Knightflyer

35th Annual AHS Student Design Competition

Reconfigurable VTOL Aircraft

Sponsored by the Army Research Lab

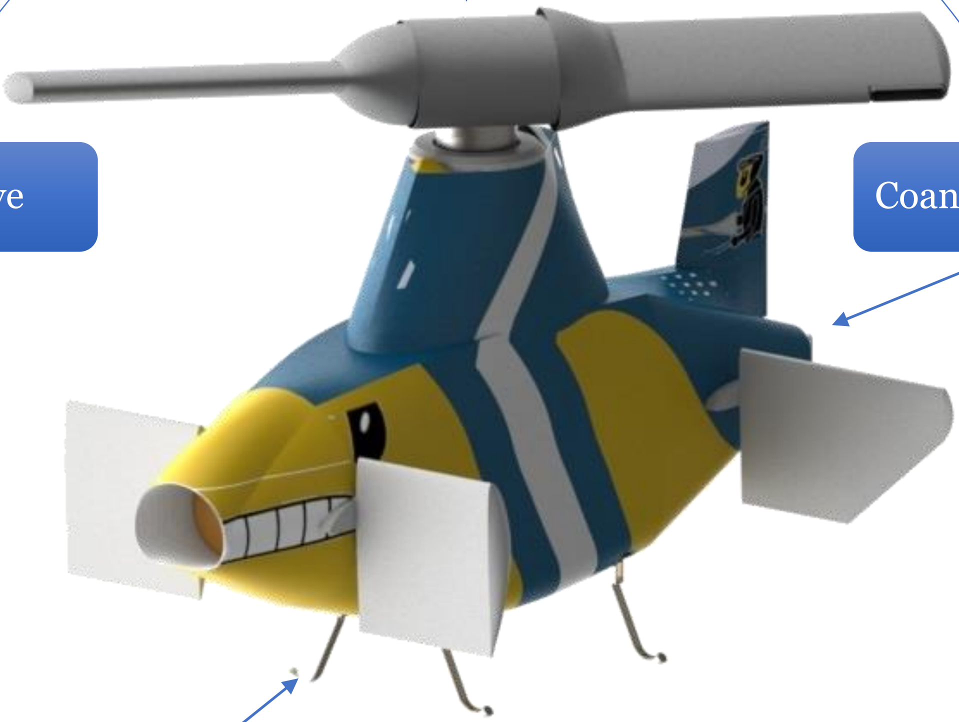
Vertical Lift Research Center of Excellence
Guggenheim School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30313

Georgia Tech College of Engineering
Daniel Guggenheim School of Aerospace Engineering

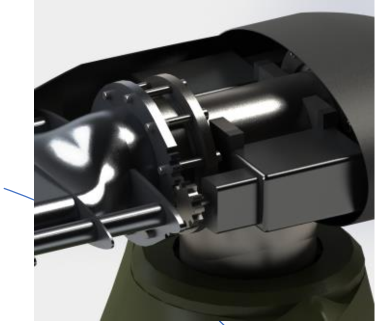
Knightflyer

Georgia Tech’s Knightflyer

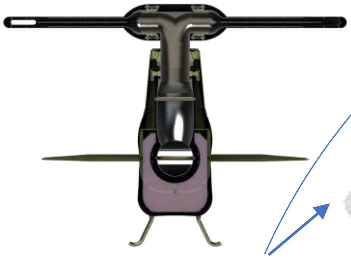
Innovation through the application of advanced technology and robust analytical methods.



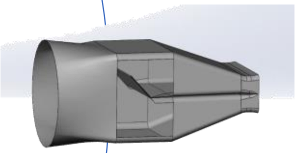
Stopped Rotor



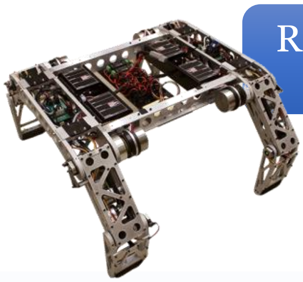
Reaction Drive



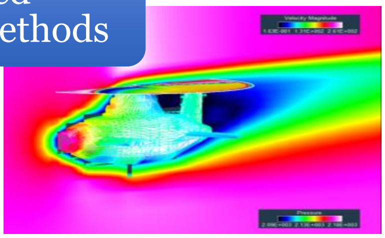
Coanda Effect Nozzle



Retractable Robotic Landing Gear



Advanced Analytical Methods

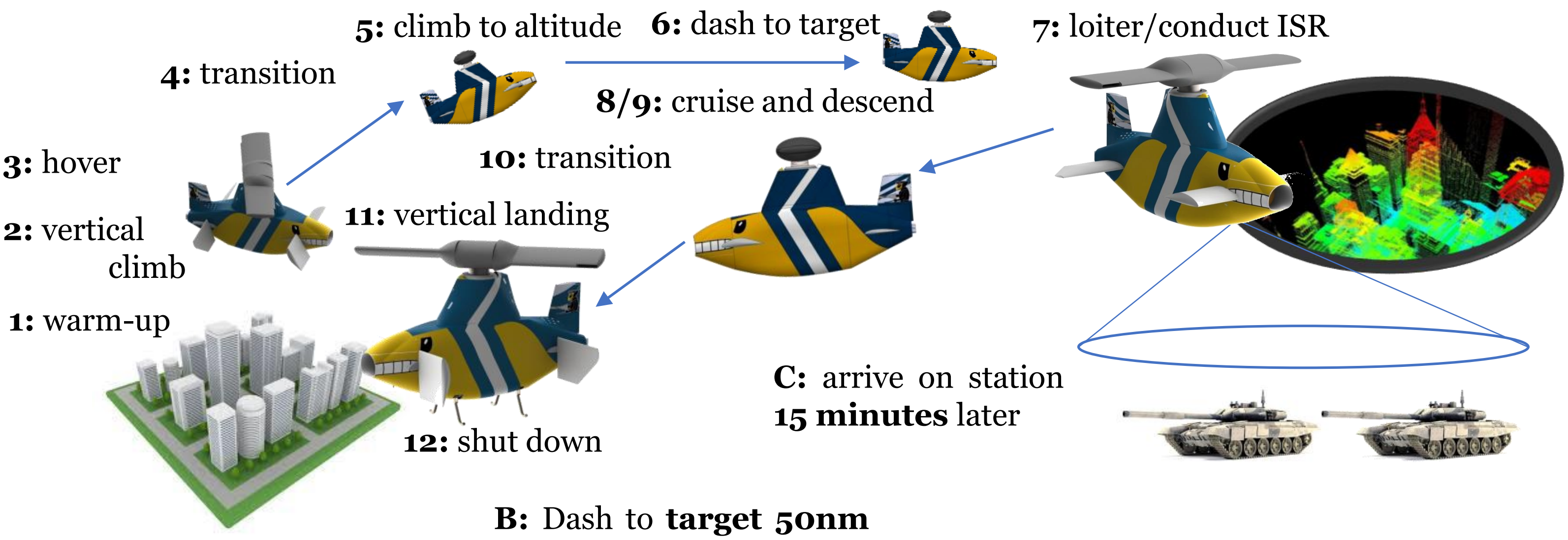


Performance Summary

Performance Metric	SLS	3000m
Max Speed (kph)	*402*	*346*
Hover Endurance (hrs)	*1.36*	*1.16*
Full Range (km)	*194*	*223*
Full Endurance (hrs)	*1.71*	*1.71*

Rotor Metrics of Interest	
Tip Speed (ft/s)	*525*
Rotor Solidity	*0.22*
Disk Loading (lb/ft2)	*17.7*
Figure of Merit	*0.836*

Vehicle Weight Breakdown (kg)	
Empty Structural	*298*
Scaled FJ-33 Engine	*66*
Payload Specification	*100*
Onboard Fuel	*136*



1: warm-up

2: vertical climb

3: hover

4: transition

5: climb to altitude

6: dash to target

7: loiter/conduct ISR

8/9: cruise and descend

10: transition

11: vertical landing

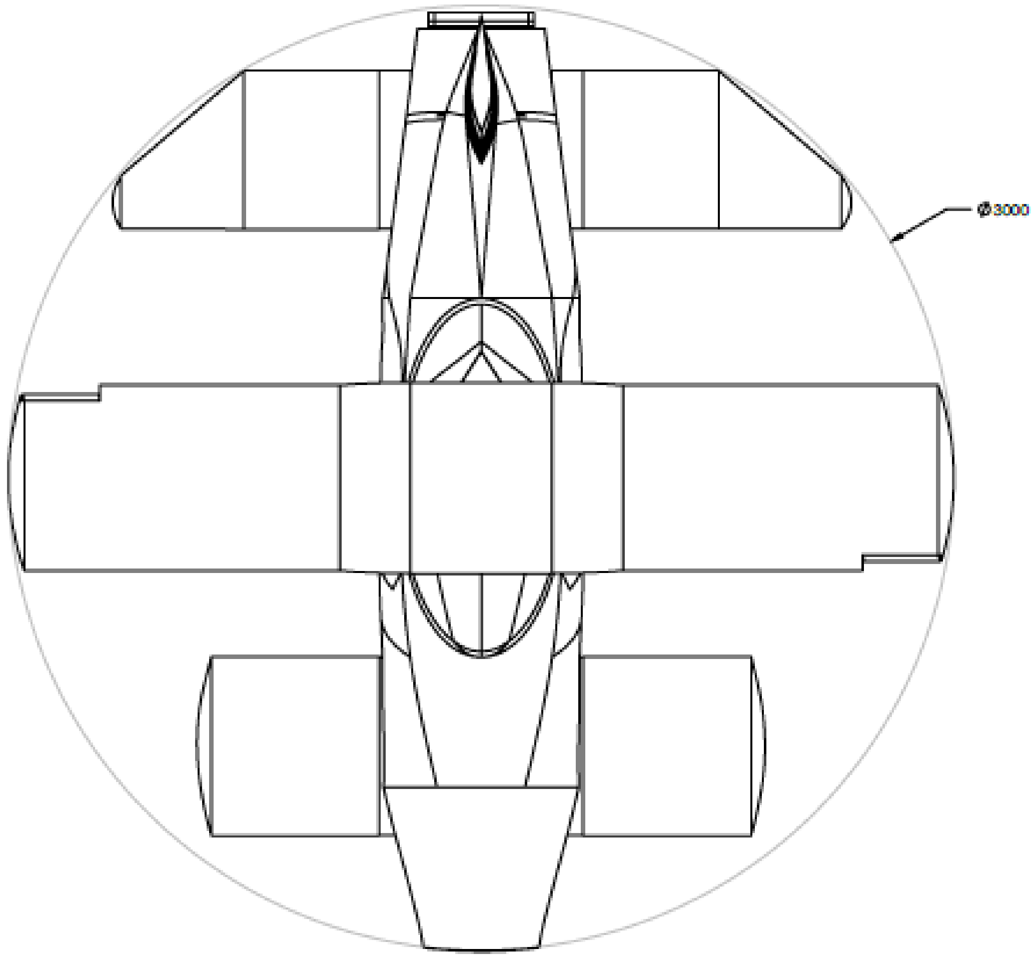
12: shut down

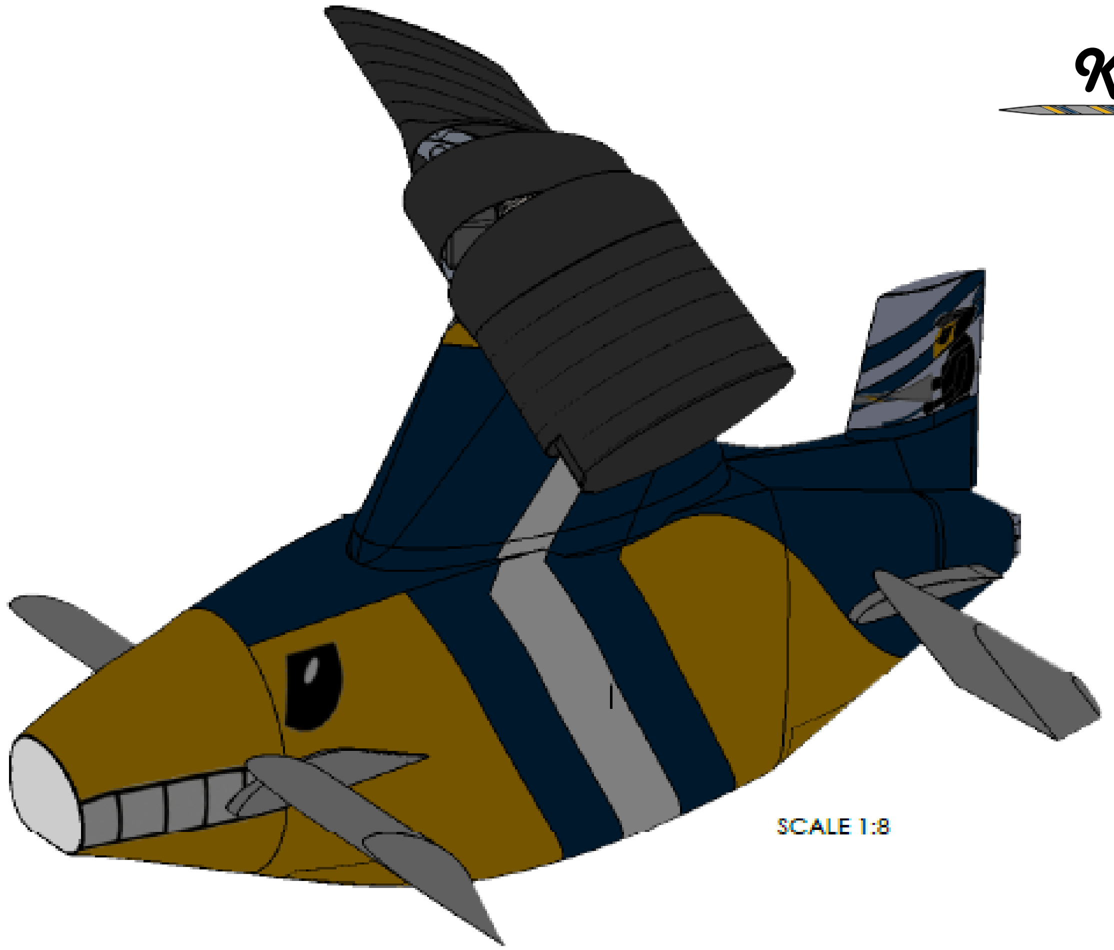
A: Hide in clutter of city to avoid detection by enemy forces

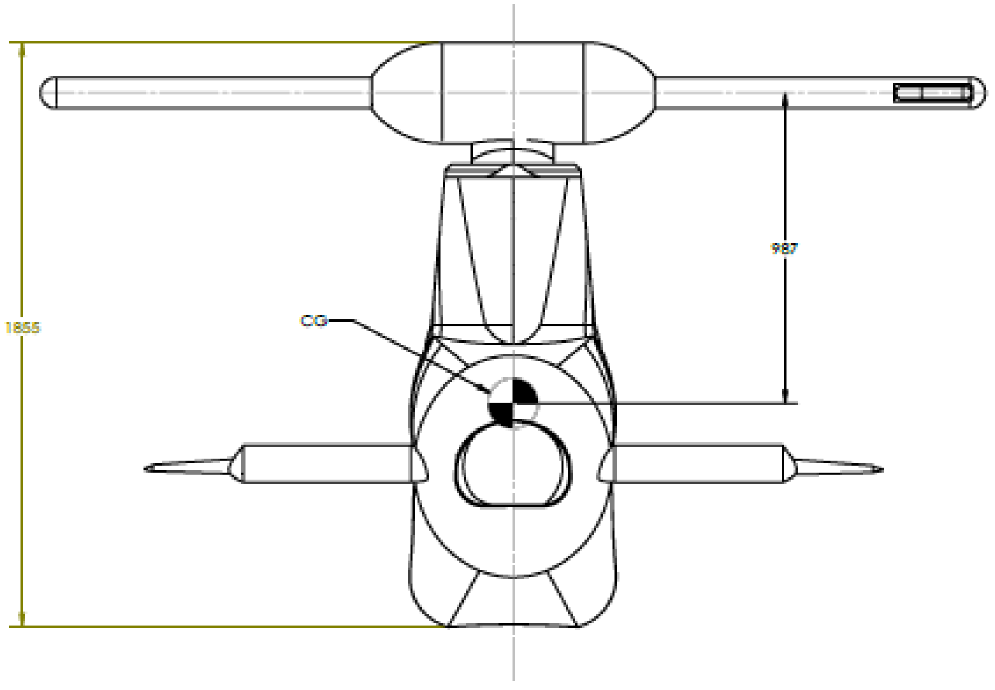
B: Dash to **target 50nm** away at **206 kts**, 2x the speed of Predator and 1.5x speed of Apache

C: arrive on station **15 minutes** later

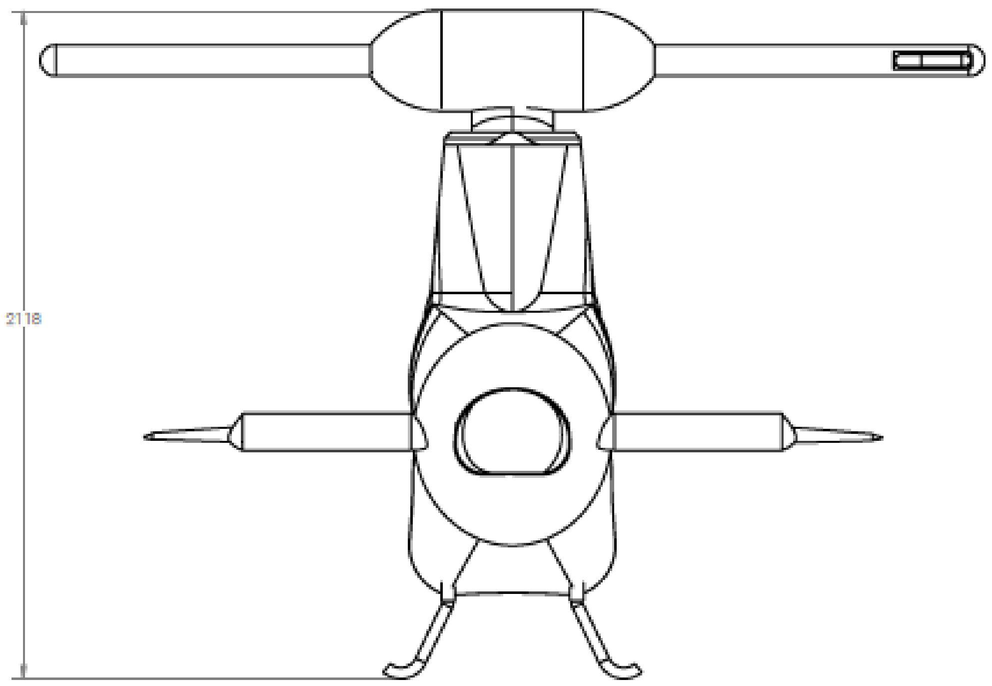
D: Loiter over target for **25 minutes** to provide ISR or targeting support for other assets



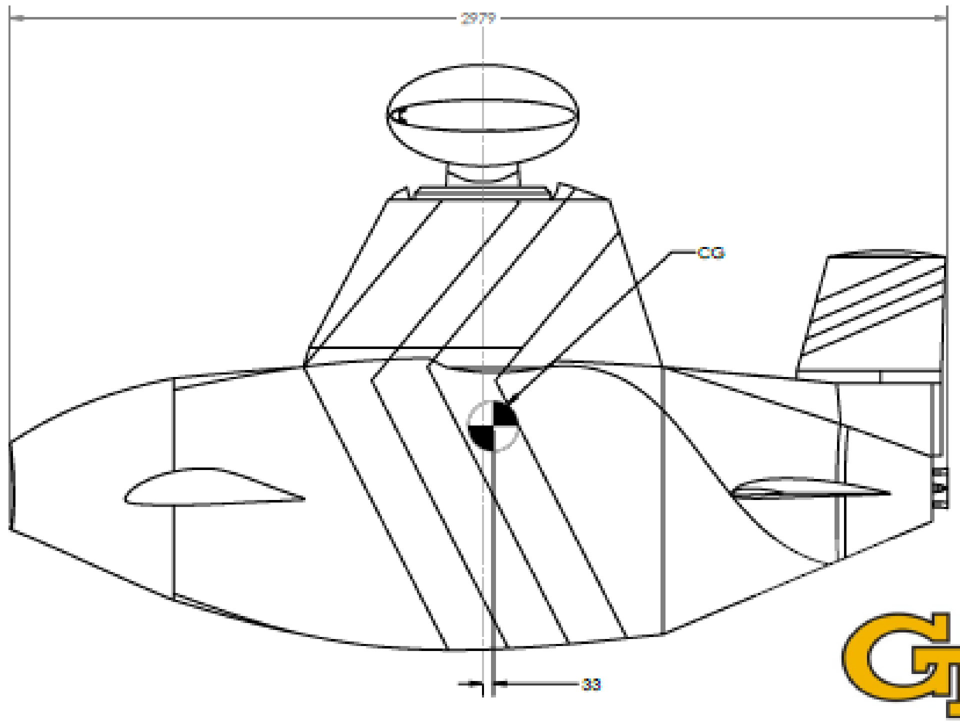




Landing Gear Retracted



Landing Gear Extended



NOTE: Weight and Center
of Gravity Consider a 100kg
Payload

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	C. Crouch	
CHECKED	D. Ahrens	
ENG APPR.	A. Murphy	
MFG APPR.		
Q.A.		
COMMENTS:		

Georgia Institute of Technology
Daniel Guggenheim School of Aerospace Engineering

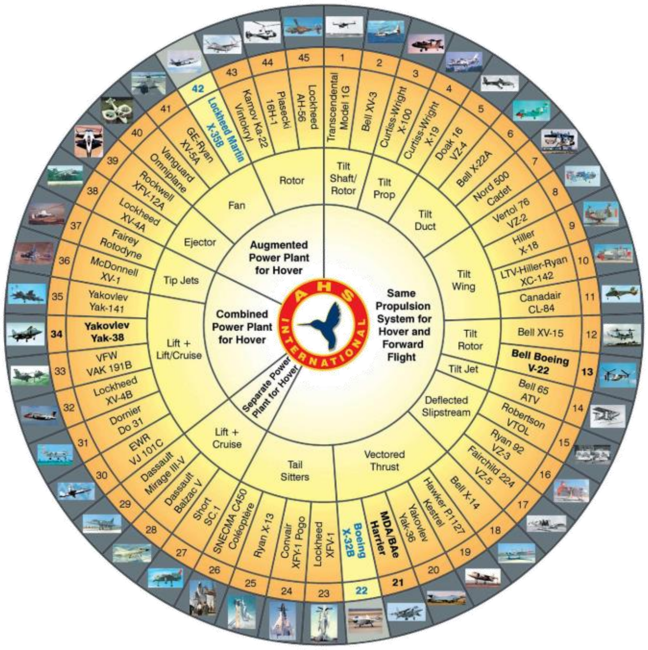
TITLE:
General
Arrangement

SIZE D
DWG. NO. KNIGHT FLYER
REV 01
SCALE: 1:12
WEIGHT: 586.4 kg
SHEET 1 OF 1

Background and Competition

Background:

The tradeoff between helicopters and fixed-wing aircraft presents a **fundamental problem** for organizations seeking certain capabilities. The American Helicopter Society's (AHS) VSTOL Wheel lists the numerous attempts that have been made in an attempt to solve this tradeoff by providing both helicopter-like launch and recovery with aircraft-like flight performance. The wheel, with some exceptions, has been marked by a failure to live up to promises.



Competition:

For the 35th Annual AHS Student Design Competition, the Army Research Lab tasked teams with designing a Group 3 unmanned air vehicle (UAV). The vehicle was to achieve high-speed forward flight (relative to current VTOL aircraft) and efficient hover through the use of novel reconfigurable propulsive and lifting devices. The proposed aircraft design was required to have its main lifting device be a reconfigurable system. Because the system was required to be both new and novel, tilt-rotors and tail sitters were eliminated from the competition.

Requirements and Brainstorming

Design/Qualitative Requirements	Restrictions and Quantitative Requirements		Scoring Metrics
Reconfigurable on its own	**Max Takeoff Weight (MTOW)**	*600kg*	**Hover time in hours**
No part of the vehicle may be removed or jettisoned	**Operating Altitude**	*3000m*	**Cruise range at velocity for best range**
The aircraft must be controllable and stable throughout the flight	**Maximum Airspeed**	*Greater than 180 knots*	**Dash speed**
Designs should be new and novel	**Payload**	*100kg*	**Estimated Drag Area**
	Max vehicle span in hover	*3m*	

Initial Brainstorming Activity:

The team initially sought to explore the possible design space and determine which vehicle configuration would provide the best capability. Three designs were evaluated:

Reaction Drive Stopped Rotor

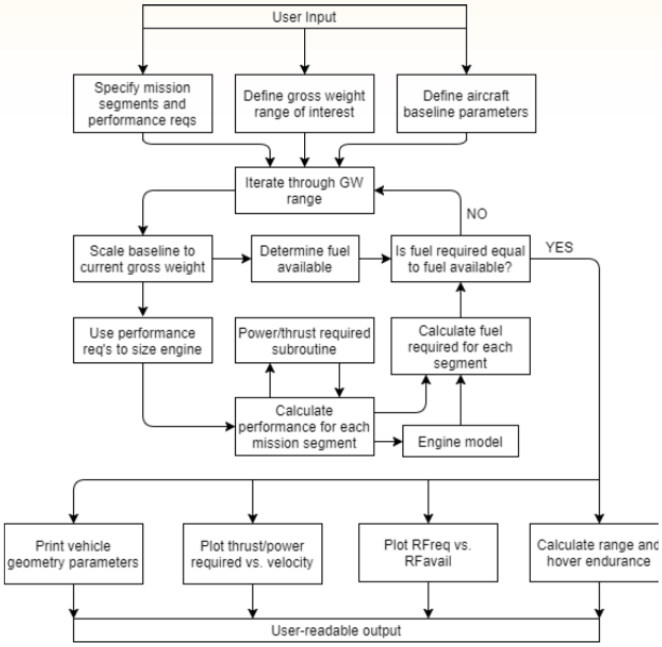
Distributed Electric Propulsion (DEP) Stowed Rotor

Disc Rotor

Trade Study and Mission Development

Initial Code Development:

The team first developed a MATLAB based analysis tool to compare vehicle performance parameters. This code accommodated differences such as electric or traditional fuel-powered, compound (helicopter) and airplane performance, and shaft-driven or tip-driven rotors. From this code, the team could evaluate the different design configurations:

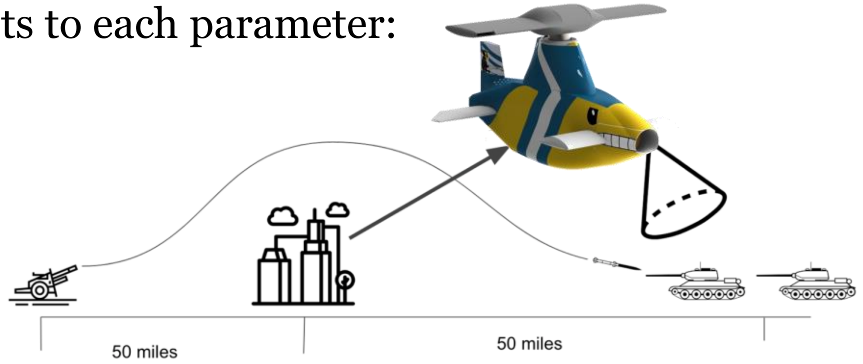


Mission/CONOPS Development:

In order to actually evaluate each vehicle the team had to create a notional mission. Because the requirements did not specify any range requirements, nor penalize a team for weight, the team chose to instead size each vehicle to the maximum allowable weight and measure performance. To compare performance parameters, a CONOPS was developed that highlighted the use of such a vehicle.

The notional vehicle was assumed to be an Army ISR aircraft, capable of hiding within cities to avoid detection and then rapidly flying to a point downrange to provide cueing for long-range fires via its onboard sensors. Because of this, the team assigned the following weights to each parameter:

1. Dash Speed – 10%
2. Hover Endurance – 16%
3. Cruise Range – 43%
4. Complexity – 19%
5. Tech Readiness – 12%



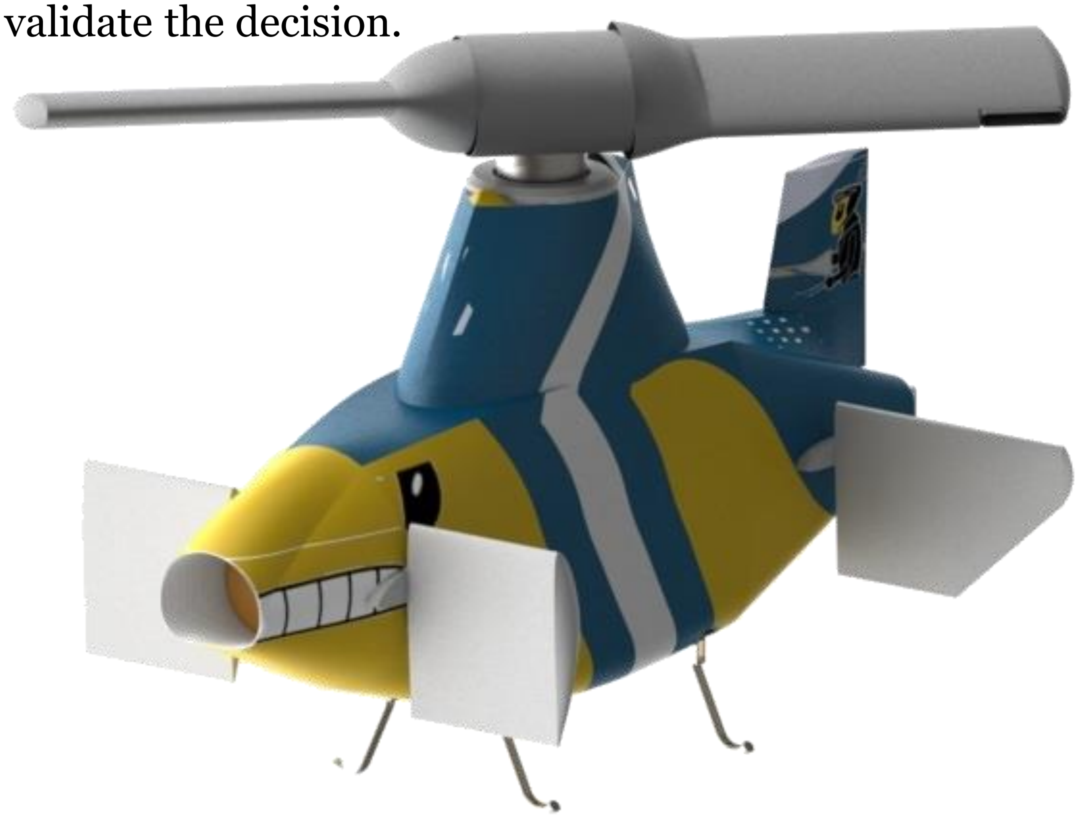
Configuration Trade Study Results

Trade Study Results:

The team used the previously developed MATLAB code and qualitative analysis to evaluate each design, with the results shown below:

	Dash speed	Hover endurance	Cruise range	Complexity	Tech Readiness
Weight	10.13%	16.25%	43.02%	18.16%	12.43%
Target	Max	Max	Max	Min	Max
TJ SRW	446	0.48	208.04	High	High
DEP SR	281	0.28	164.24	Average	Low
DR	279	0.48	147.09	Very High	Low

As the results show, and as a Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) down-select confirmed, the reaction drive stopped rotor showed the most promising performance potential. With the vehicle selected, the team moved into more detailed engineering tasks to further explore and validate the decision.

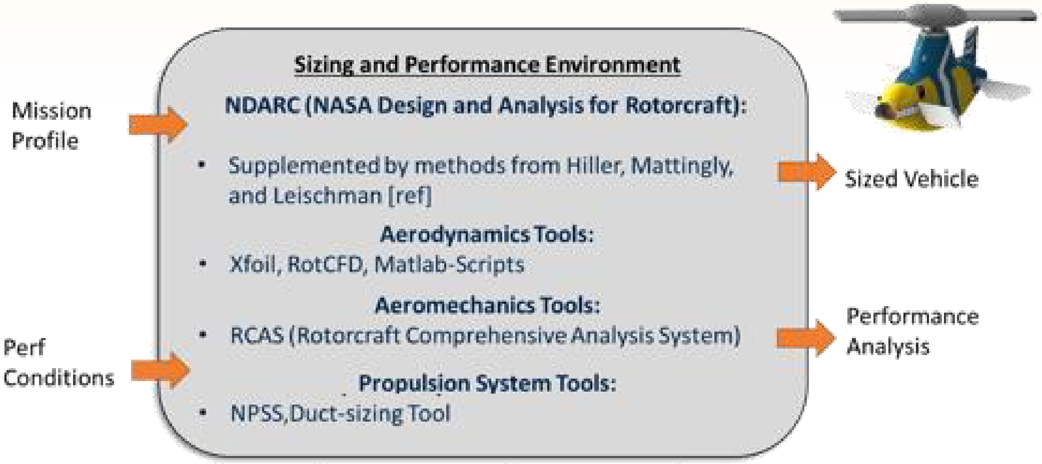


Engineering Development Plan

With the vehicle selected, the team worked to understand some of the key risks associated with such a vehicle. Since the vehicle was similar to the Boeing X-50 Dragonfly, the team conducted an extensive "lessons-learned" exercise.

Major Design Challenges	Design Solutions
1. The propulsion system is **highly coupled** with all other parts of the design, requiring extensive analysis.	Develop robust analysis tool including Numerical Propulsion System Sim (NPSS) cycle analysis and custom-built duct loss sizing tool to verify weight and performance.
2. It is **extremely difficult** to estimate the weight using classical regression methods due to a lack of comparable systems.	Construct parametric CAD model to rapidly evaluate weight changes to ensure model is converged.
3. Complex flow patterns over the fuselage and control surfaces can result in **degraded performance** and must be examined.	Leverage Computational Fluid Dynamics (CFD) tools such as RotCFD and ANSYS Fluent to validate aerodynamic performance.
4. A **large, un-commanded positive pitching moment** during transition caused X-50 to depart controlled flight.	Analyze ability of unique technology (ACHEON coanda nozzle) to provide pitch control during transition region.
5. It would be necessary to develop a **robust control logic** to ensure controllability over the course of takeoff and landing, forward flight, and most importantly, transition.	Use FlightLab and custom MATLAB scripts to verify that the vehicle is stable over all regions of flight.

Performance Engineering



Mission Profile

Perf Conditions

Sizing and Performance Environment

NDARC (NASA Design and Analysis for Rotorcraft):

- Supplemented by methods from Hiller, Mattingly, and Leischman [ref]

Aerodynamics Tools:

- Xfoil, RotCFD, Matlab-Scripts

Aeromechanics Tools:

- RCAS (Rotorcraft Comprehensive Analysis System)

Propulsion System Tools:

- NPSS,Duct-sizing Tool

Sized Vehicle

Performance Analysis

NDARC XFOIL npss SukraHelitek ART

The team created an **integrated design environment** to fully capture the complexity of the vehicle. NASA's Design and Analysis for Rotorcraft (NDARC) tool provided a bundled, physics-based tool to integrate other analyses provided by RotCFD, Xfoil, NPSS, and other custom built tools. This allowed the team to rapidly update the model and test new technologies. It is believed that the use of NDARC's powerful engine to simulate a reaction drive stopped rotor is a **first in VSTOL aircraft design.**

Performance Improvement:

Early on in the design process, it was realized that significant performance gains could be made through the use of zero-net-mass-flux jets on the fuselage and synthetic jets on the canard and tail. These devices help to keep flow attached, reducing drag and increasing lift by up to 15%.

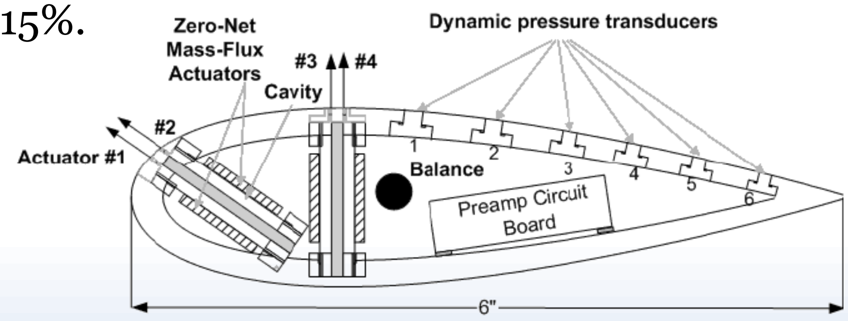
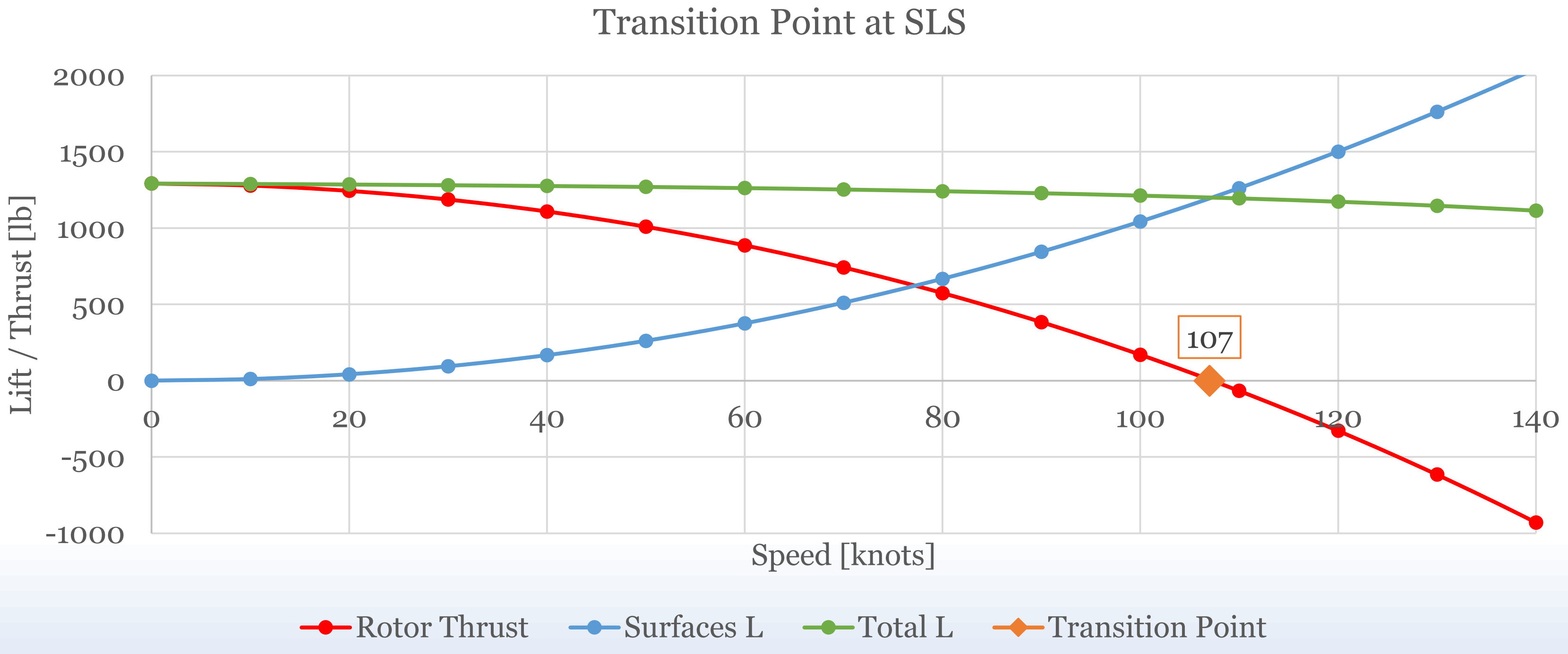


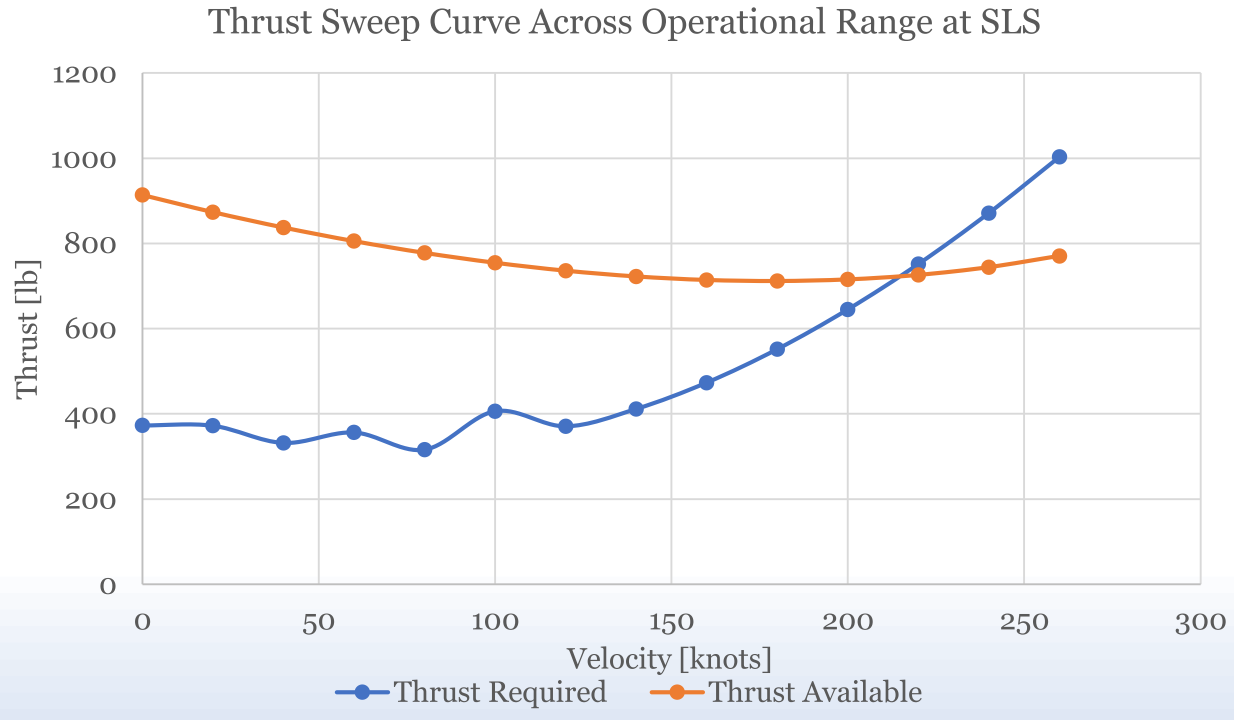
Image from **"Adaptive Control of Post-Stall Separated Flow Application to Heavy Vehicles"** by Cattafesta, Tian, and Mittal.

Mission Analysis and Performance Charts

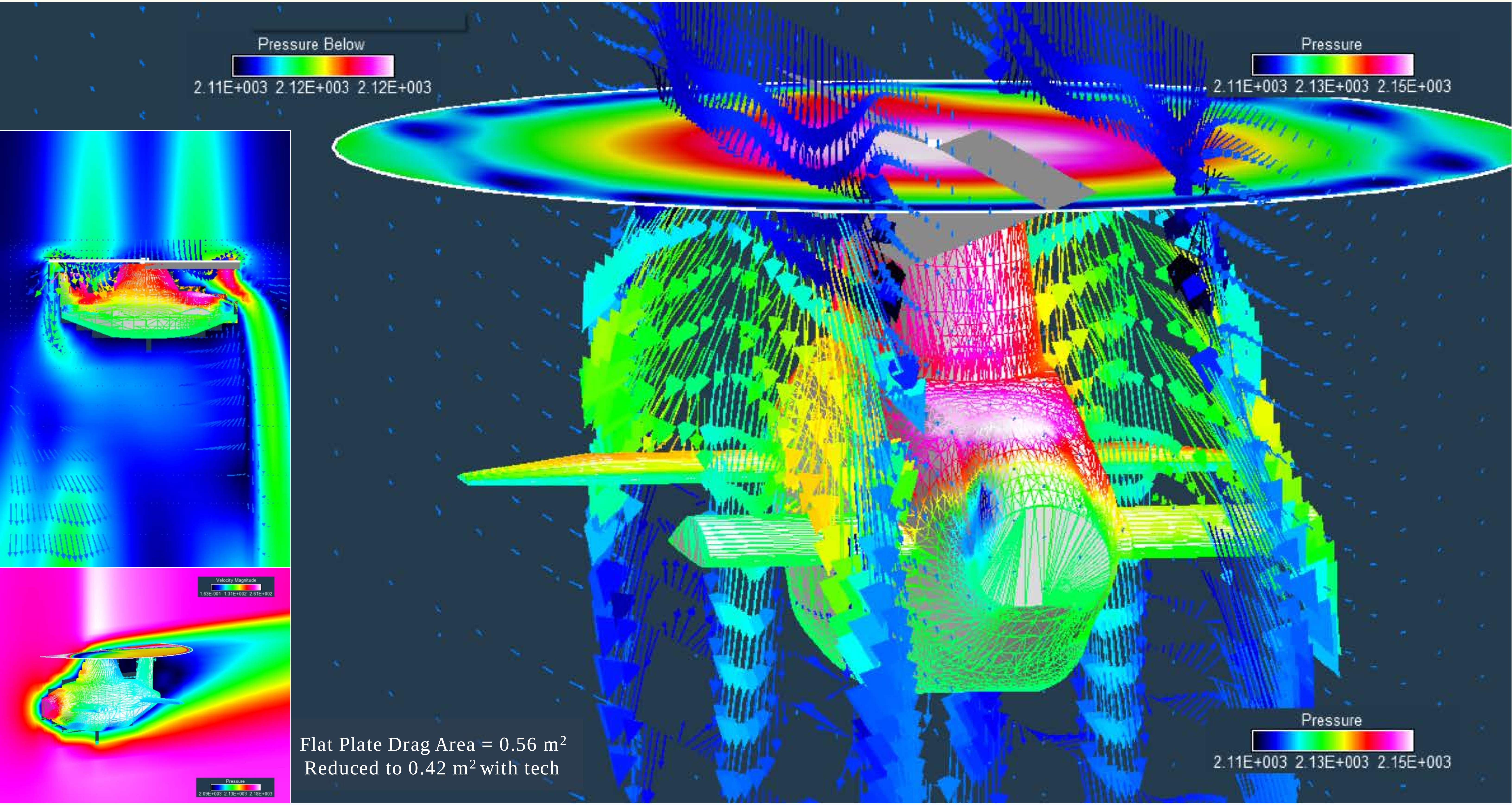
Knightflyer

Segment		Kind	Length (min/nm)	Speed (knots)	ROC (ft/min)	Altitude (ft)	Temp (deg F)	Weight (lb)	Rotor power required [hp]	Rotor thrust required [lb]	Exhaust thrust required [lb]	Engine power level	TSFC [lb/lb-hr]	Fuel burned [lb]	Energy Consumed [MJ]	L/D	D/q [ft^2]
1	Warm-up	Time	5.00	0	0	4000	95	1350	222.1	214.3	0	49%	0.593	10.6	206	0	0
2	Vertical Climb Out of city	Time	2.00	20	530	4000	95	1339.4	235.3	227.0	10.4	55%	0.569	4.6	89	5.51	7.02
3	Hover	Time	0.50	0	0	6000	95	1334.8	229.3	221.3	0	53%	0.593	1.1	21	0	0
4	Transition to forward flight mode	Distance	5.0	82.34*	0	6000	95	1333.7	20.0	18.0	616.9	100%	0.3959	15.2.	295	2.01	18.0
5	Climb to operating altitude	Climb (time)	10.00	120	531	6000	95	1318.5	0	0	417.2	71%	0.439	25.7	500	3.0	8.22
6	Dash to operational zone	Distance	50.0	206	0	10000	95	1292.8	0	0	492.0	100%	0.617	76.3	1481	2.46	4.92
7	Loiter at best endurance	time	25.00	104	0	10000	95	1216.5	0	0	252.6	49%	0.434	48.7	945	4.5	8.75
8	Cruise at best range	distance	50.0	155	0	10000	95	1167.8	0	0	345.4	70%	0.508	59.4	1153	3.2	6.18
9	Descend	Climb (time)	20.00	100	-250	10000	95	1108.4	0	0	286.9	44%	0.429	13.2	257	3.7	10.05
10	Transition to helicopter mode	Distance	5.0	82.34*	0	6000	95	1095.2	20.0	18.0	616.9	100%	0.3959	15.2	295	2.01	18.0
11	Vertical descent to land	Time	5.00	10	-200	6000	95	1080.0	161.0	155.5	0	36%	0.593	10.0	149	5.51	0
12	Shut-Off	Time	5.00	0	0	4000	95	1070.0	100..0	95.0	0	22%	0.593	10.6	206	0	0


Transition Point at SLS


Thrust Sweep Curve Across Operational Range at SLS

Verifying performance with CFD



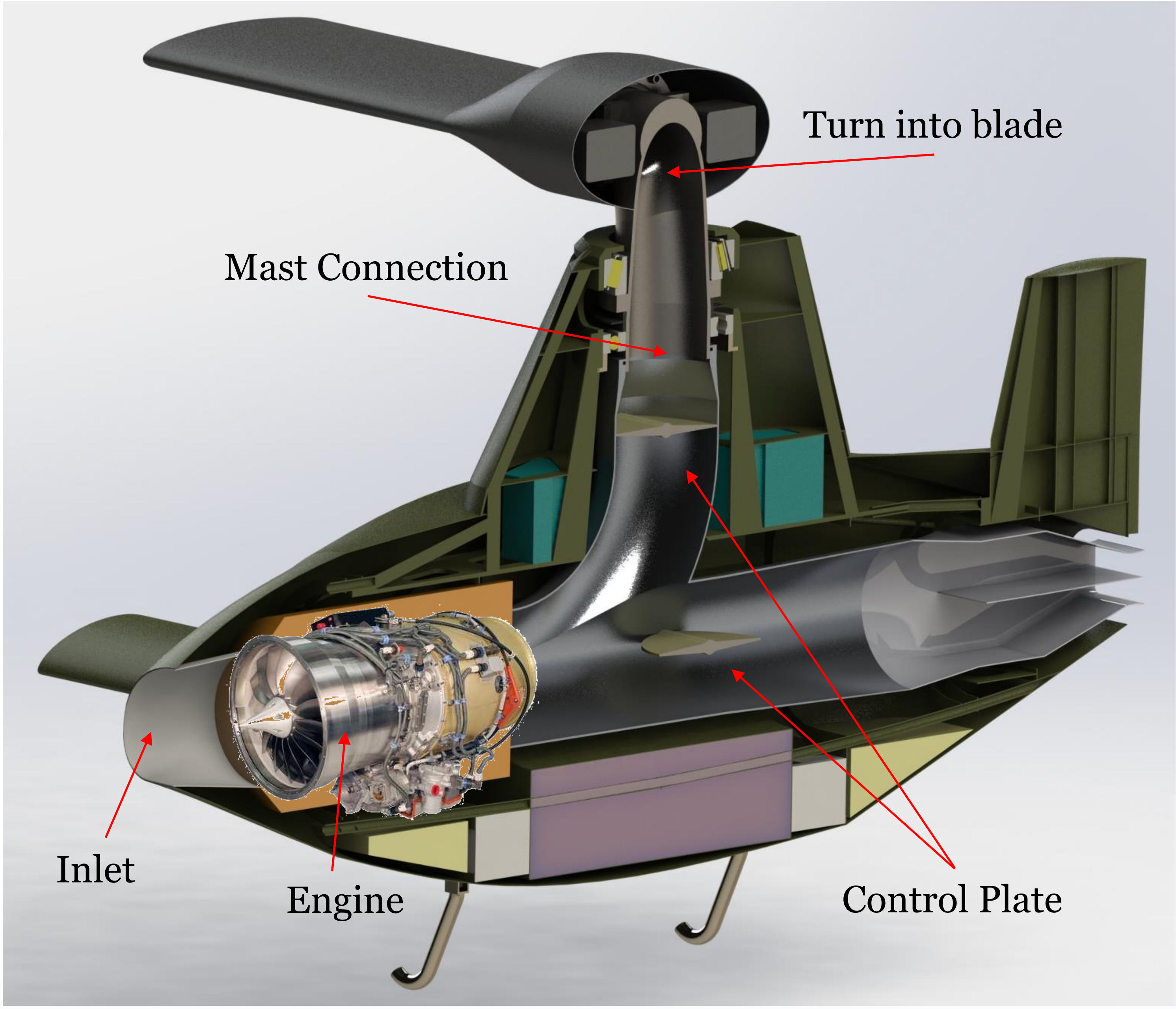
Flat Plate Drag Area = 0.56 m^2
Reduced to 0.42 m^2 with tech

Rotor downwash analyzed to determine **rotor performance** and **control surface authority.** Analysis conducted in both hover and transition states. Determining how the downwash angle would change was extremely important for **scheduling** the control surface movement during transition. In order to validate the vehicle's **forward flight performance** and measure the flat plate drag area, a number of simulations were run with the vehicle in a forward flight configuration.

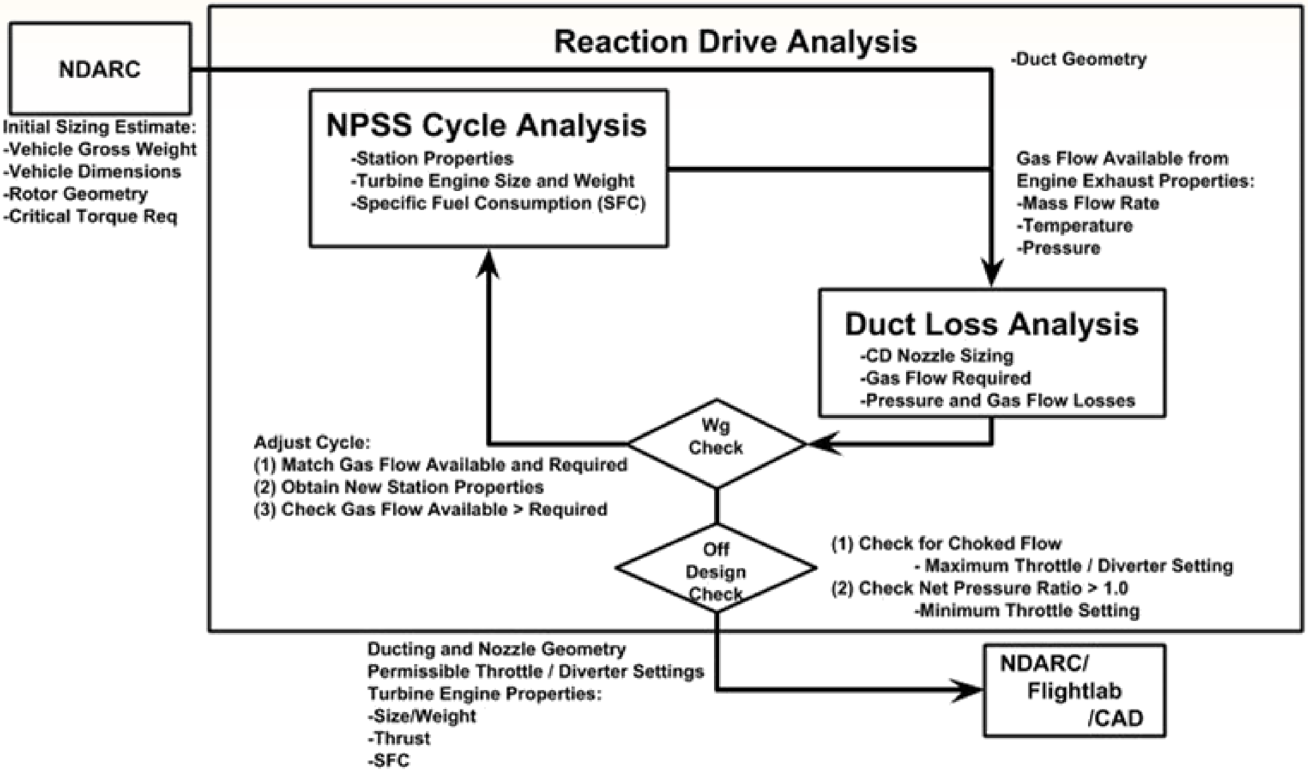
Propulsion System Design

Propulsion Overview:

The key feature of the Knightflyer is a unique reaction drive propulsion system that, through the use of control plates, can toggle between forward and vertical flight modes. This allows the vehicle to both hover and achieve high forward flight speeds, the key advantage of this vehicle.



Propulsion System Design Logic



NDARC

Initial Sizing Estimate:
-Vehicle Gross Weight
-Vehicle Dimensions
-Rotor Geometry
-Critical Torque Req

Reaction Drive Analysis

-Duct Geometry

NPSS Cycle Analysis
-Station Properties
-Turbine Engine Size and Weight
-Specific Fuel Consumption (SFC)

Gas Flow Available from Engine Exhaust Properties:
-Mass Flow Rate
-Temperature
-Pressure

Duct Loss Analysis
-CD Nozzle Sizing
-Gas Flow Required
-Pressure and Gas Flow Losses

Wg Check

Adjust Cycle:
(1) Match Gas Flow Available and Required
(2) Obtain New Station Properties
(3) Check Gas Flow Available > Required

Off Design Check

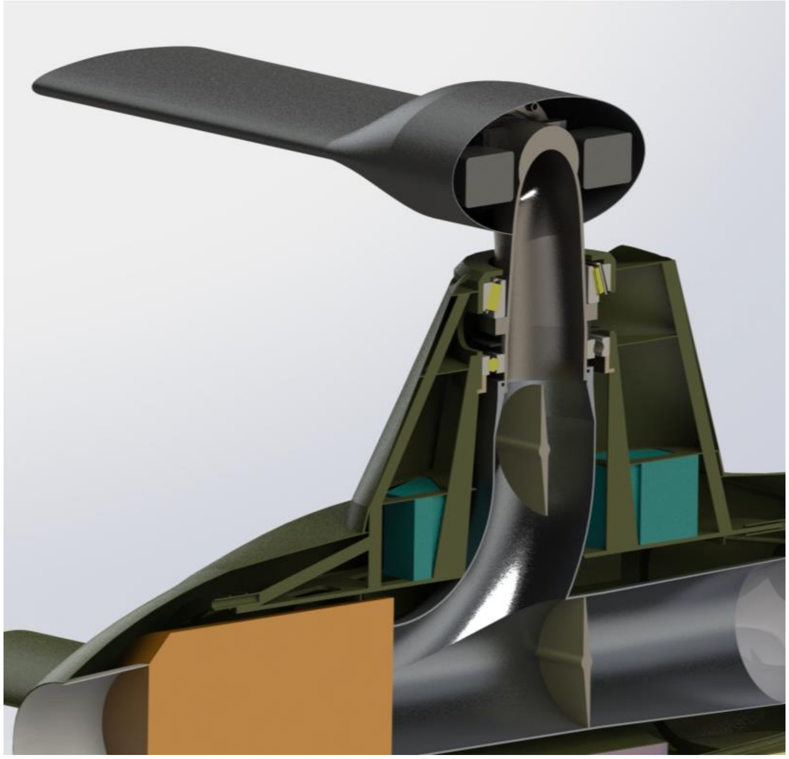
(1) Check for Choked Flow
- Maximum Throttle / Diverter Setting
(2) Check Net Pressure Ratio > 1.0
-Minimum Throttle Setting

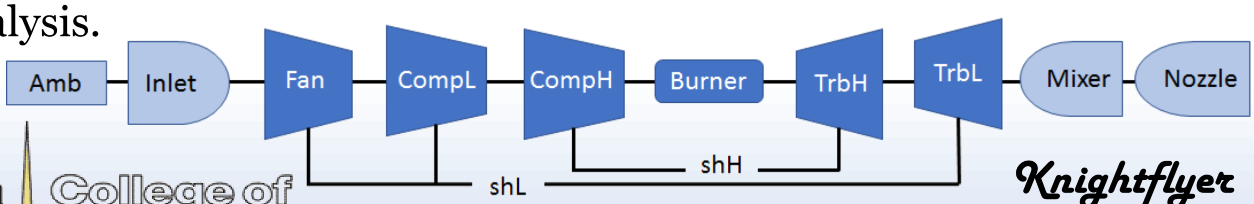
Ducting and Nozzle Geometry
Permissible Throttle / Diverter Settings
Turbine Engine Properties:
-Size/Weight
-Thrust
-SFC

NDARC/ Flightlab /CAD

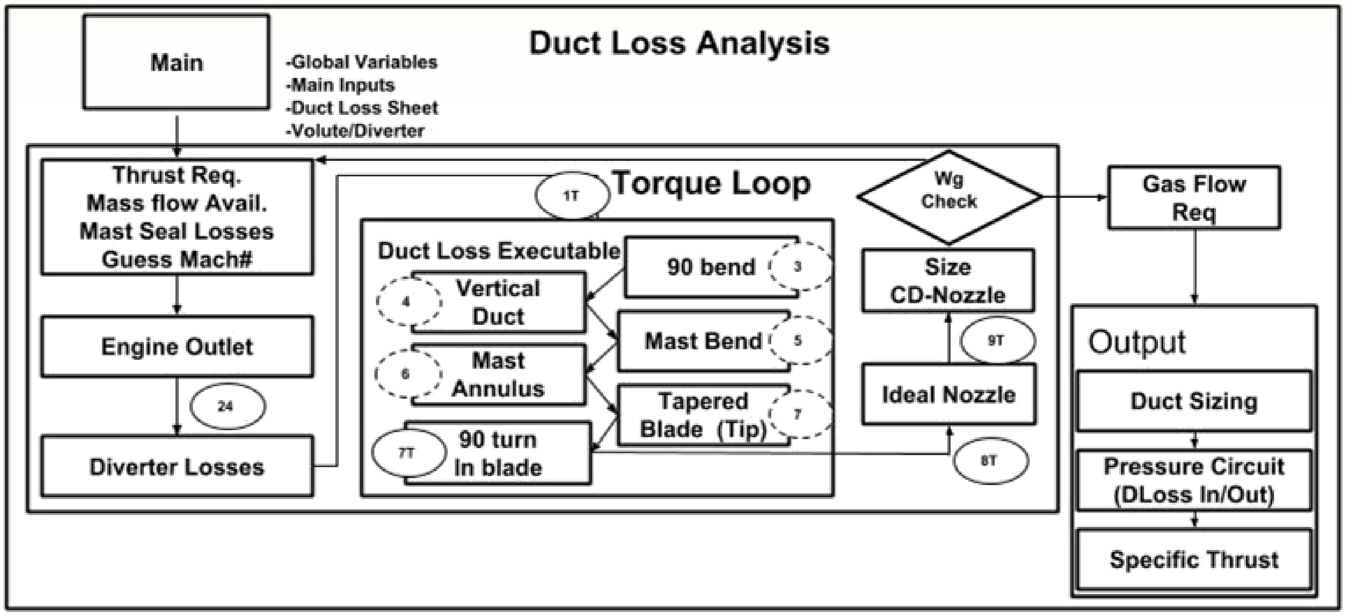
Turbofan station properties directly influence ducted flow. This required an iteration between NPSS cycle analysis and duct loss analysis:

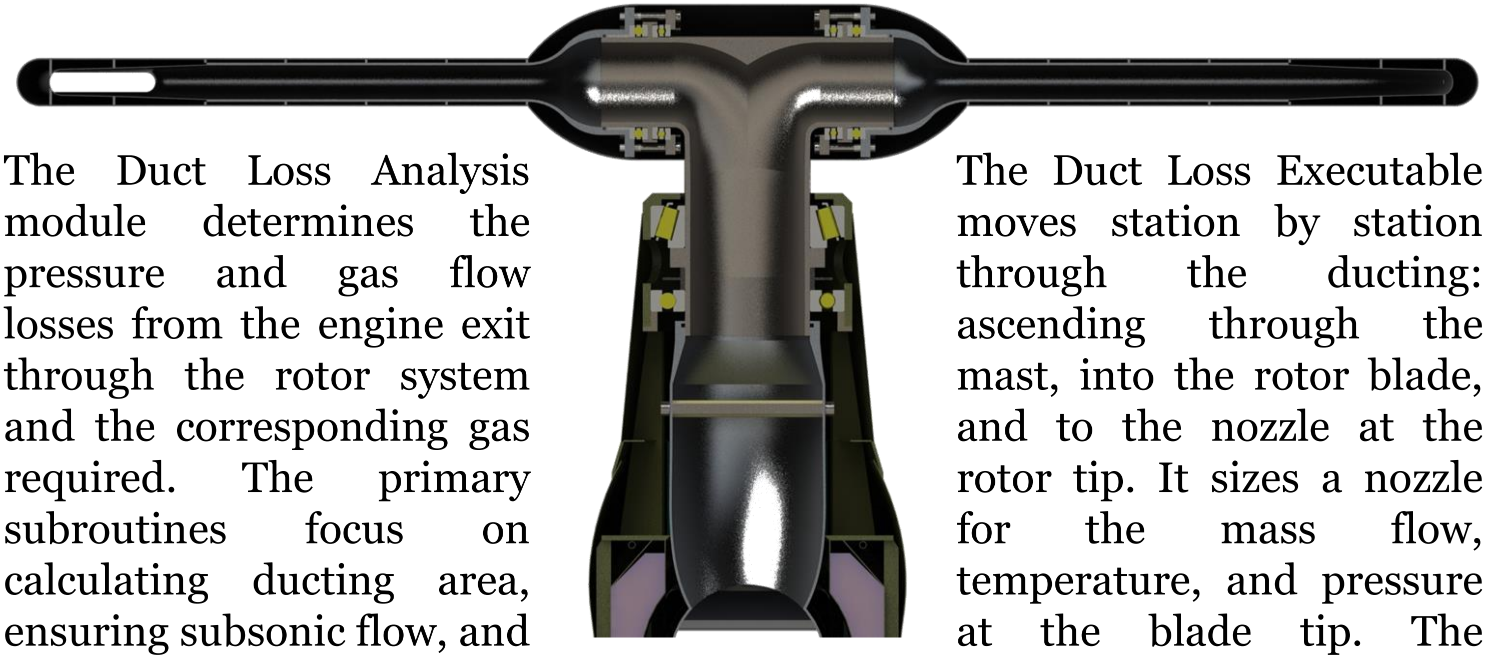
1. Obtain size estimate through NDARC and other tools.
2. Analyze duct losses for initial NPSS station properties.
3. Check engine gas flow matches requirements.
4. If yes, perform off-design analysis. If no, refine NPSS cycle or duct design.
5. Use converged properties in NDARC for more detailed analysis.





Duct Loss Analysis

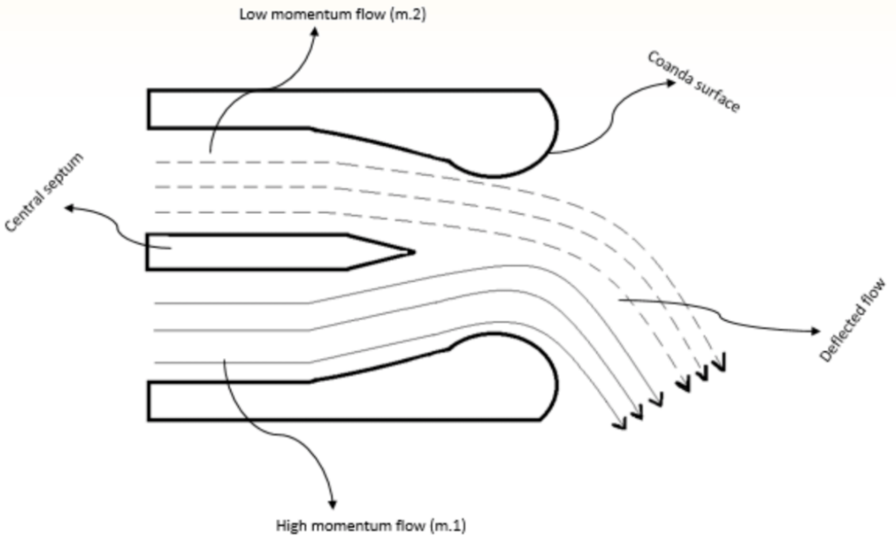




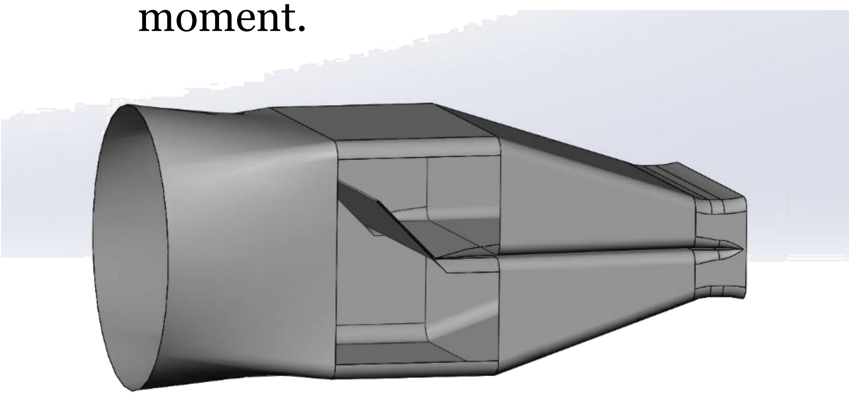
The Duct Loss Analysis module determines the pressure and gas flow losses from the engine exit through the rotor system and the corresponding gas required. The primary subroutines focus on calculating ducting area, ensuring subsonic flow, and calculating pressure losses due to bends and friction. The code was modified specifically for this application from work done at Georgia Tech.

The Duct Loss Executable moves station by station through the ducting: ascending through the mast, into the rotor blade, and to the nozzle at the rotor tip. It sizes a nozzle for the mass flow, temperature, and pressure at the blade tip. The calculated gas flow required becomes a primary output along with the pressure and temperature losses at each station.

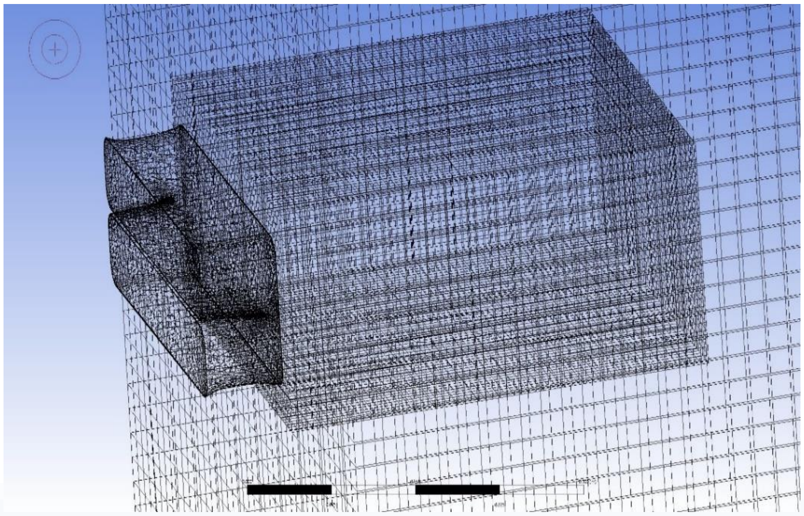
Coanda-Effect Nozzle

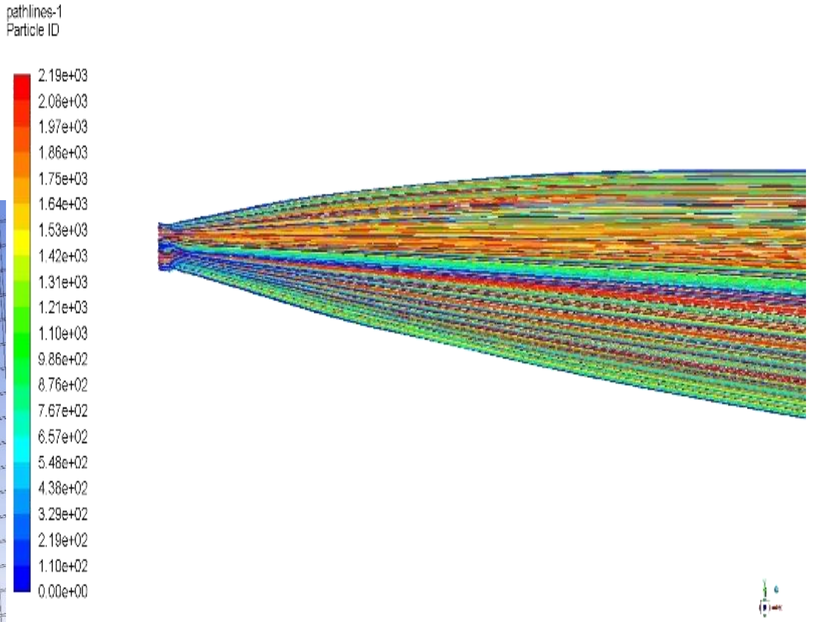


The failure of the X-50 showed that **pitch control at low speeds** and during transition was a major challenge. To overcome this, the team developed a **Aerial Coanda High-Efficiency Orienting Jet Nozzle** (ACHEON). This nozzle allows the vehicle to **vector thrust** and create both a force at the tail and a corresponding vehicle moment.



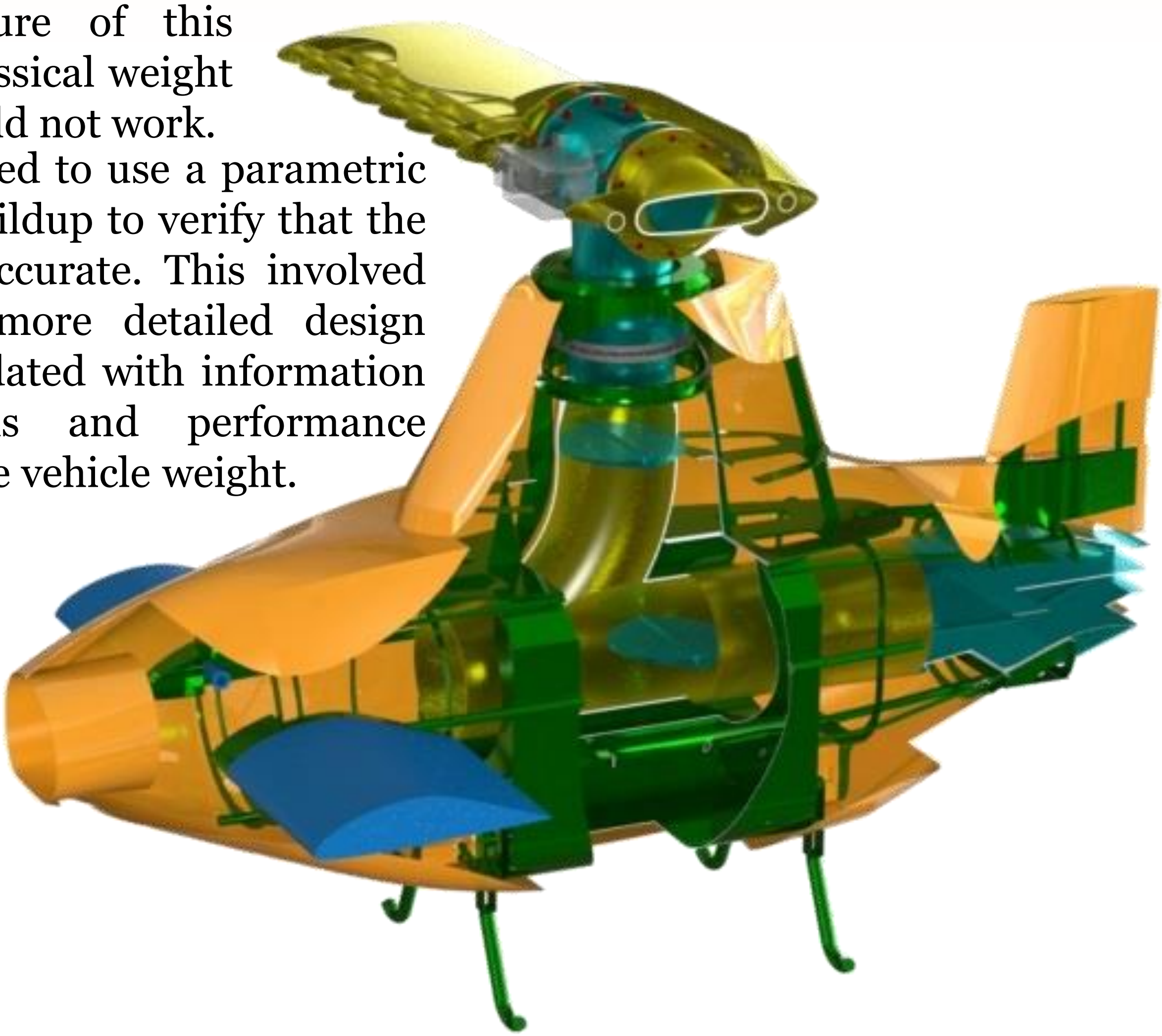
Extensive work on the nozzle design proved that this concept would work for the Knightflyer. Controls analysis showed that, due to the large moment arm, only around **100N** of force would be needed to maintain pitch control. This was verified through CFD, as shown below. This small vertical thrust component reduces losses and helps the vehicle to transition under control.





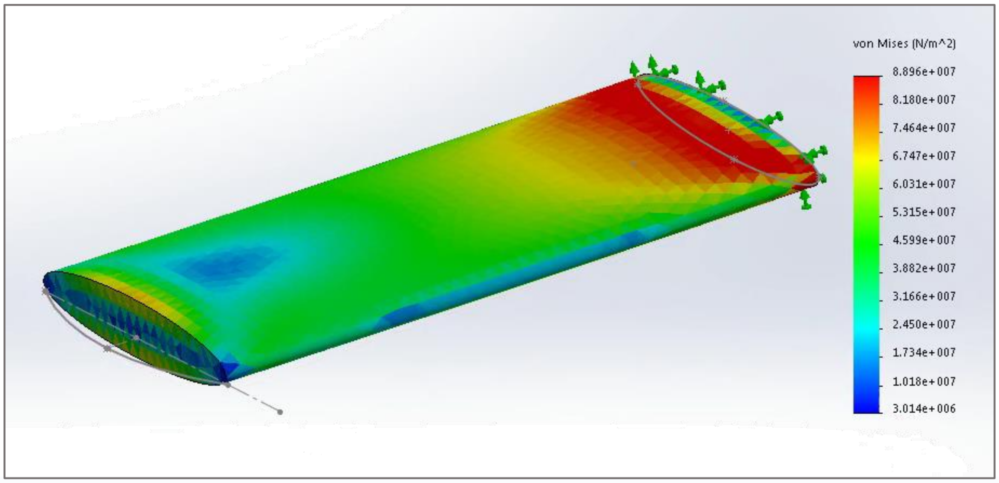
Parametric CAD and Structural Analysis

The innovative nature of this design meant that classical weight buildup methods would not work. Instead, the team opted to use a parametric CAD-based weight buildup to verify that the vehicle weight was accurate. This involved using progressively more detailed design models that were updated with information from other systems and performance analysis to validate the vehicle weight.



Material
Magnesium Alloy
Aluminum Alloy
Titanium Alloy
Carbon Fiber
Light Weight Plastic
Stainless Steel

The structure was analyzed in SolidWorks to verify that the material and design choices would result in a functioning vehicle. At all times, the vehicle exhibited satisfactory stress and displacement metrics.

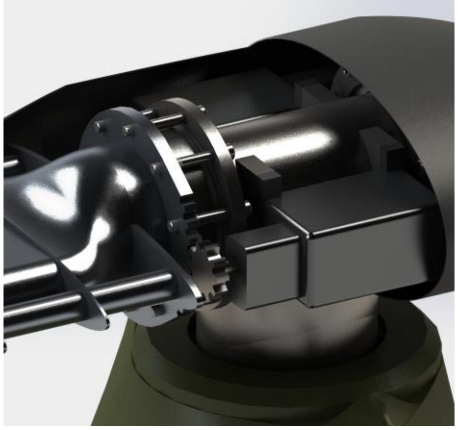


Controls and Transition

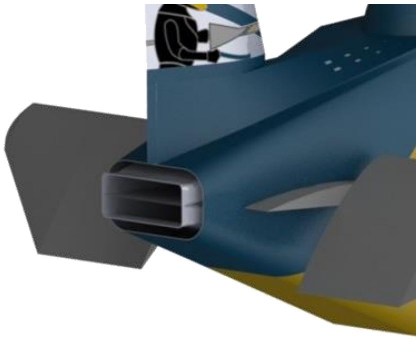
Controls:

The controllability of the vehicle was a major design concern throughout the process. Fortunately, the unique design of the vehicle provided the team with numerous control options, resulting in a very controllable design.

1: Differential tail and canard deflection provides pitch and roll authority during the hover phase. Once transitioned, these control surfaces fill their traditional role of aileron and elevator.



2: Individual blade control gives the vehicle cyclic authority just through the rotor. This allows for additional control authority which is especially important at low speeds or at low rotor power settings.



3: Lastly, the ACHEON nozzle gives the vehicle additional pitch control at low speeds and throughout the transition process, the most dangerous part of flight and the Boeing X-50's downfall.

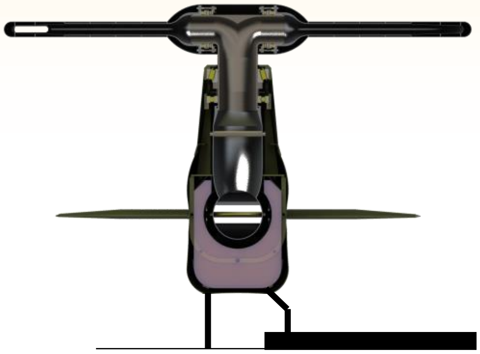
Transition:

1: In Hover Mode, the canard and tail are deflected upwards to minimize inference with the rotor downwash. Differential canard deflection provides additional yaw and roll capability.

2: As the vehicle begins to accelerate into forward flight, the canard and tail are scheduled to start pitching down to a) maintain alignment with downwash and b) begin providing lift so the rotor can be unloaded (and ultimately stopped)

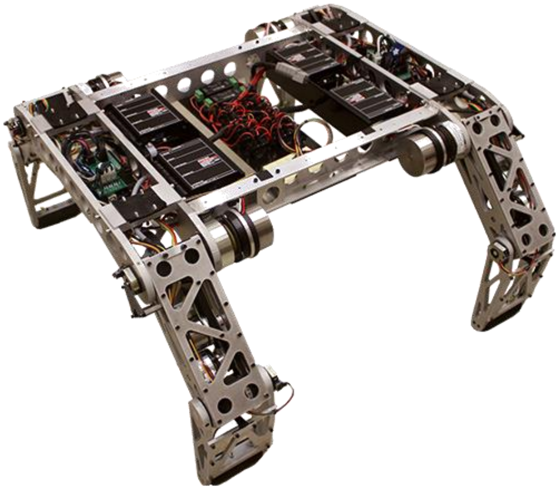
3: At around 110 knots, the rotor is fully stopped and the vehicle flies as an airplane. To transition back to hover mode, the reverse process is conducted.

Other Technology Highlights



Landing Gear

Given the vehicle's city operating environment, the team felt that an advanced landing gear option (developed at Georgia Tech) would allow for increased capability and safety.



This robotic landing gear system allows a vehicle to land on uneven terrain typical of cities and building tops. This only further expands a VTOL aircraft's utility. Studies have shown a reduction in risk of damage by up to **5x** and takeoffs and landings on slopes of up to **20 degrees.**

Sensor Suite

It is envisioned that the Knightflyer will primarily operate as a surveillance aircraft. As a result, the team equipped the aircraft with LiDAR, radar, and an electro-optical/infrared sensor package. This is necessary not only for surveillance, but also for its own autonomous operation in a congested city environment.

Ball Aerospace LIDAR Sensor Example

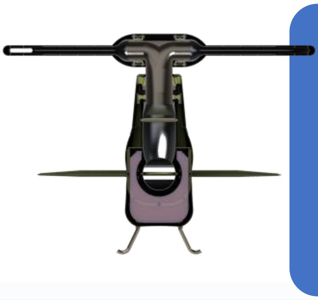
Summary

Explore

- Multiple vehicle variants were evaluated to determine fundamental tradeoffs and design choices
- Advanced technologies were studied to improve performance

Analyze

- The team created an integrated design environment using a premier rotorcraft design tool and other software suites
- A detailed propulsion and duct-loss program ensured the vehicle would be modelled accurately



Perform

- Top Speed (SLS) of 402 kph
- Hover endurance (SLS) 1.36 hours
- Range (3000m) of 264 km
- Flat plate drag area of 4.5 ft^2