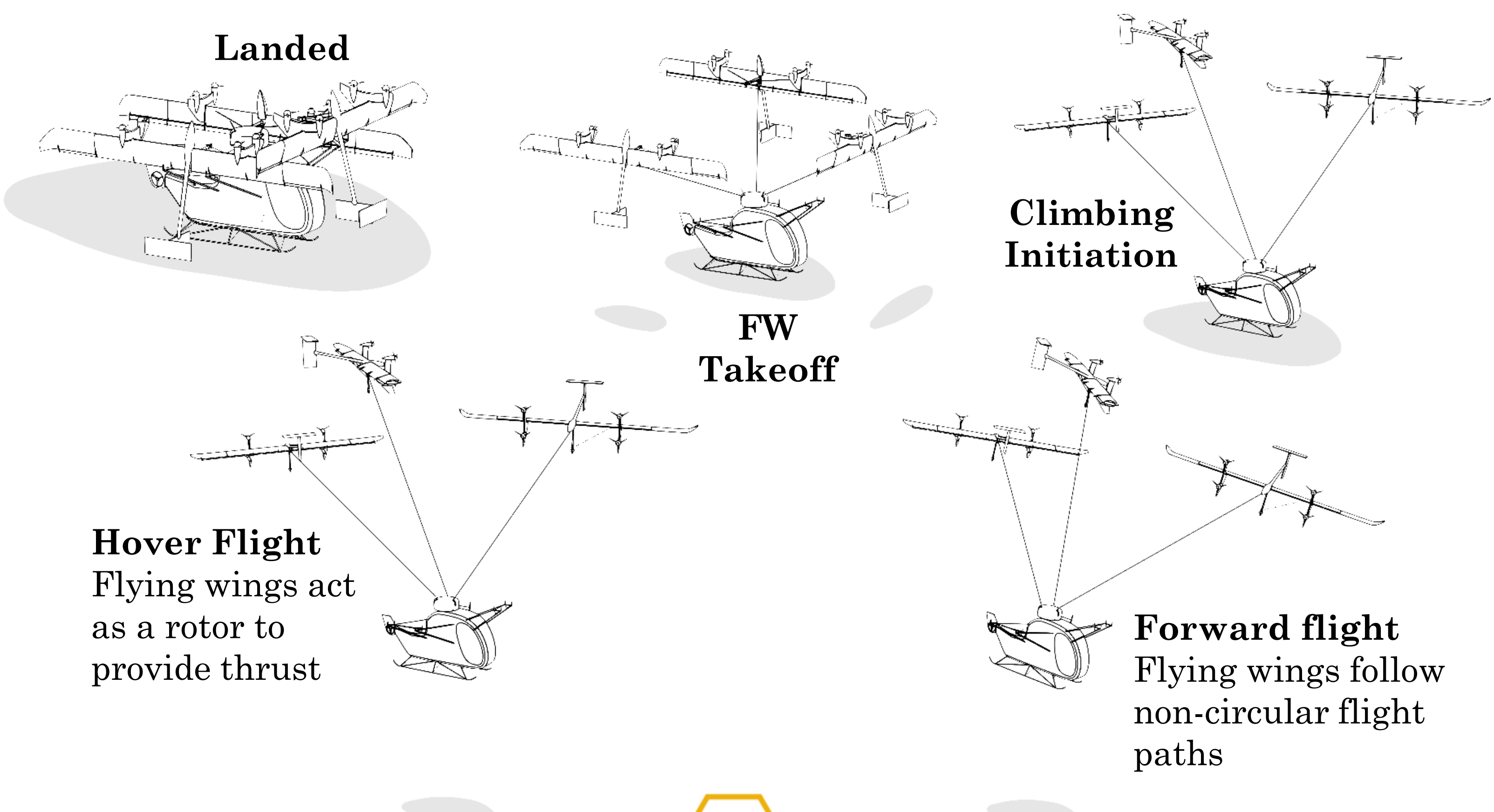
Advanced Capabilities Through Simple Components



Rotor Replaced by Tethered Fixed-Wing Aircraft

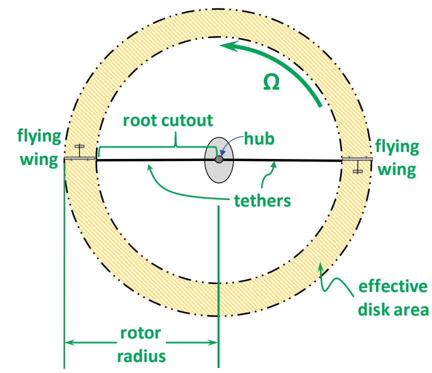
- Very large equivalent disk area, very low disk loading and reduction in induced power.
- Hybrid-electric power pack located in the central vehicle (HIVE).
- Electrical power sent through the tether.
- Large number of operating parameters (e.g., speed, radius, tether length) allows operation closer to optimality throughout flight.

Phases of flight



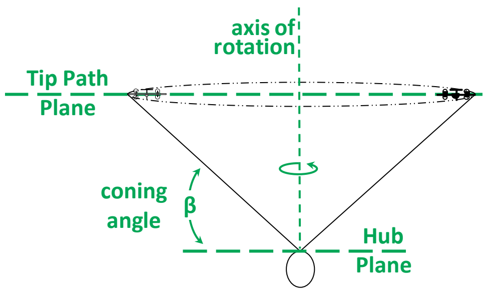
Reconfigurable Rotor FAQ

1. *How is this a rotor?*



The circular flight path carved by the flying wings create a rotor disk. The flying wings act as tip driven rotors that provide full collective and cyclic rotor control. The long tether serves as a rotor blade's large rootcut out with a high coning angle. The joining of the tethers to the fuselage is the rotor's hub.

2. *Why is the rotor reconfigurable?*



The flight path of the flying wings define the tip path plane of a highly configurable rotor disk. Because the flight path is customizable, the RCR can change its rotor disk in real-time to optimize hover efficiency. The rotor is so configurable that the flight path can be elliptical with slight elevation changes to minimize power loss due to wake turbulence.

3. *What makes this better than traditional vertical lift rotor(s)?*

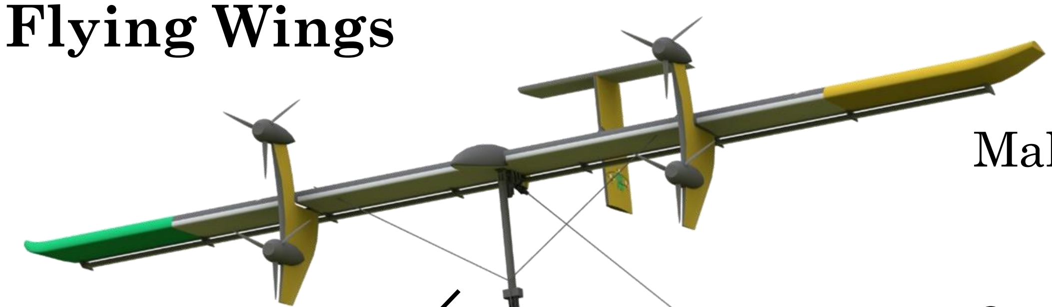
The reconfigurable rotor generates the same thrust as a traditional rotor but at much lower required power. The RCR is able to optimize its blades for a given flight condition and achieve very low disk loadings. These advantages make for a more efficient hover and increased endurance.

4. *How does the RCR achieve endurance hover?*

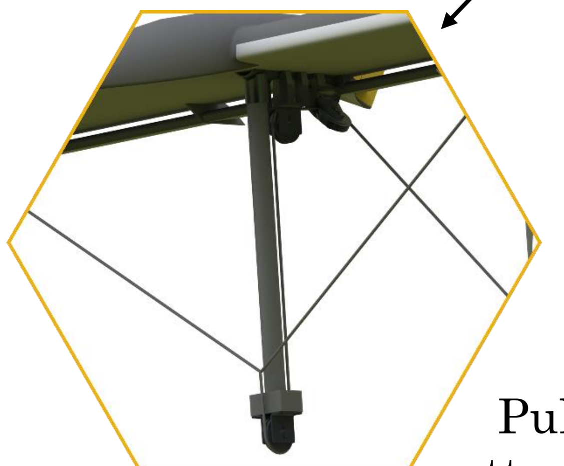
While traditional rotors achieve hover endurance through dependence on technology to achieve extreme weight empty fraction and fuel efficiency, the RCR achieves hover endurance through reconfiguration. A traditional, fixed rotor design is optimized to one condition, meaning that it operates at less than optimal for the vast majority of flight. The reconfigurable rotor achieves endurance hover by optimizing the rotor throughout the flight. The RCR is able to vary speed, rotor radius, disk loading, and disk shape to remain at peak efficiency during fuel burn, altitude changes, and airspeed requirements. Remaining at peak efficiency provides the RCR a significant advantage over a 24-hour endurance flight.

System Overview & Highlights

Flying Wings

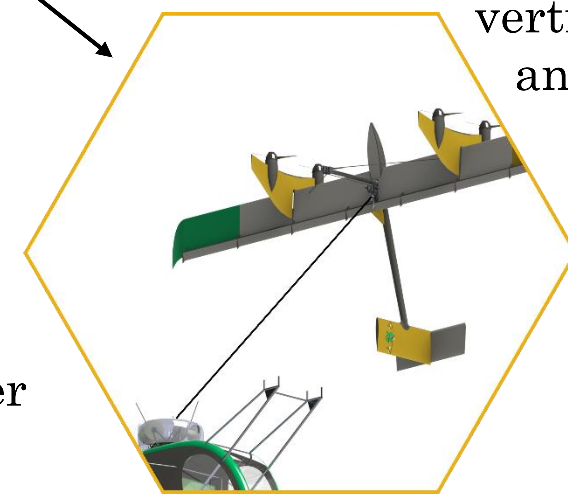


Built and tested Makani Wing 7



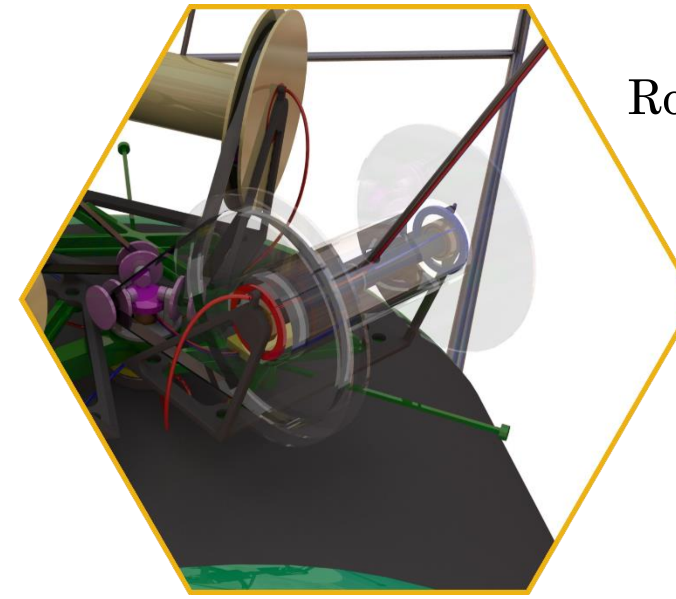
Pulley tether attachment allows roll in flight

Quadrotor tailsitter for vertical takeoff and landing

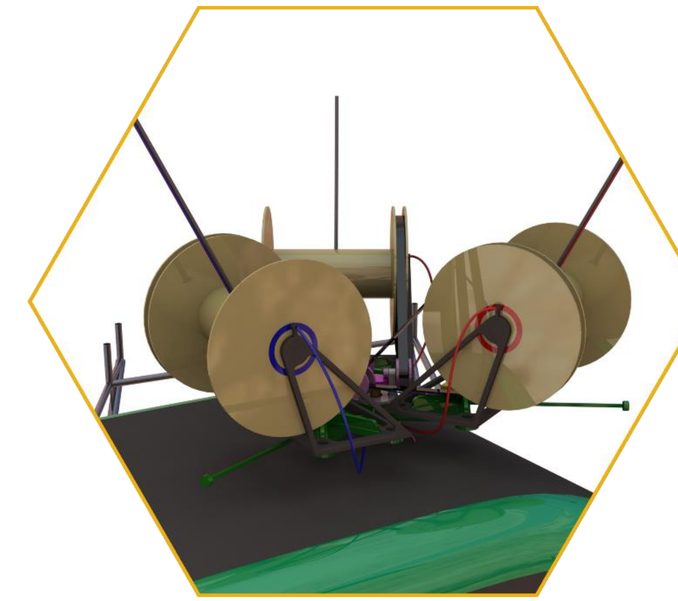


Hub tether attachment

Rotating hub turns with flying wings



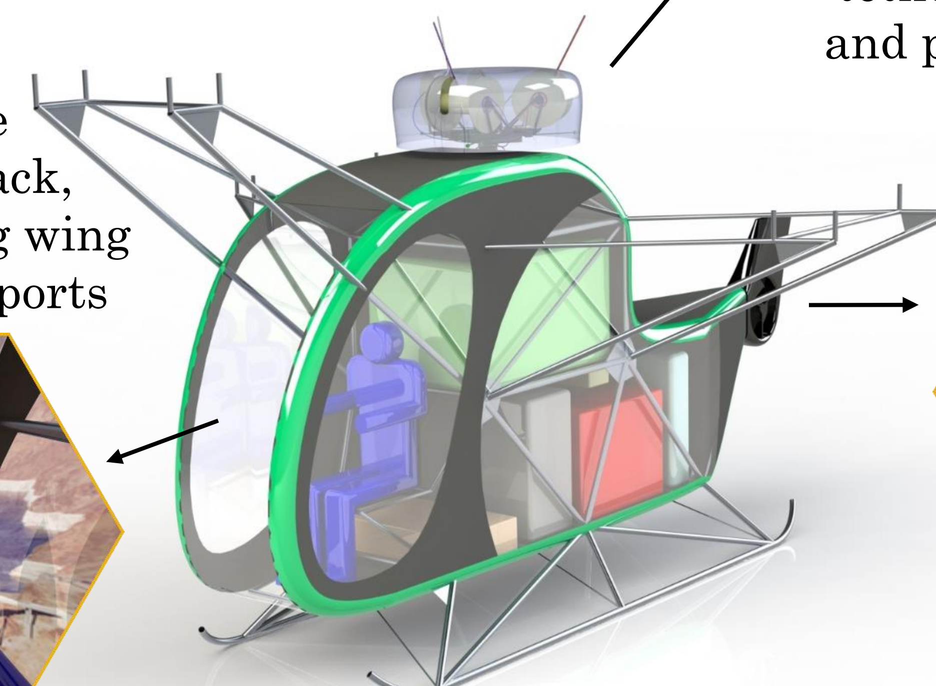
Slip rings on hub and reels transmit power to the rotor through tethers

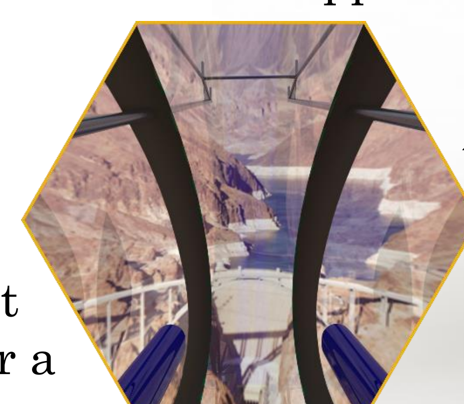


Reel system retracts tethers upon landing and prevents tangling

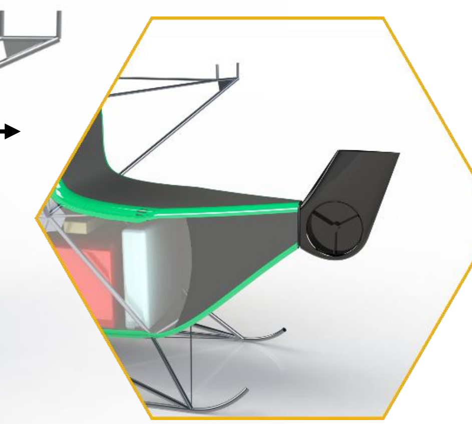
HIVE

Simplified tubular structure contains power pack, fuel and flying wing supports





Spacious and low vibration environment with good visibility for a human passenger



Compact tail rotor counters the low rotor torque

Power Plant

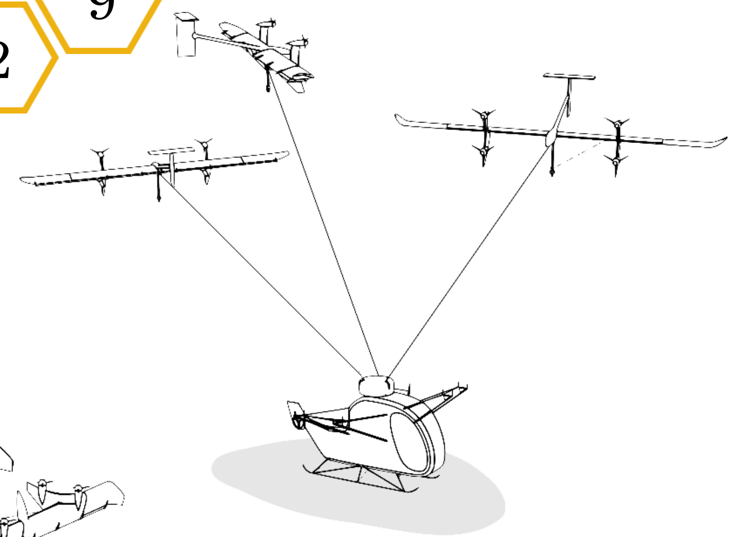
FAA Certified Continental CD-155 diesel engine connects to two EMRAX 268 generators

Mission Profile

9

2

Raise / Lower HIVE
Transition from/to tailsitter
to reconfigurable rotor



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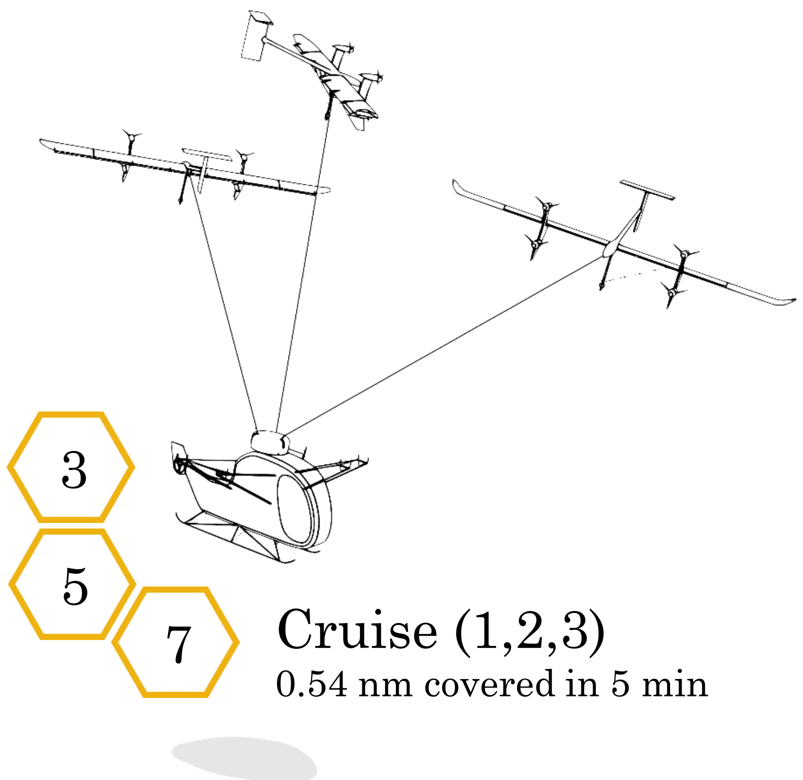
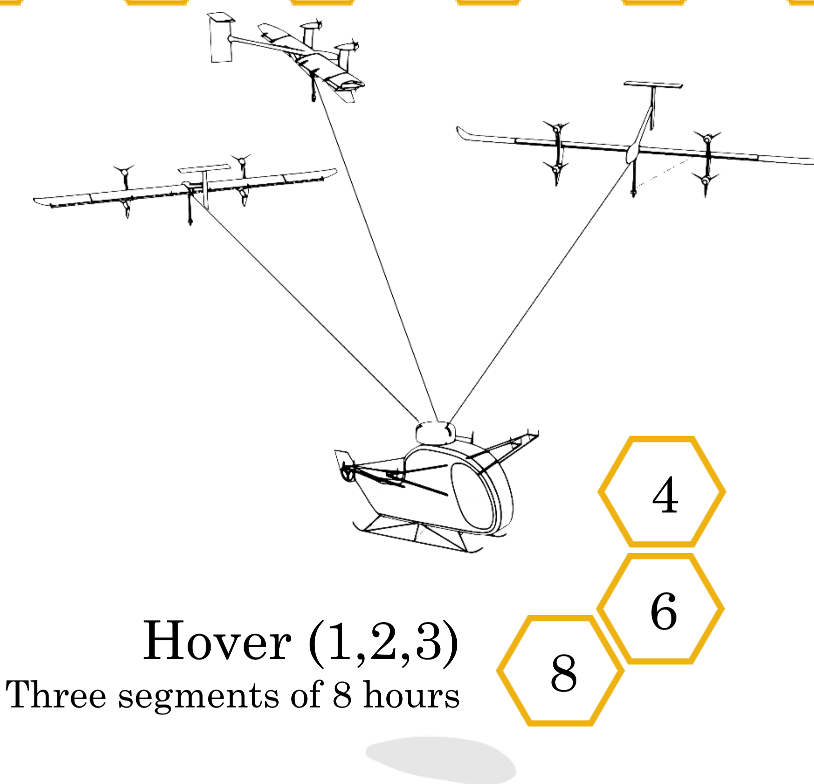


Cruise (1,2,3)
0.54 nm covered in 5 min



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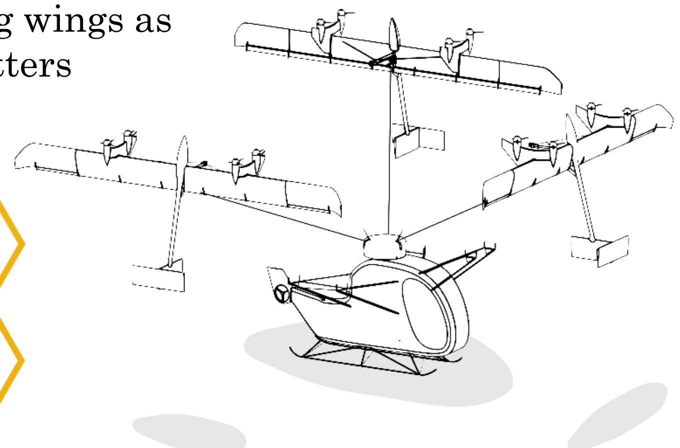
6

8

Hover (1,2,3)
Three segments of 8 hours

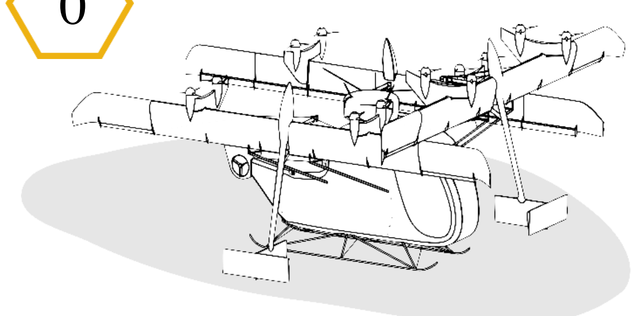
Wing takeoff / Landing
Flying wings as
tailsitters



1

10

0



Landed
Flying wings on HIVE supports

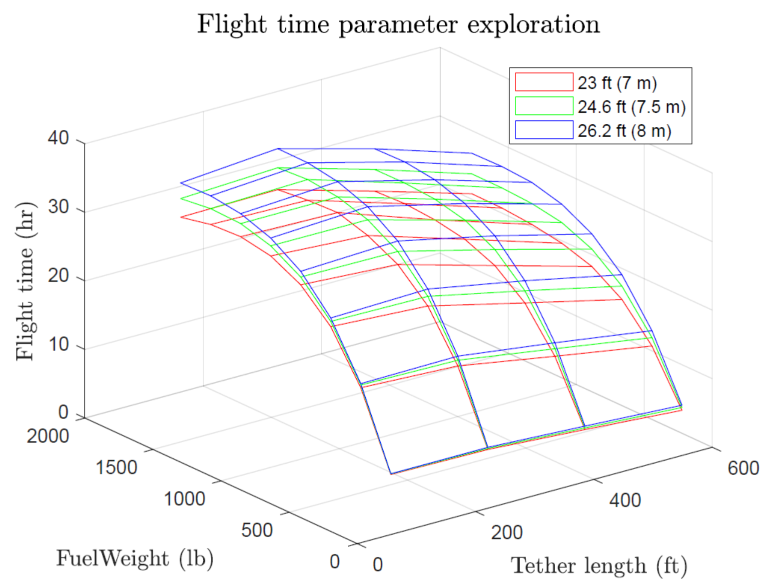
Mission by Phase Data Table

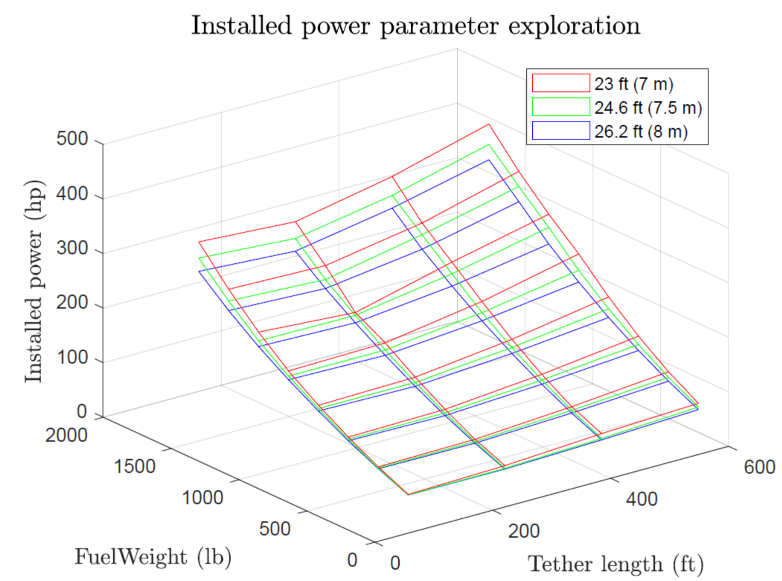
	Phase	Time	Each Flying Wing						HIVE						
			Configuration	Flight Mode	Airspeed	Altitude	Power Req	Weight	Flight Mode	Airspeed	Altitude	Weight	Power Generated	SFC	Fuel Burned
		min			ft/s	ft	hp	lbf		ft/s	ft	lbf	hp	lbf/hp-hr	lbf
0	Preflight	1	Tailsitter	NA	0	0	0	149.9	Landed	0.0	0.0	1984.2	1.7	0.364	0.01
1	Wing Takeoff	7	Tailsitter	Vertical Climb	39.4	78.8	24.7	157.5	Landed	0.0	0.0	1981.8	89.4	0.354	3.70
2	Raise HIVE	7	Reconfig Rotor	Orbiting Climb	110.2	600.1	32.9	818.3	Vertical Climb	0.0	477.6	1975.5	118.3	0.363	5.01
3	Cruise 1	5	Reconfig Rotor	Orbit	110.2	679.7	29.6	817.3	Cruise	32.8	557.2	1975.0	106.5	0.359	3.19
4	Hover 1	480	Reconfig Rotor	Orbit	110.2	679.7	27.8	721.4	OGE Hover	0.0	557.2	1687.4	100.3	0.357	286.66
5	Cruise 2	5	Reconfig Rotor	Orbit	110.2	679.7	28.0	720.7	Cruise	0.7	557.2	1685.3	101.0	0.357	3.01
6	Hover 2	480	Reconfig Rotor	Orbit	110.2	679.7	22.3	645.0	OGE Hover	0.0	557.2	1458.2	80.6	0.351	226.18
7	Cruise 3	5	Reconfig Rotor	Orbit	110.2	679.7	22.4	644.5	Cruise	3.5	557.2	1456.5	81.1	0.351	2.37
8	Hover 3	480	Reconfig Rotor	Orbit	110.2	679.7	17.0	585.8	OGE Hover	0.0	557.2	1280.5	61.9	0.354	175.24
9	Lower HIVE	5	Reconfig Rotor	Orbiting Descer	110.2	345.4	15.6	500.0	Vertical Descer	0.0	222.9	1279.2	57.0	0.355	1.69
10	Wing Land	6	Tailsitter	Vertical Descen	0.0	51.0	20.9	152.9	Landed	0.0	0.0	1276.9	75.8	0.355	2.69
11	Reserve	30	Reconfig Rotor	Orbit	110.2	679.7	17.0	580.7	OGE Hover	0.0	557.2	1265.2	61.9	0.354	10.95
		1506													714.8

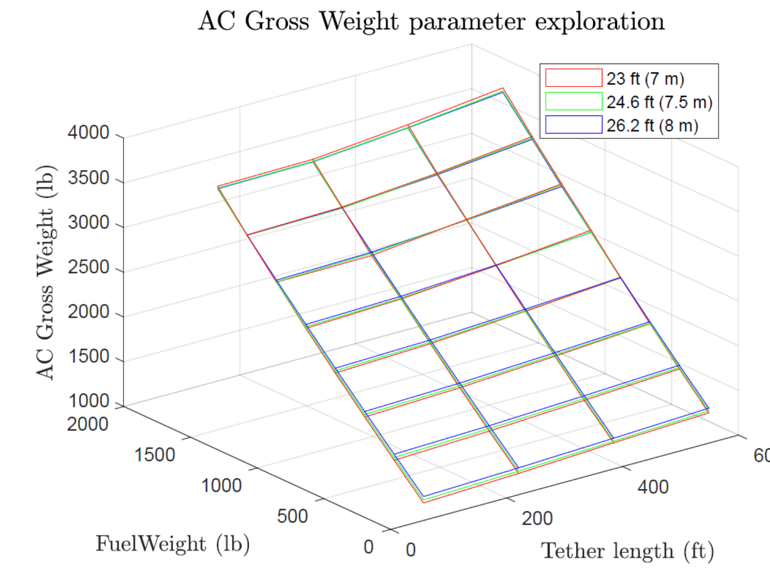
Design Space Exploration and Propeller Optimization

Design Space Exploration

Enlarging the FW decreases power output and increases flight time



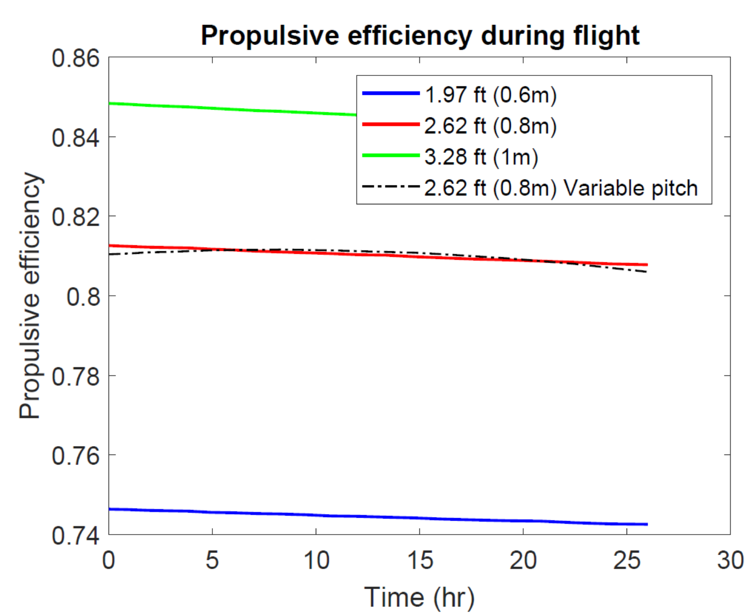


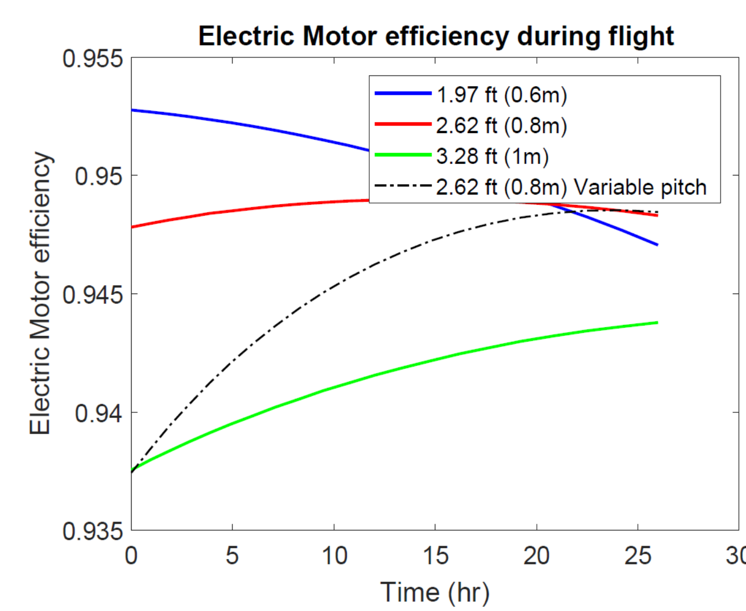


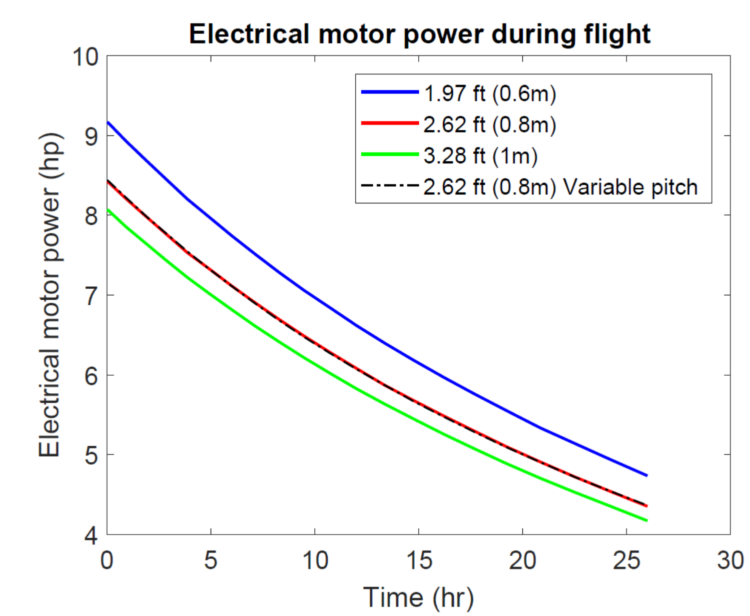
Aircraft weight is mostly independent from the tether length and FW wingspan

Propeller Optimization

- Fixed and variable pitch propellers of various sizes tested.
- Aircraft optimized separately from the propellers to speed the process. Results combined afterwards.
- Propeller trust curve from the global optimization used as an input to the propeller optimization







The 2.62 ft propeller was chosen for its good balance between performance, size/weight and complexity

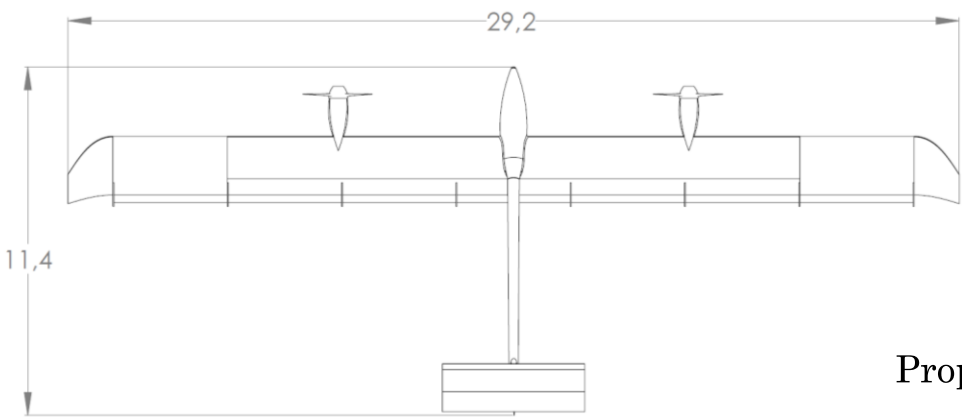
Aircraft Description

Swarm Properties and Performance

Max. Gross Weight	2,700 lb
Rotor Radius	93 ft
Rotor RPM	11
Rotor Tip Speed	126 ft/s
Power Loading	15.9 lb/hp
Disk Loading	0.16 lb/ft²
Figure of Merit	0.41
Max. Hover Endurance	31 hrs
Max. Forward Speed	26 kts

Highlights

- **25.1 hour** hover with **75%** of fuel tank capacity.
- Outstanding hover endurance at max. gross weight: **31 hours**
- Extremely low power engine: **155 hp**
- **Off-the-shelf components** for critical systems: powerpack, structure and propulsion.

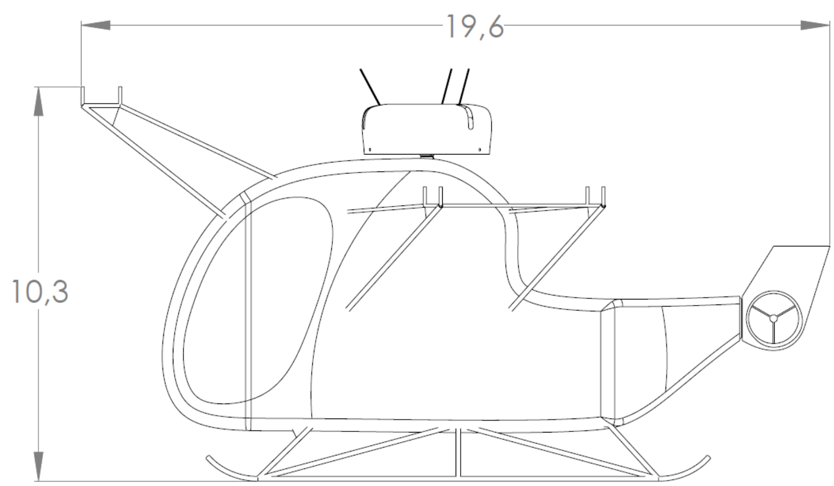


Single Flying Wing Properties

Weight	150 lb
Aspect Ratio	16
Wing Airfoil	NACA 4412
Airspeed	65 kts
Total Thrust	111 lb
Propeller Type	Fixed-Pitch
Propeller Diameter	2.62 ft
Propeller RPM	4,390

HIVE System Weight Distribution (lb)

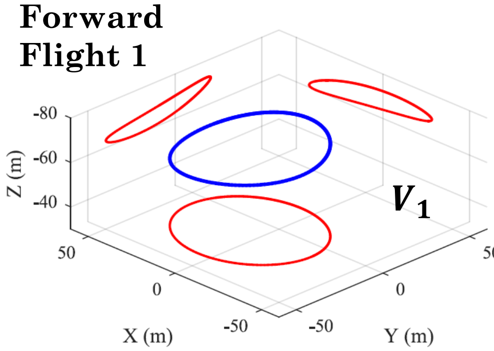
Structure	340
Powerpack	552
Landing Gear	31
Payload	176
Fuel Tank	59
Mission Fuel	716
Accessories	110
Total	**1,984**



Success Through Robust Design

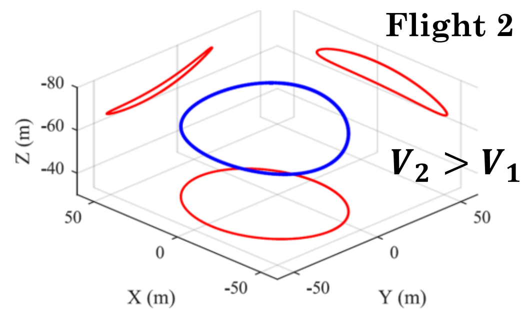
Avoiding technology leaps by solving the challenge through rotor reconfiguration

Forward Flight 1



Reconfigurable rotor **constantly optimizes** itself throughout flight to maintain **high efficiency** in hover and forward flight (see graphs).

Forward Flight 2

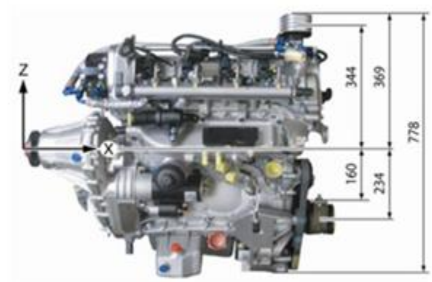


- Flying Wing design based on successful **Makani Wing 7.**
- Choose from **off-the-shelf diesel engine** or **future LPE** engine with **greater endurance/payload.**

Makani Wing 7

Swarm Flying Wing

	Standard CD-155	Improved LPE
Engine	Continental CD-155	Scaled Liquid Piston Engine
Rated Power	155 hp	155 hp
Fuel Efficiency	0.375 lb/hp-hr	0.32 lb/hp-hr
Endurance/ Payload	31 hours 176 lbs	34+ hours or 320 lbs
System Life Cycle Costs	$12.0 million	$10.5 million



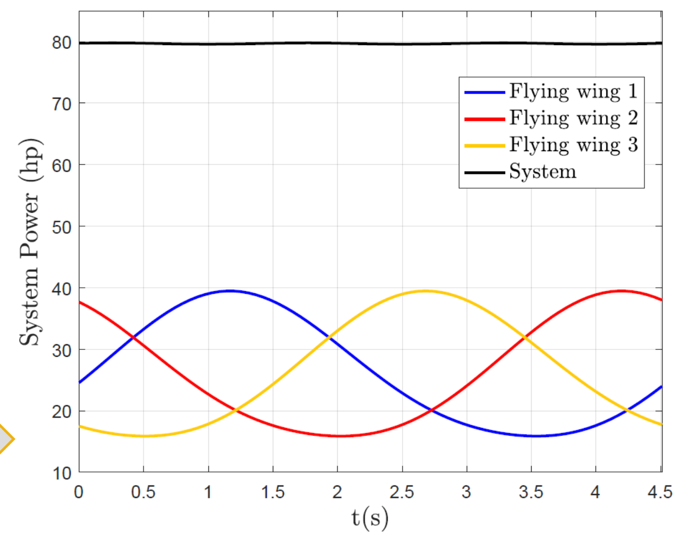
Continental CD-155

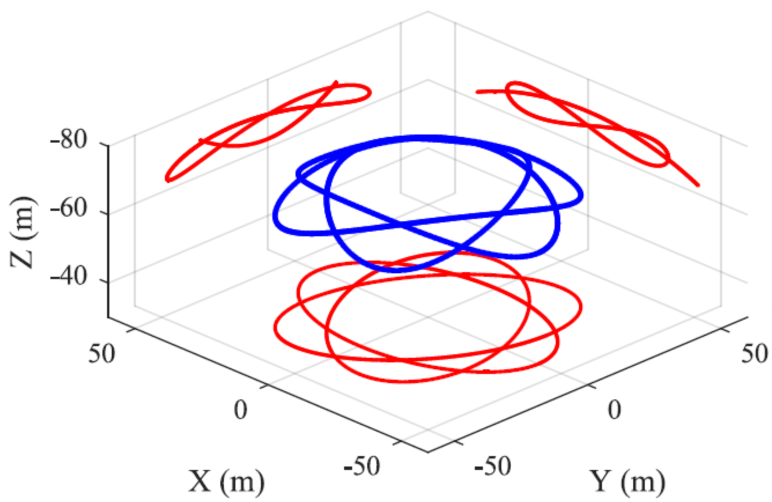
Liquid Piston Engine (LPE)

Performance Overview

- Low disk loading: **0.16 lb/ft²**
- High power loading**: 15.9 lb/hp**
- Max. forward speed in hover configuration: **26 kts**
- Alternating flying wing power demands in forward flight sum up to a practically **constant power requirement** for the system (fluctuations below 1%).

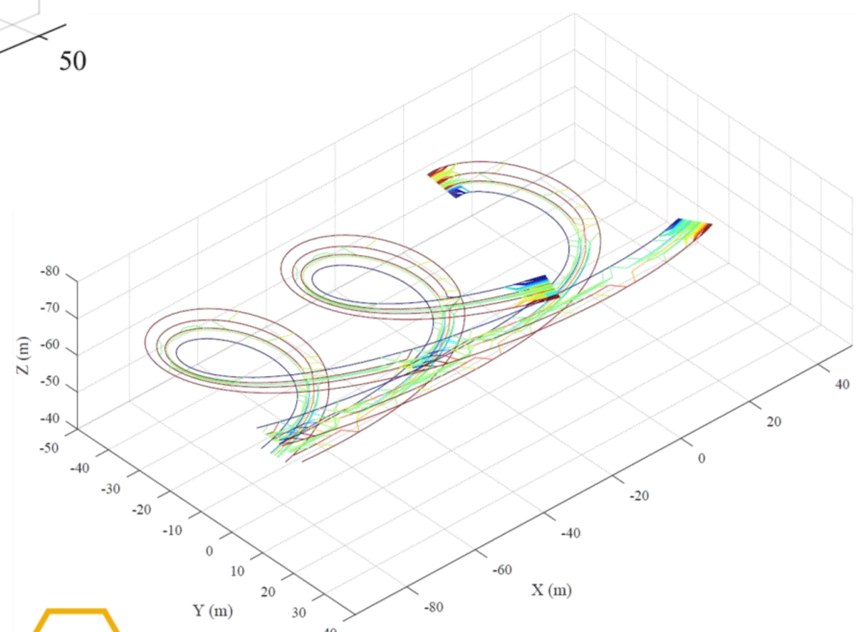
Required Power in 20 kts Forward Flight for One Rotor Cycle





Optimal rotor trajectories (e.g., elliptical) can lead to **50% lower** power requirement in hover.

A **high-fidelity aerodynamic model** can prescribe optimal rotor trajectories for desired forward speeds.



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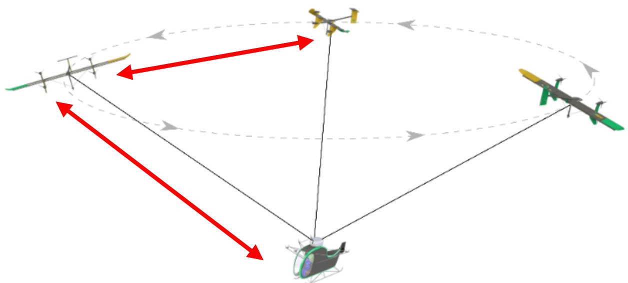
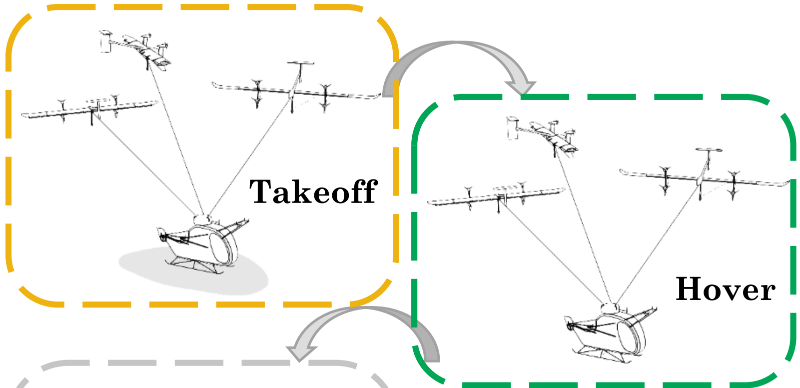
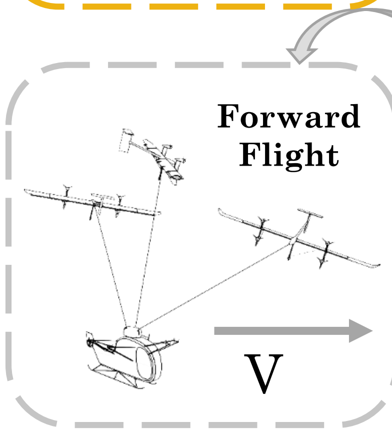
Stability and Controls

Redundant datalink and sensor fusion



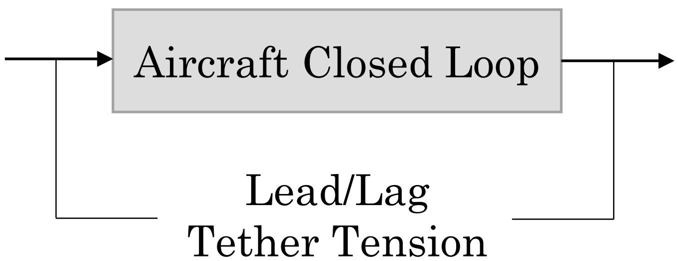
Gain scheduling as a function of phase of flight



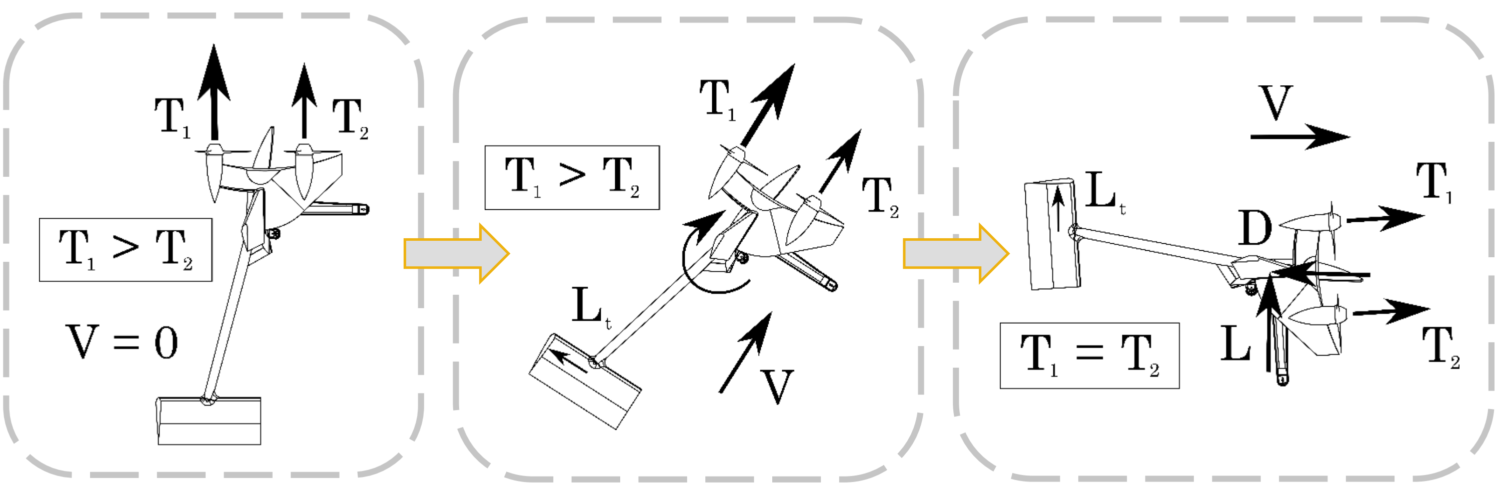


Synchronization of flying wing trajectories to enable the different phases of flight

Aircraft control augmented by unconventional sensors



Tailsitter Transition Maneuver



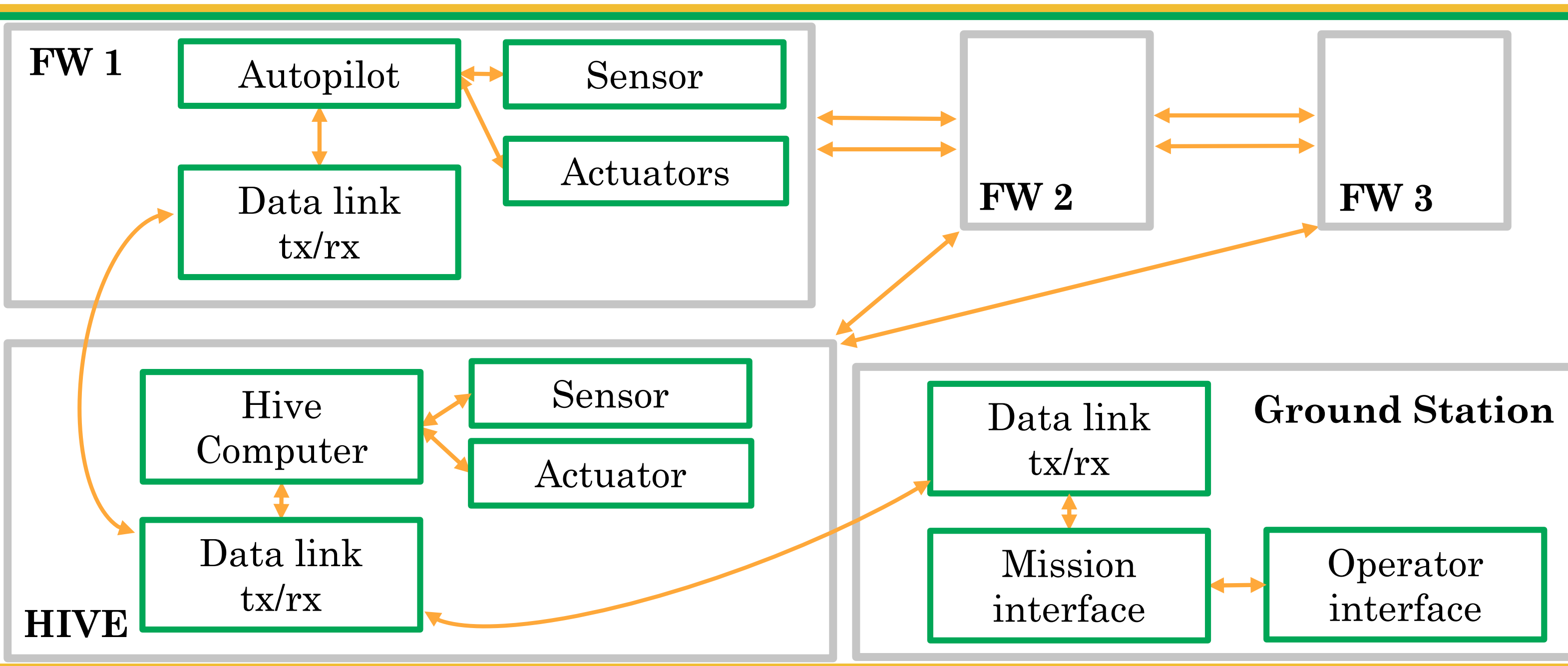
Vertical differentiel thrust to initiate transition to level flight

Transition through varying feedback control

Entry into level flight with forces on lifting surfaces

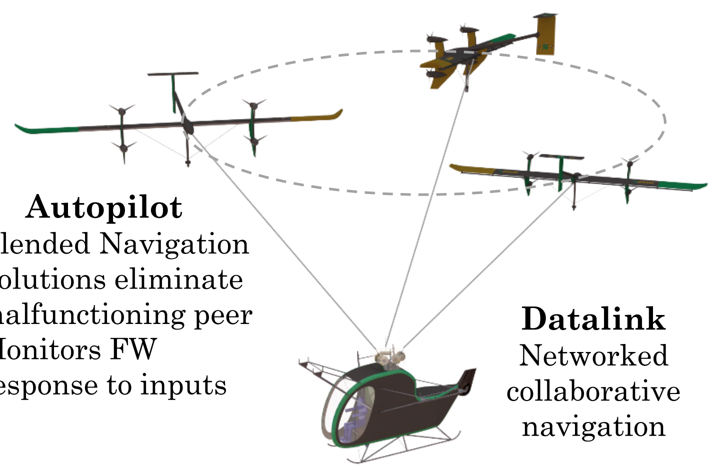
GNC and Avionics Suite

GNC Architecture



Standardized COTS Sensor Suite

- Air Data Computer (ADC)
- Attitude Heading Reference System
- GPS
- Radar Altimeter
- Proximity Transponder: relative position to HIVE, FW's and Ground Control Station (GCS)
- Tether Tension Monitor



Autopilot

- Blended Navigation Solutions eliminate malfunctioning peer
- Monitors FW response to inputs

Datalink

Networked collaborative navigation

Integrated Vehicle Health Monitoring System

- Full Authority Digital Engine Control (FADEC)
- Generator Output
- Battery Charge/Discharge Rate
- Electrical System Diagnostics
- Voltage at Tether/Wing Interface
- Flying wing (FW) Power Consumption

HIVE Design

Compact integration of all components in a robust lightweight structure

Integrated flying wing supports

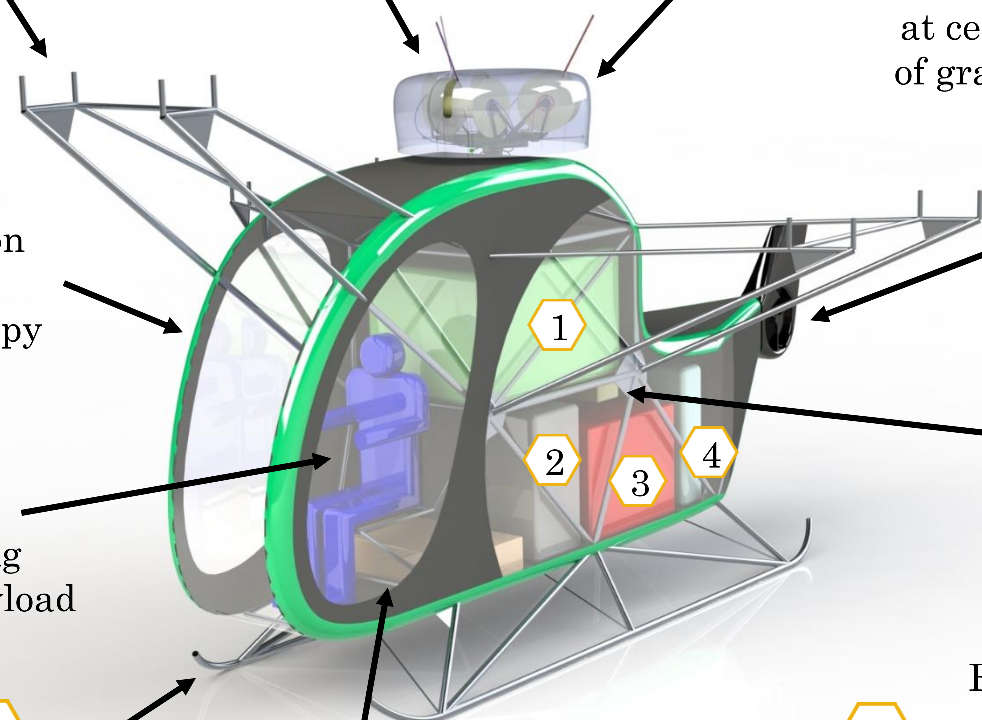
Compact hub and tether reels with fairing

Aluminum tubular frame

1 Fuel tank at center of gravity

Lightweight carbon fiber skin and polycarbonate canopy

Small low power tail rotor



Power control electronics

Room for a 80 kg human shaped payload

4 Radiator

Simple landing skids

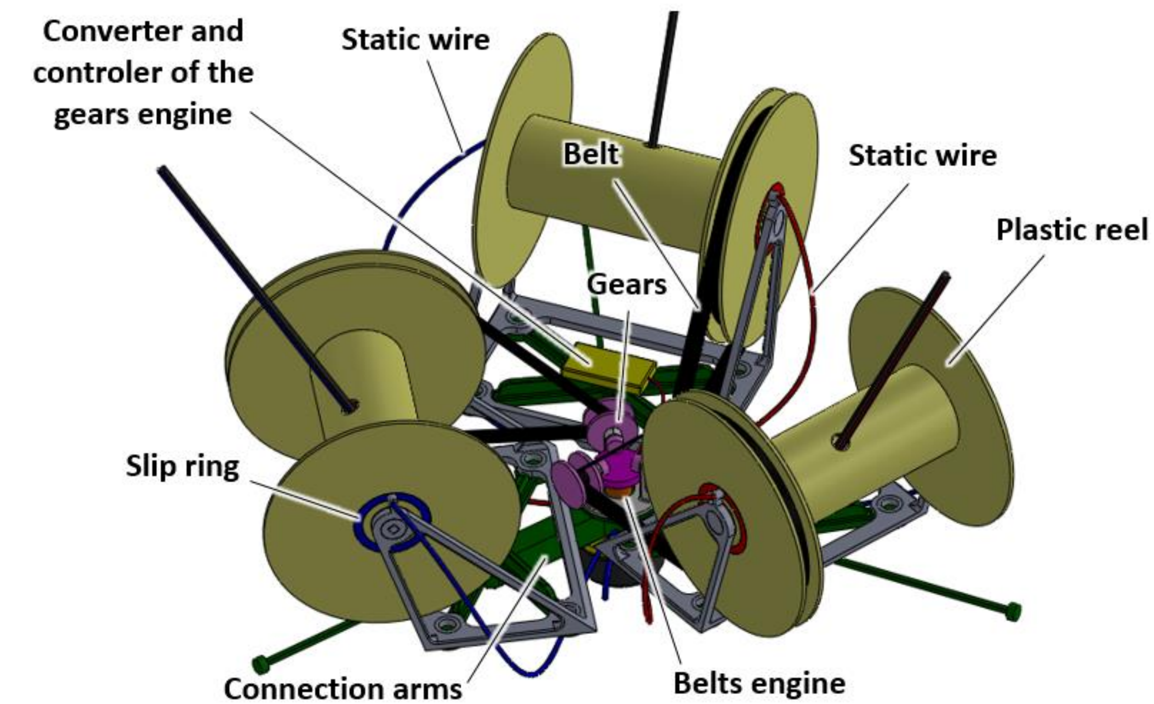
3 Diesel engine

Safety battery for emergency landing

2 Generator

Rotating Hub

System of bearings and slip rings maintain mechanical and electrical connection between tethers and HIVE

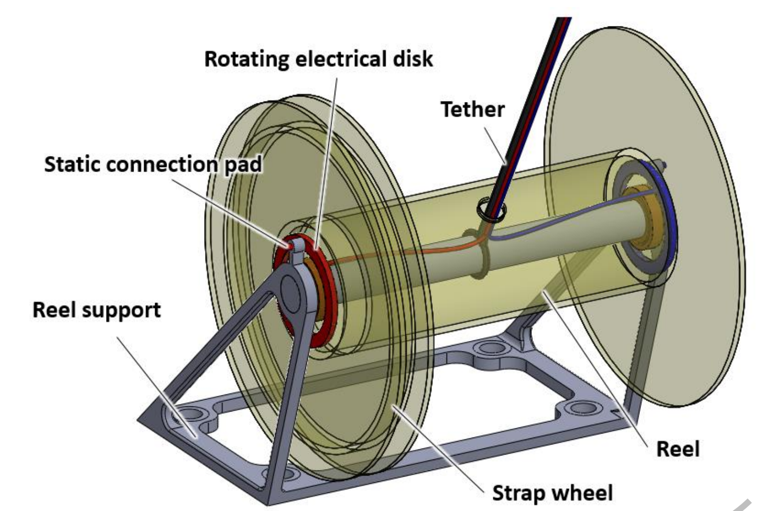


Reel System

Reel and supports link tethers to the hub

Central shaft takes load and slip rings transmit power

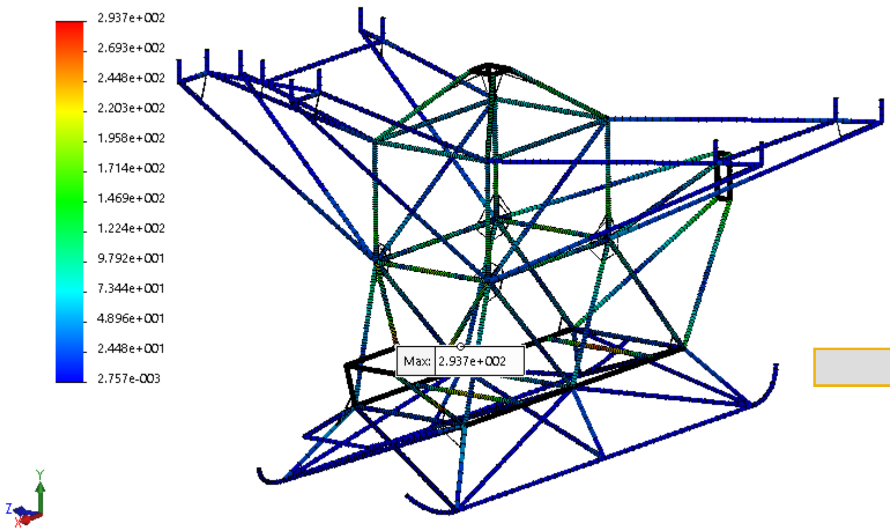
Reels wind tethers during flying wings takeoff and landing



HIVE and Hub Stress Analysis

The frame's structural integrity **validated with FEA's, through all mission phases** with load factors of 2:

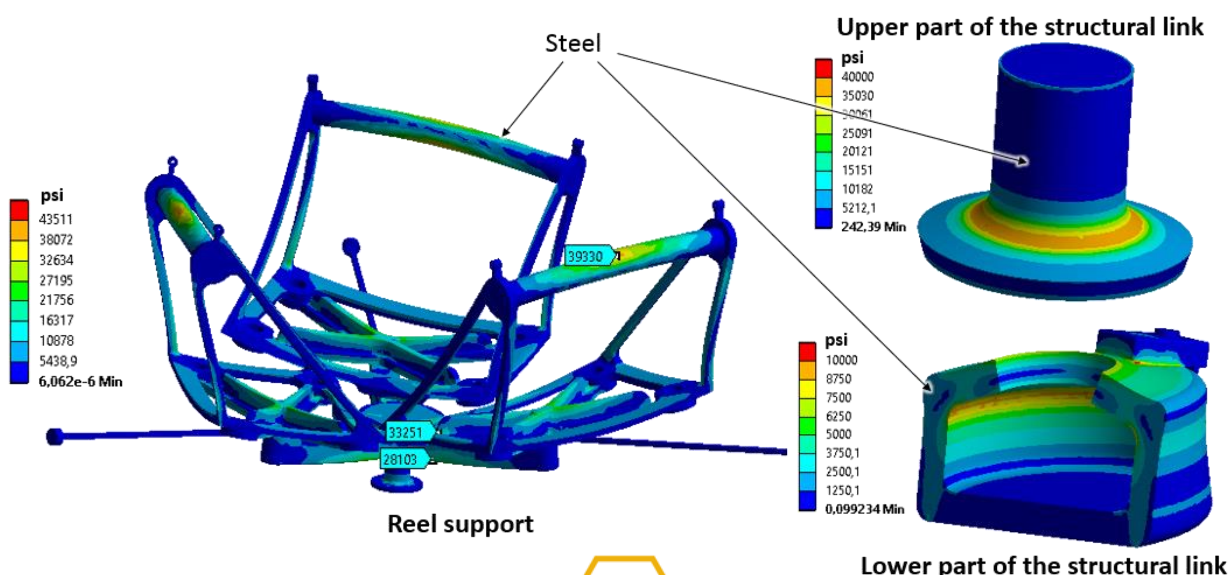
- Takeoff
- Flight
- Landing



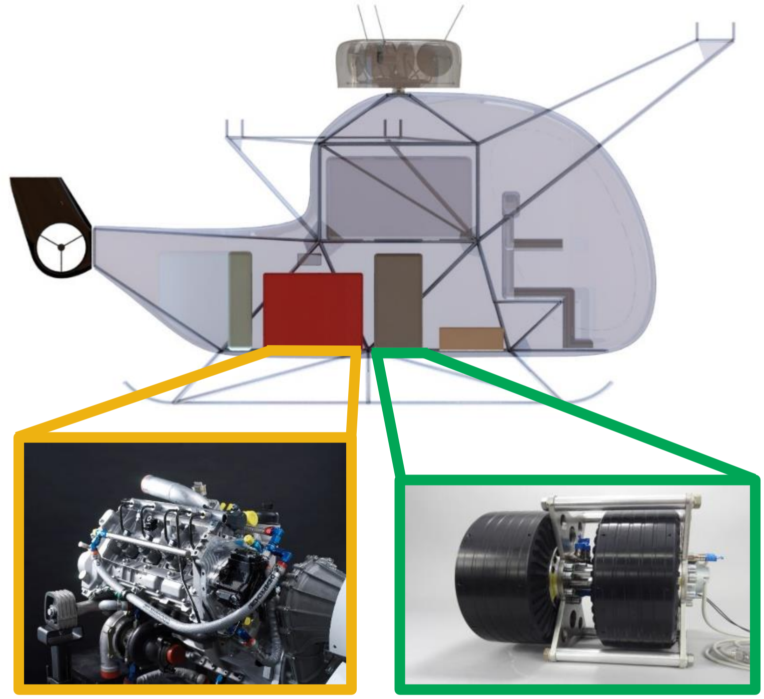
Lightweight tubular frame provides stiffness and resistance

Hub

- High strength steel parts in hub resist to loads in all flight conditions.
- High safety factors in bearing parts (over 8) maximize fatigue life.



Powerplant



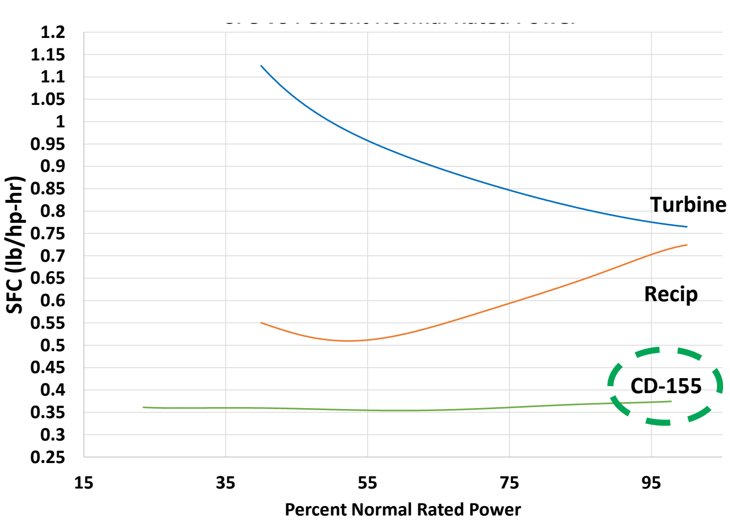
Continental CD-155 Aero Diesel

- **Hybrid-electric** primary drive with battery backup
- Certified design: 2100 hr TBO
- **Scaleable/interchageable** with CD-135 for low horsepower applications
- **Excellent SFC** at all regimes improves during mission, minimizing fuel load

2 EMRAX 268 Motor/Generator

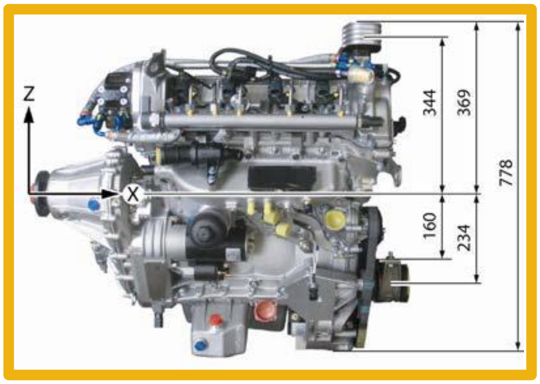
- Over **92% efficiency** during peak demand.
- High power density: **2.6 hp/lb**
- **Series arrangement** provides partial power with a failed generator.
- Common **cooling system** reduces weight.
- Scaleable/Customizable
- Developed for aviation applications.

SFC vs. Percent Normal Rated Power



Delivering the Power

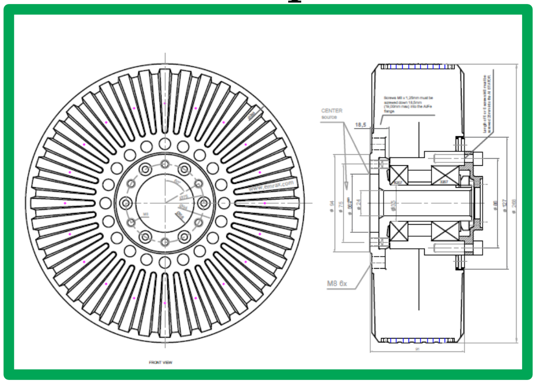
CD155 Specifications



Performance	RPM	HP	kW
Max continuous power	2300	155	114
Best economy	1940	97	71

Weight		
Engine and dry ind. gearbox	295 lb	134 kg
Liquid cooling system (estimated)	50 lb	23 kg

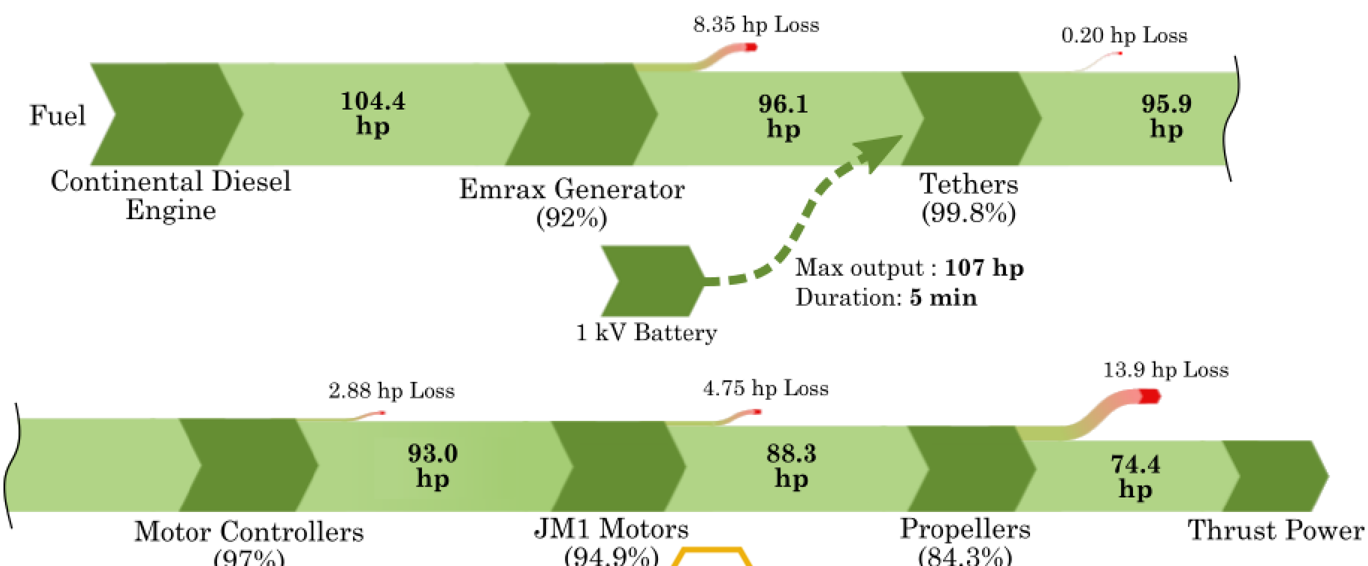
Emrax 268 Specifications



Specifications		
Weight	45 lb	20 kg
Diameter	10.6 in	268 mm
Width	3.6 in	91 mm

Performance		
Efficiency	92-98 %	
Continuous power	65-110 hp	50-85 kW

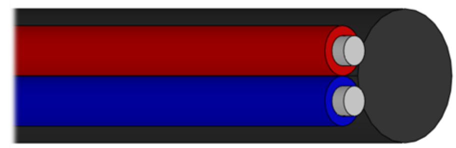
Power Losses: Hybrid technology minimizes total energy losses from mechanical energy output to useful thrust.

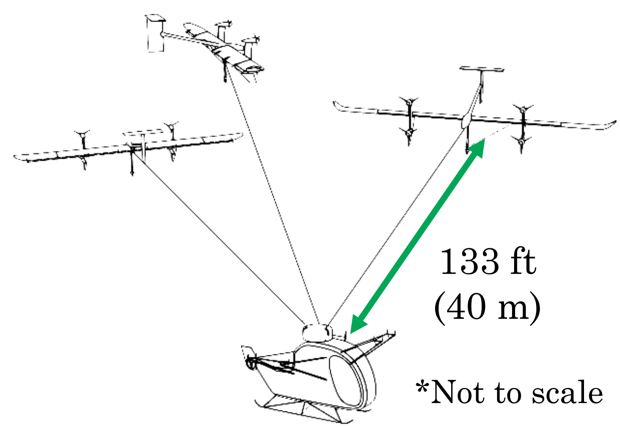


Tether Design

Component Overview

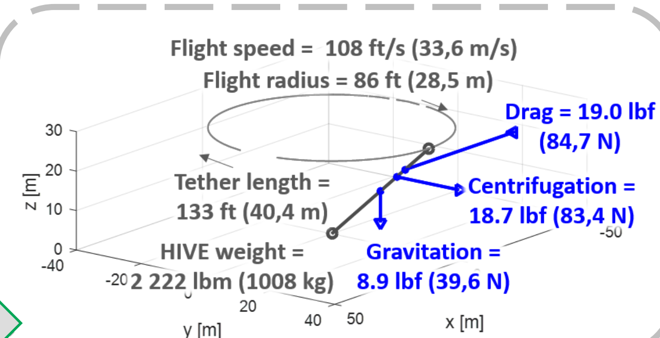
- Tethers are made of a **structural cable** and two isolated **electrical wires made of aluminum**.
- Structural cable carrying all the load is made of **Dyneema fiber** – also used in aviation rescue hoists.
- The cables are linked together with a sheath.
- Electrical wires slightly longer then the structural cable, to avoid a mechanical load.

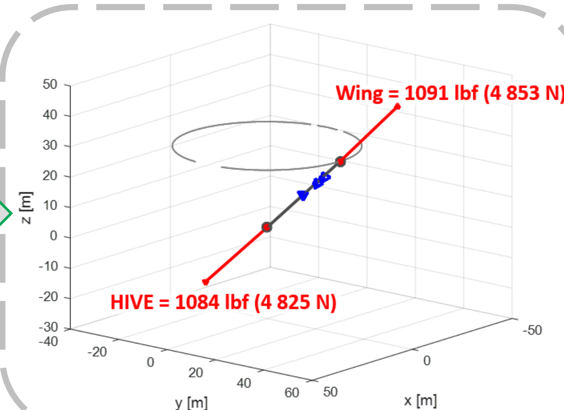




Characteristics in Operation

- Low power losses: **0.02%**
- **Forces on tethers:** aerodynamic drag, centrifugal, gravitational, and tensile (from centrifugal force on flying wing).
- Tether max. applied → **1,091 lb**
- Safety Factor → **29.6**





Georgia Institute of Technology

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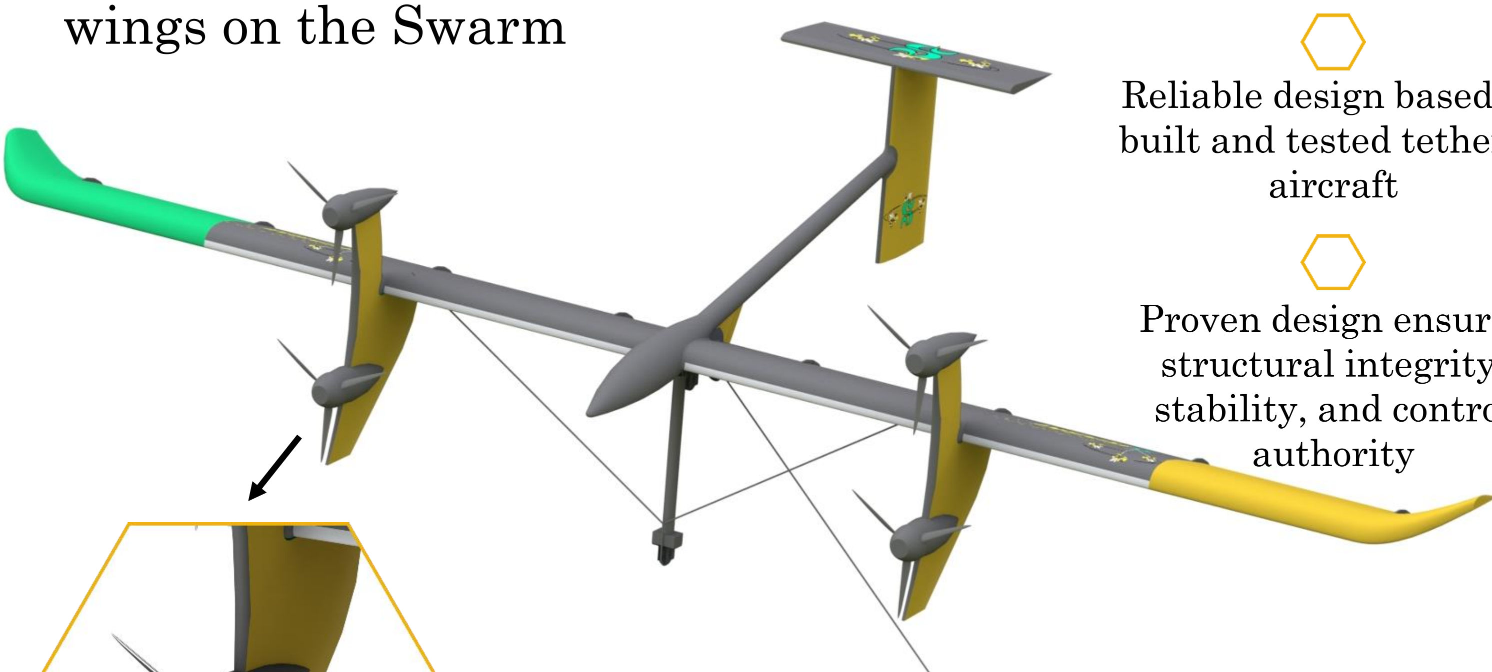
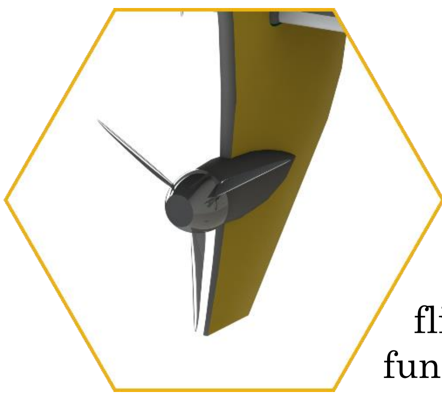
Flying Wing Design

Modified versions of the Makani Wing 7 serve as flying wings on the Swarm



Reliable design based on built and tested tethered aircraft

Proven design ensures structural integrity, stability, and control authority

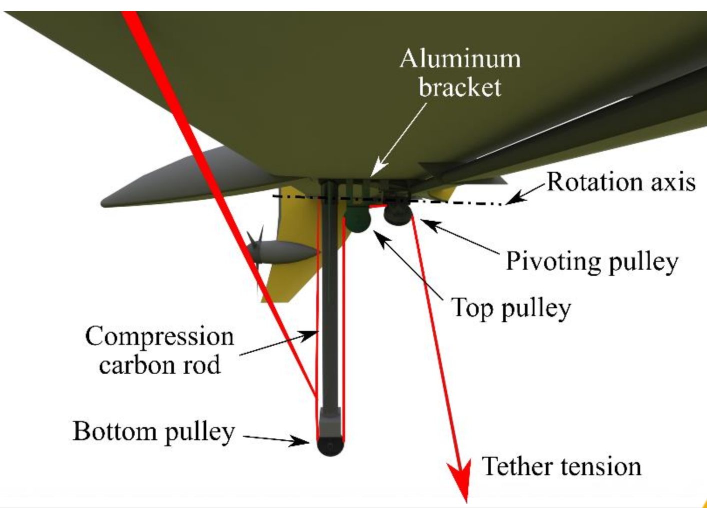


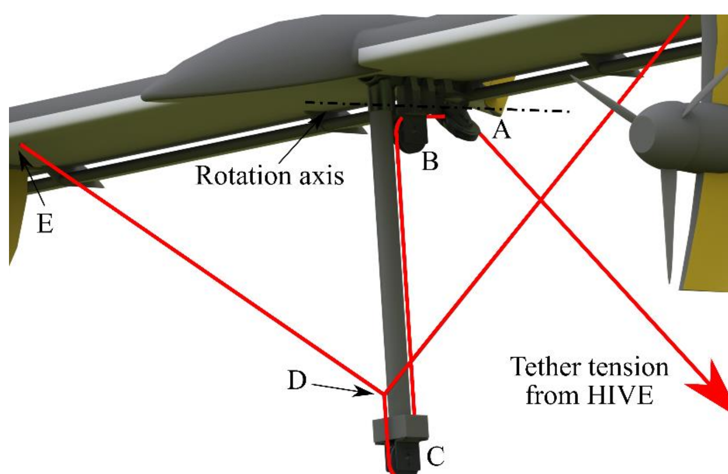
Propellers

Custom designed for maximum flight efficiency while still remaining functional in tailsitter mode

New Tether Attachment

Allows roll in banked turns while sharing load with the wings, reducing bending stresses





Safety and Reliability

Robustness and Redundancy

Powerpack

- **Dual generator** configuration
- **Backup battery**
- Diagnostic status informs GNC to **minimize power loss possibilities**

GNC

- Blended navigation solution
- Independent flight controllers
- **Alternate control** and **navigation**

ALTERNATE CONTROL

FW motor/prop failure compensated by blending other control inputs and/or differential thrust

OR

Two remaining FWs adjust formation to eliminate malfunctioning FW

EMERGENCY LANDING

HIVE executes landing in clear area and signals is sent to operator

ALTERNATE NAVIGATION

GNC cross-checks navigation inputs and eliminates an erroneous source

PREVENTIVE LANDING

HIVE signals operator to land as soon as possible

FW GLIDING DESCENT

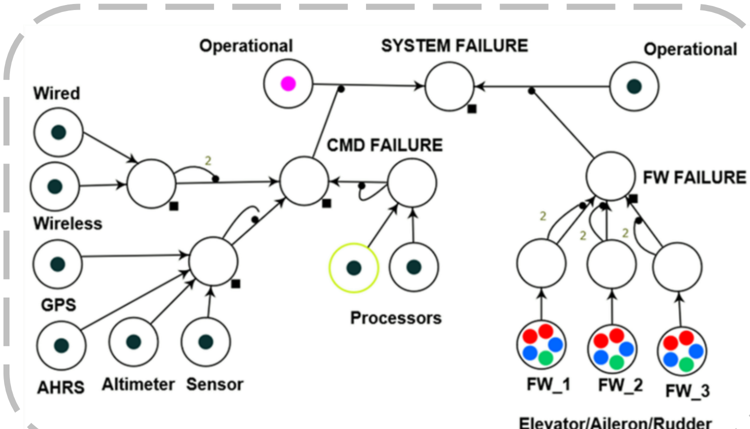
FWs execute gliding descent and flare prior to touchdown

Safety Assessment

ARP 4761 analysis identified high risk failure modes in **powerpack** and **GNC** at takeoff and landing.

Likelihood \ Severity	No Effect (5)	Minor (4)	Major (3)	Hazardous (2)	Catastrophic (1)
Probable (A)					
Remote (B)				Loss of thrust (T/O & LDG) (2B)	
Extremely Remote (C)					Erroneous Altitude or Position (1C)
Extremely Improbable (D)					

GNC Discrete Event Simulation

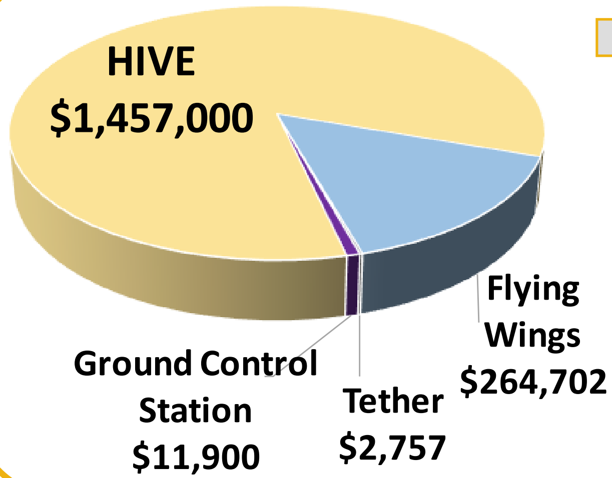


State-Based Simulation

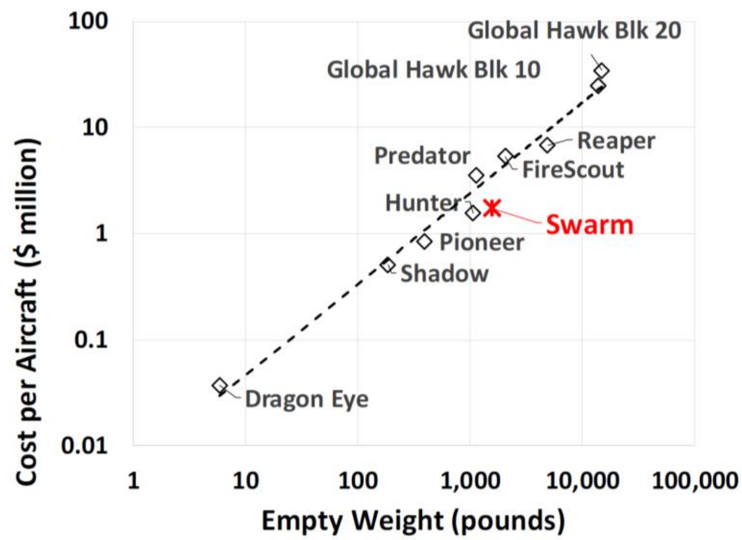
- **Simulates complex interaction** between HIVE, tether and FW subsystems.
- Accounts for **real-time reconfiguration of rotor** system during Alternate Control Regimes (**left**).

Cost & Marketing

Total Prototype of $1.74 Million



Benchmark Overview



Vehicle Operating Costs

- O&S of $506 is competitive with small commercial helicopters.
- Jet-A $5.50 per gallon buring 5.5 gallons/hour.

Closes on Aviation Gap

- **Commercial** use in construction, news/traffic reporting, advertising.
- **Civil** use in law enforcement, border monitoring, disaster relief.
- **Security Forces** use in surveillance, communications retransmission, command and control.

Eagle Eye Persistent Operation Package

- **24/7 coverage**
- **4 vehicles**
- **2,282 flight hours** per year per vehicle
- **6 pilots** per day at 4 hours each
- **$1.2 million** per system per year

Summary

The Swarm: a new concept using conventional technologies able to hover for over 24 hour

Needing very low power to fly, the Swarm easily meets every requirement while relying only on readily available technologies

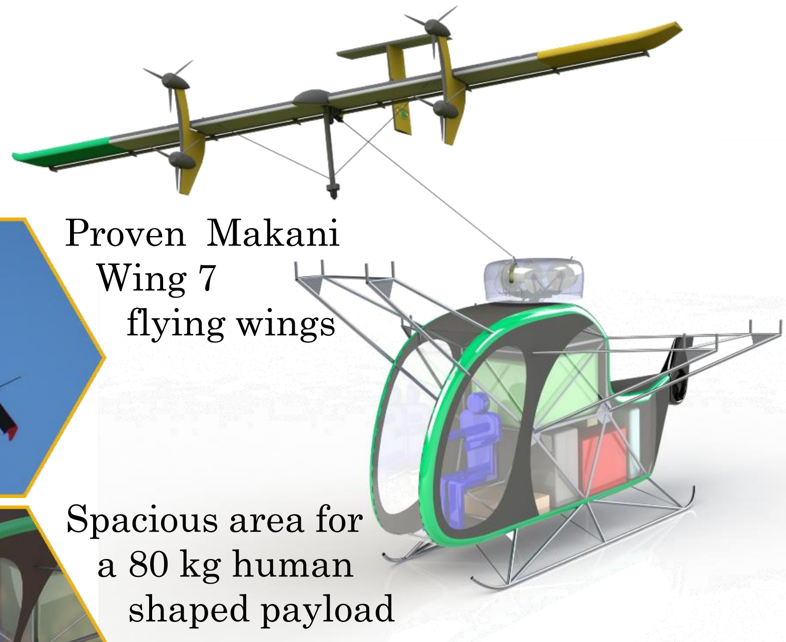
Swarm Specifications

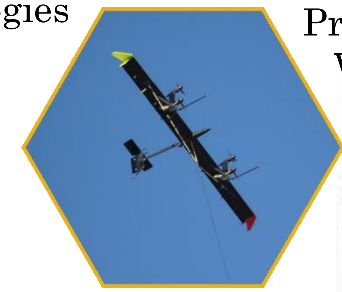
Max. Hover Endurance
31 hours

Max. Gross Weight
2,700 lb

Engine Power
155 hp

Max. Forward Speed
26 kts





Proven Makani Wing 7 flying wings

Spacious area for a 80 kg human shaped payload

FAA certified diesel engine used with commercially available generators