KARFI

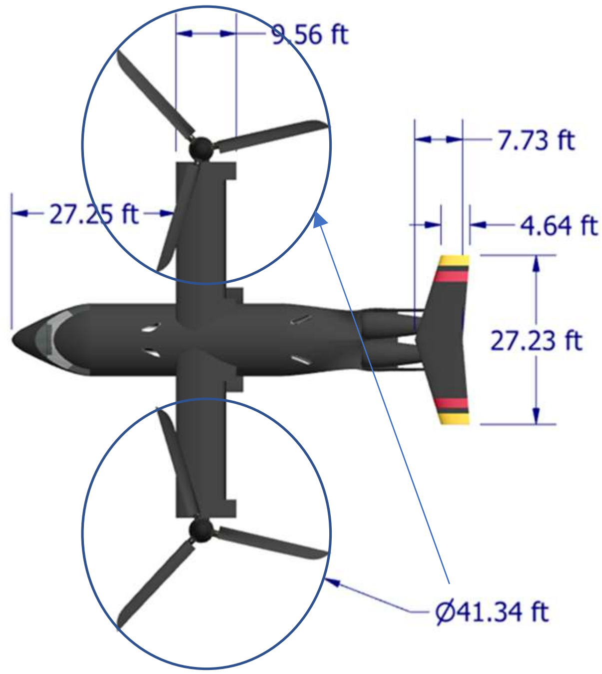
Executive Summary

Undergraduate Design Team
University of Maryland, College Park

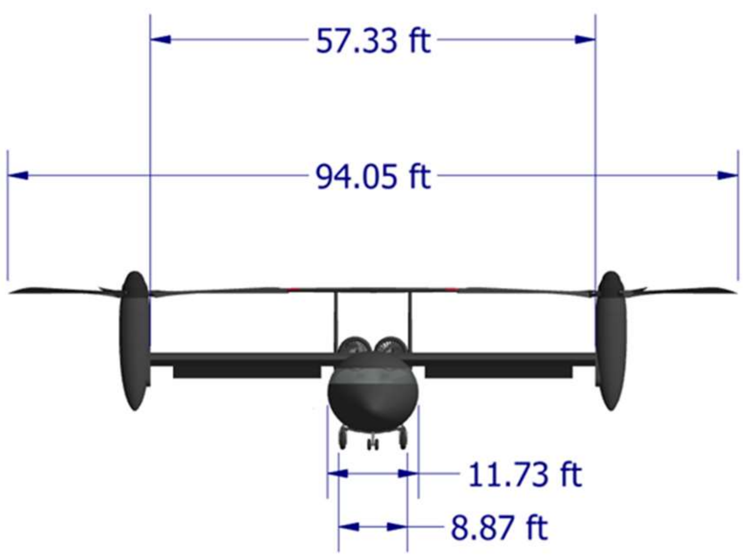
40th Annual Vertical Flight Society
Student Design Competition

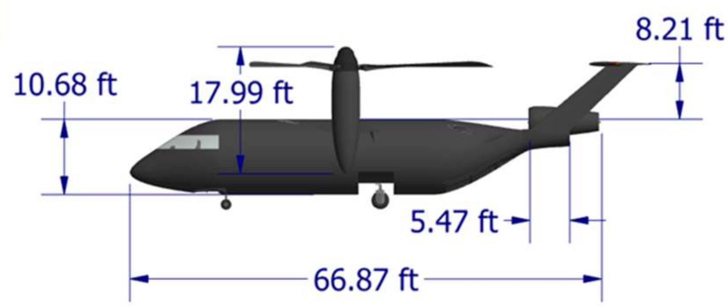
Sponsored By Sikorsky, a Lockheed Martin Company

External Dimensions



Footprint: 94.05 ft x 66.87 ft
(28.67 m x 20.38 m)





GTOW	**46,829 lb** (21,241 kg)
Empty Weight	**29,374 lb** (13,324 kg)
Payload	**5,000 lb** (2,268 kg)
Fuel Weight	**10,235 lb** (4643 kg)

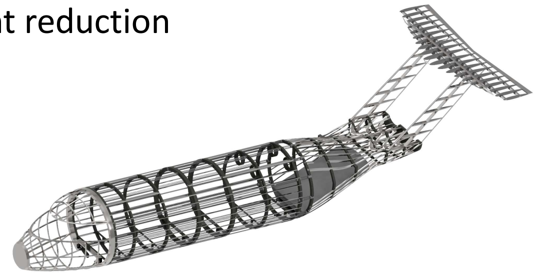
UNIVERSITY OF MARYLAND

KARFI

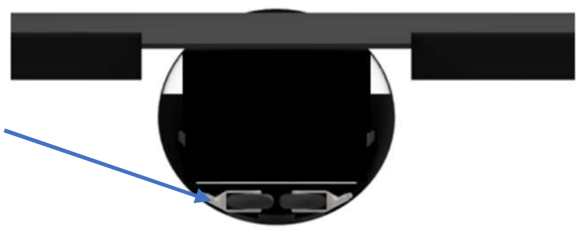
Key Features

17.9% t/c wing reduces drag in high-speed flight

Lightweight structure results in a 15% empty weight reduction

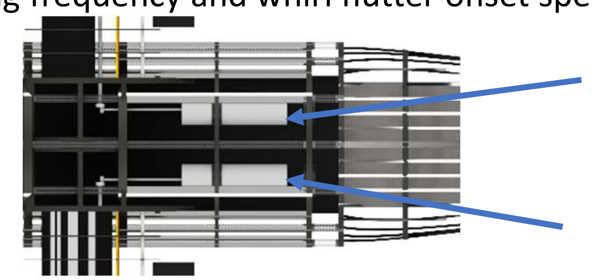


Retractable landing gear reduces drag without the need for sponsons for storage



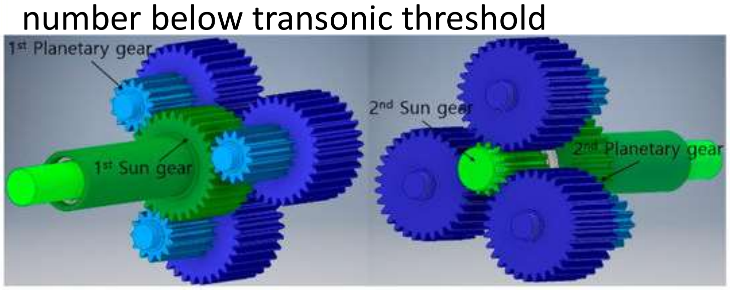
Rear loading ramp for easy cargo loading

Fuselage mounted turboshafts increase wing bending frequency and whirl flutter onset speed

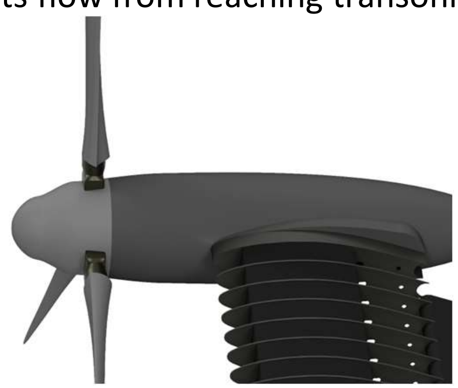


Turbofans integrated into Pi-tail reduce frontal area and increase thrust efficiency

Two-speed transmission keeps rotor tip Mach number below transonic threshold



Area-ruled nacelle modifies airflow and prevents flow from reaching transonic speeds



UNIVERSITY OF MARYLAND

KARFI

Threat Avoidance Highlights

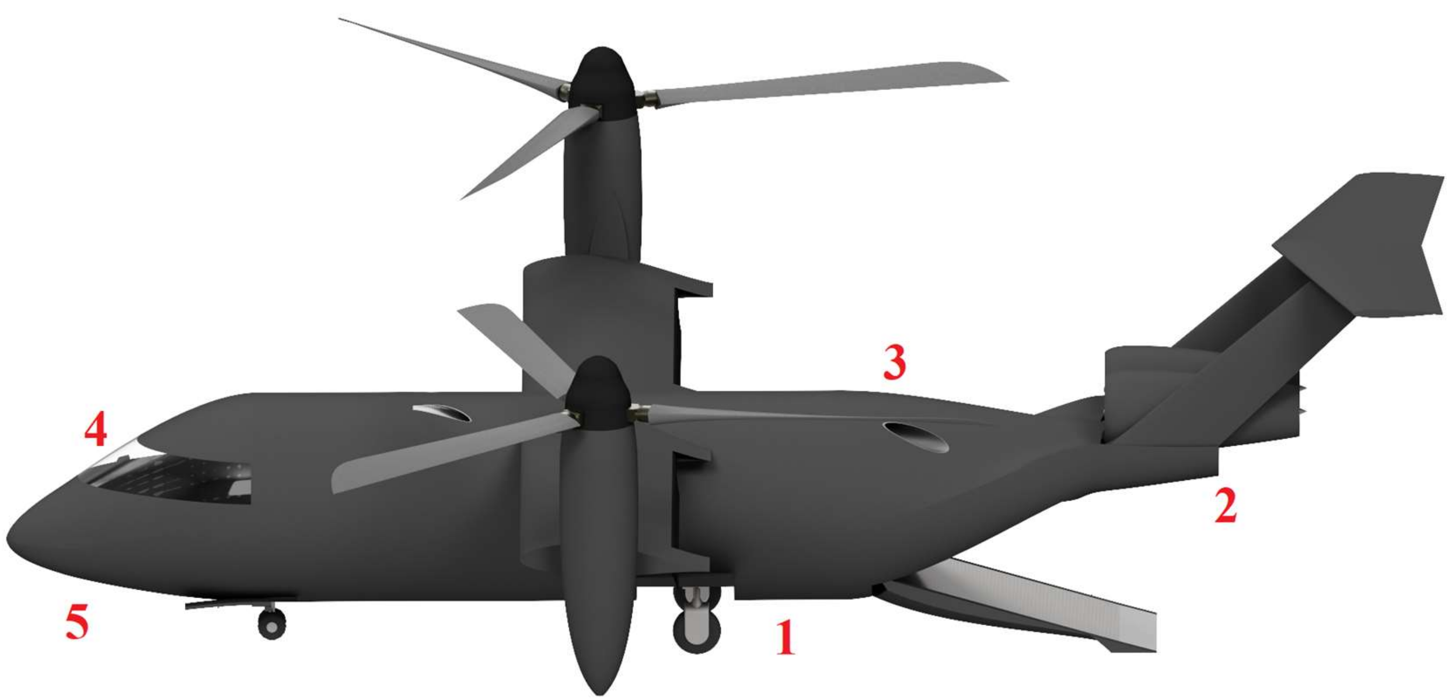
1. Countermeasures disperser system (CMDS): disperses counter measures (flares, chuffs)

2. Directed infrared counter measure system (DIRCM): protects from IR guided missiles

3. Turboshaft infrared suppresser: masks IR heat signature of the turboshaft exhaust gases

4. Inertial navigation system (INS): provides navigation without relying on external signals and is immune to external interference

5. Terrain-following system: allows the aircraft to fly at very low altitudes in order to stay below radar detection



UNIVERSITY OF MARYLAND

KARFI

Introduction

The University of Maryland undergraduate design team presents *Karfi* as its solution to the Vertical Flight Society's 40th annual student design competition Request For Proposal (RFP). The RFP challenged the teams to design a high-speed vertical takeoff and landing (HSVTOL) cargo aircraft for use in highly contested environments and on unprepared landing surfaces. "*Karfi*" is the Norse word for a mid-sized cargo or troop ship. Just as the Vikings dominated the seas with their naval capabilities, *Karfi* will dominate the skies with its unprecedented combination of aerial abilities.

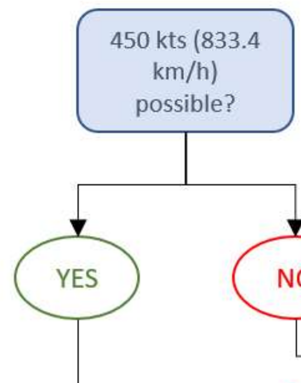
Karfi is a thrust-compounding tiltrotor design with a two-speed rotor transmission. The turboshaft engines were mounted in the fuselage to increase wing bending frequency and whirl flutter onset speed. The proprotors were designed for high Figure of Merit (FM) and turbofan engines are used to provide the bulk of the propulsive thrust in cruise. In forward flight, the proprotor RPM is reduced by a novel two-speed transmission to keep the rotor tip speed below the drag divergence Mach number. The turbofan engines are integrated into the empennage, with a design inspired by an Aurora Flight Sciences study. This has the result of reducing frontal drag area and ingesting the boundary layer of the fuselage, thus increasing thrust efficiency by 2-4%. The cabin houses a large cargo bay with a rear loading ramp for convenient loading and unloading of the payload. The fuselage structure was designed to handle the loads of a high-speed vehicle while minimizing aircraft weight. *Karfi*'s wings are thinner than a standard tilt rotor design, made possible by its graphite-epoxy composite torque box which provides the necessary strength and stiffness in flight. This configuration has allowed *Karfi* to accomplish the requirements set forth by the RFP with a disk loading of only 19.5 lb/ft ^{2} which allows operation in semi-prepared landing zones.

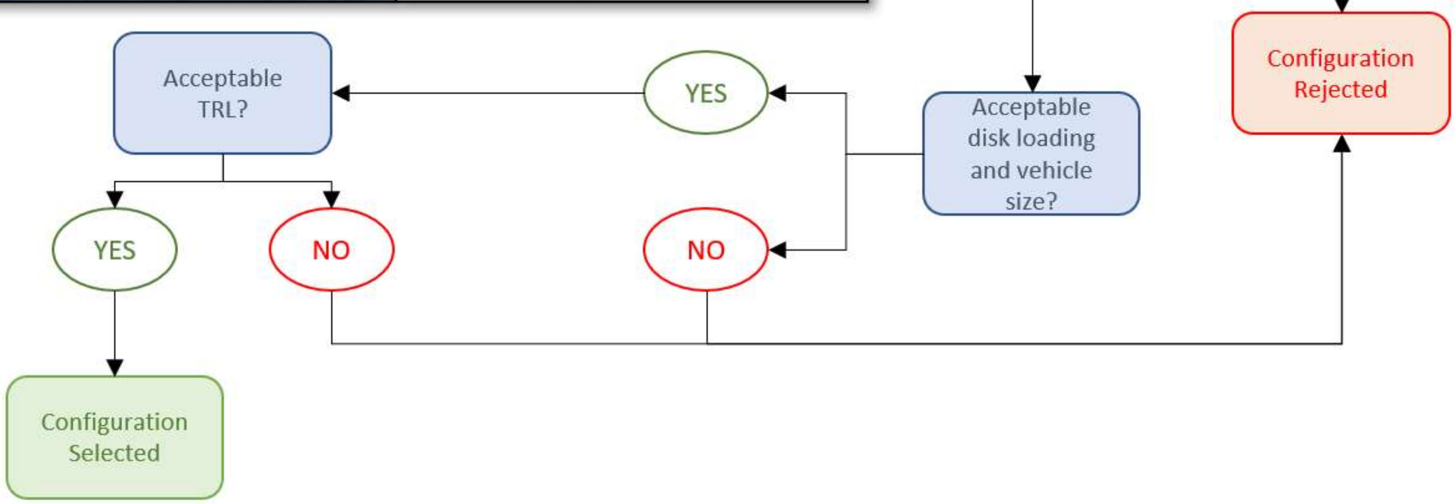
GTOW	**46,829 lb** (21,241 kg)
Empty Weight	**29,374 lb** (13,324 kg)
Payload	**5,000 lb** (2,268 kg)
Cruise Speed	**450 kts** (833.4 km/h)
Disk Loading	**19.5 lb/ft^2** (933.67 Pa)

UNIVERSITY OF MARYLAND

KARFI

Vehicle Configuration Selection





Final Selection: thrust-compounding tiltrotor with 2 speed transmission

- High TRL
- Mechanically simple
- Lower risk of component fatigue
- Relatively low disk loading
- Turboshaft thrust compounded with turbofan thrust in cruise

UNIVERSITY OF MARYLAND

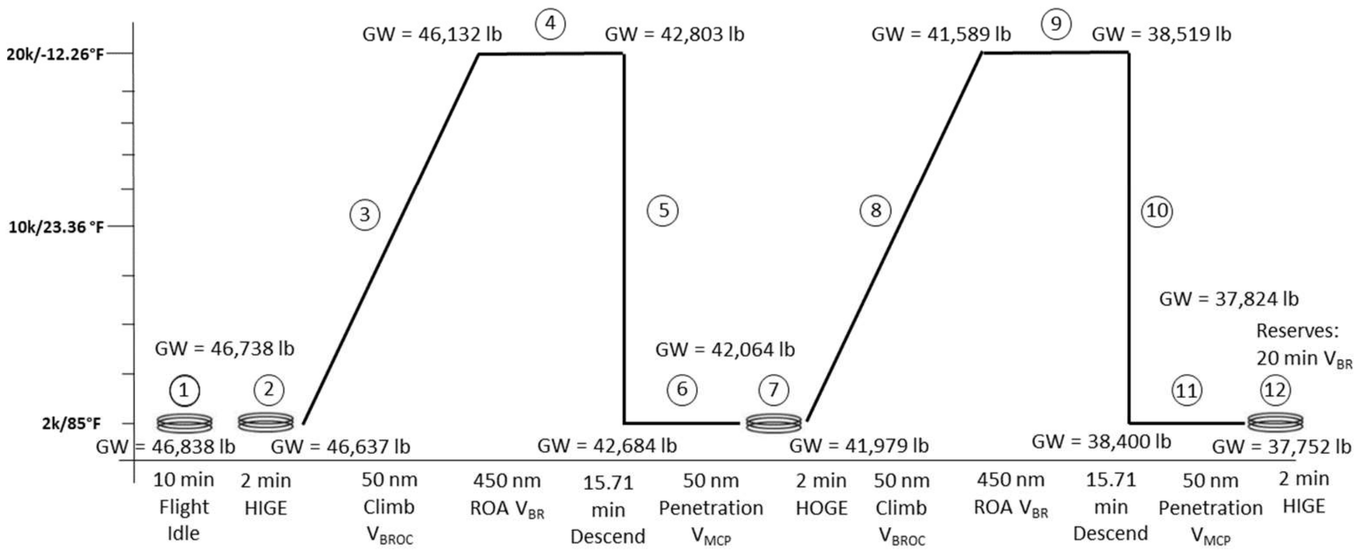
KARFI

Mission Profile

Karfi can carry a 5,000 lb payload over the mission profile shown below. *Karfi* finishes the mission with fuel reserves equivalent to 20 minutes of flight at best range speed (V_{BR}).

Takeoff Criteria

- 2k/85^{o}F
- HIGE Takeoff
- HOGE at Mid-Mission (MMGW)
- 90% Engine MRP, 100% Const. XMSN Torque



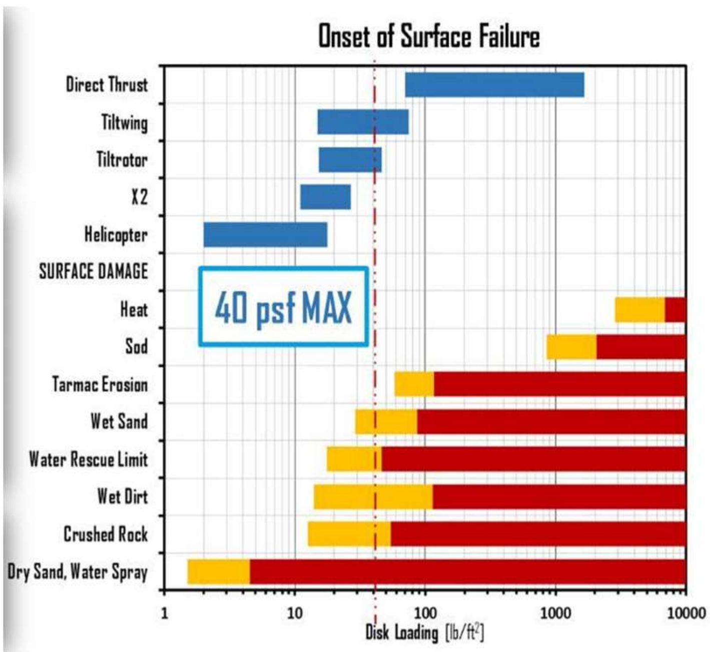
	Mission Segment											
Parameter	1	2	3	4	5	6	7	8	9	10	11	12
Airspeed **[kts]** (km/h)	-	-	**200** (370.4)	**450** (833.4)	**200** (370.4)	**450** (833.4)	-	**200** (370.4)	**450** (833.4)	**200** (370.4)	**450** (833.4)	-
Turboshaft Power Required **[hp]** (kW)	**776.7** (579.2)	**8,204** (6,118)	**4,435** (3,307)	**10,056** (7,499)	**652.3** (486.4)	**15,280** (11,394)	**6,890** (5,138)	**3,879** (2,893)	**9,268** (6,911)	**652.3** (486.4)	**14,180** (10,574)	**5,875** (4,380)
Turboshaft Available Required **[hp]** (kW)	**8,688** (6,479)	**8,688** (6,479)	**8,688** (6,479)	**5,324** (3,970)	**8,688** (6,479)	**8,688** (6,479)	**8,688** (6,479)	**8,688** (6,479)	**5,324** (3,970)	**8,688** (6,479)	**8,688** (6,479)	**8,688** (6,479)
Turboshaft SFC **[lb/hp-h]**	**0.682** (0.415)	**0.370** (0.225)	**0.367** (0.223)	**0.385** (0.234)	**0.697** (0.424)	**0.358** (0.218)	**0.370** (0.225)	**0.367** (0.223)	**0.385** (0.234)	**0.697** (0.424)	**0.358** (0.218)	**0.370** (0.225)
Turbofan Thrust Required **[lb]** (N)	-	-	-	**5,461** (24,292)	-	**8,016** (35,657)	-	-	**5,461** (24,292)	-	**8,016** (35,657)	-
Turbofan Thrust Available **[lb]** (N)	-	-	-	**8,526** (37,926)	-	**14,250** (63,387)	-	-	**8,526** (37,926)	-	**14,250** (63,387)	-
Turbofan TSFC **[lb/lb-h]** (kg/kN-h)	-	-	-	**0.51** (51.8)	-	**0.51** (51.8)	-	-	**0.51** (51.8)	-	**0.51** (51.8)	-
Specific Range **[nm/lb]** (km/kg)	-	-	-	**0.033** (0.135)	-	**0.021** (0.086)	-	-	**0.033** (0.135)	-	**0.021** (0.086)	-
Endurance **[hr]**	-	-	-	**2.71**	-	**1.61**	-	-	**2.71**	-	**1.61**	-

UNIVERSITY OF MARYLAND

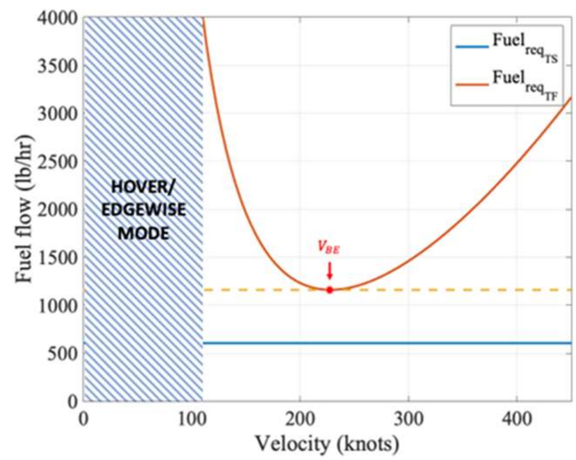
KARFI

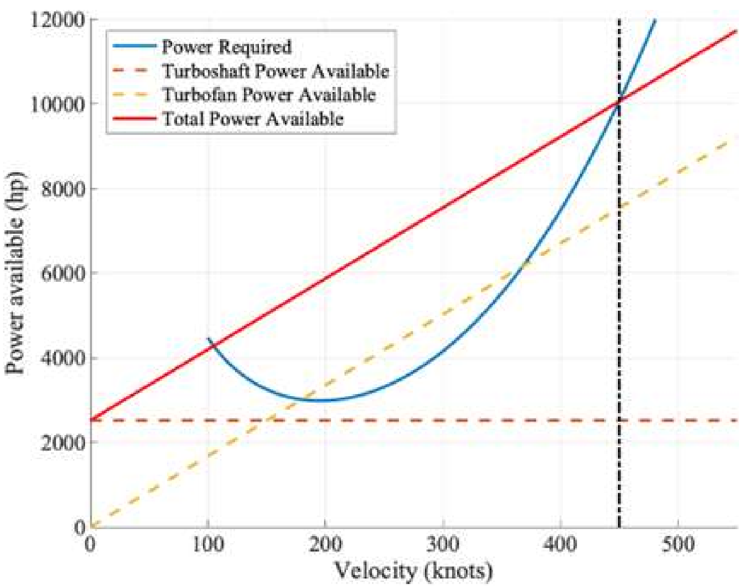
Vehicle Performance

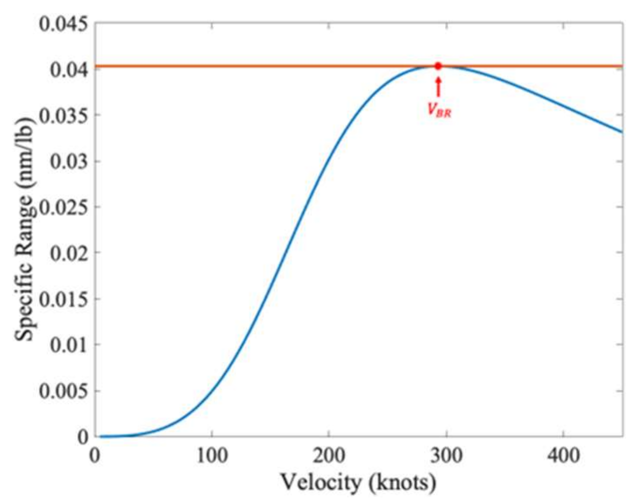
Karfi meets all the RFP mission requirements while maintaining a disk loading capable of landing on unprepared surfaces and performing water rescue missions.



V_{Cruise}	**450 kts** (833 km/h)
V_{Climb}	**200 kts** (370 km/h)
V_{BR}	**293 kts** (543 km/h)
V_{BE}	**227 kts** (421 km/h)
Disk Loading	**19.5 lb/ft²** (933.67 Pa)



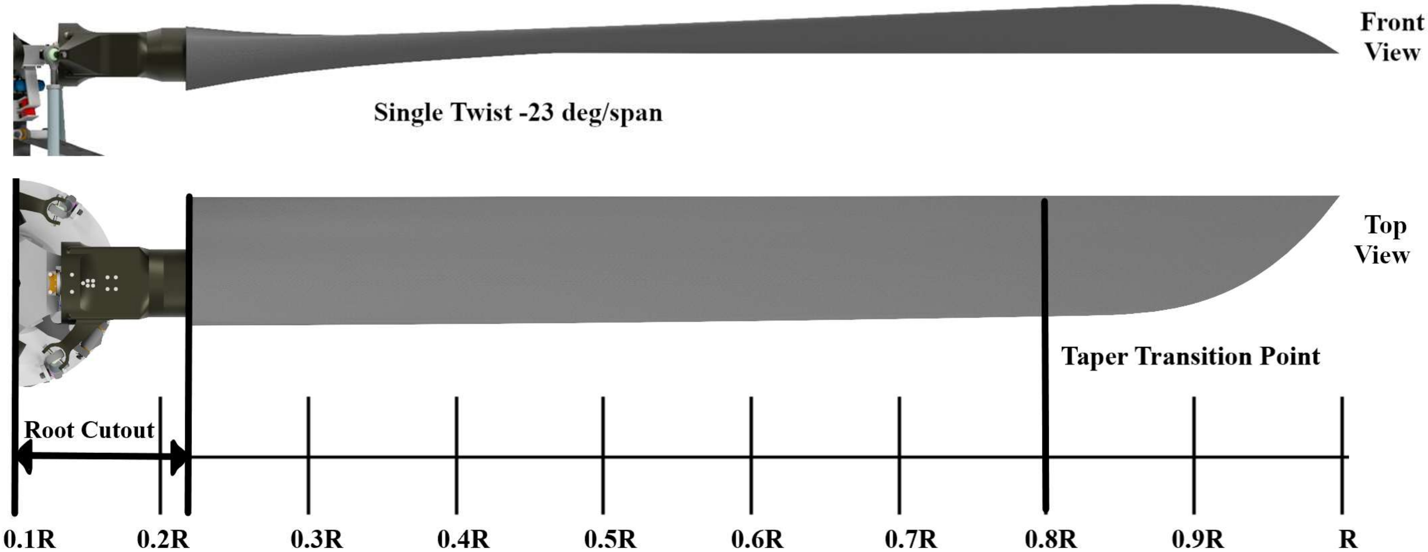




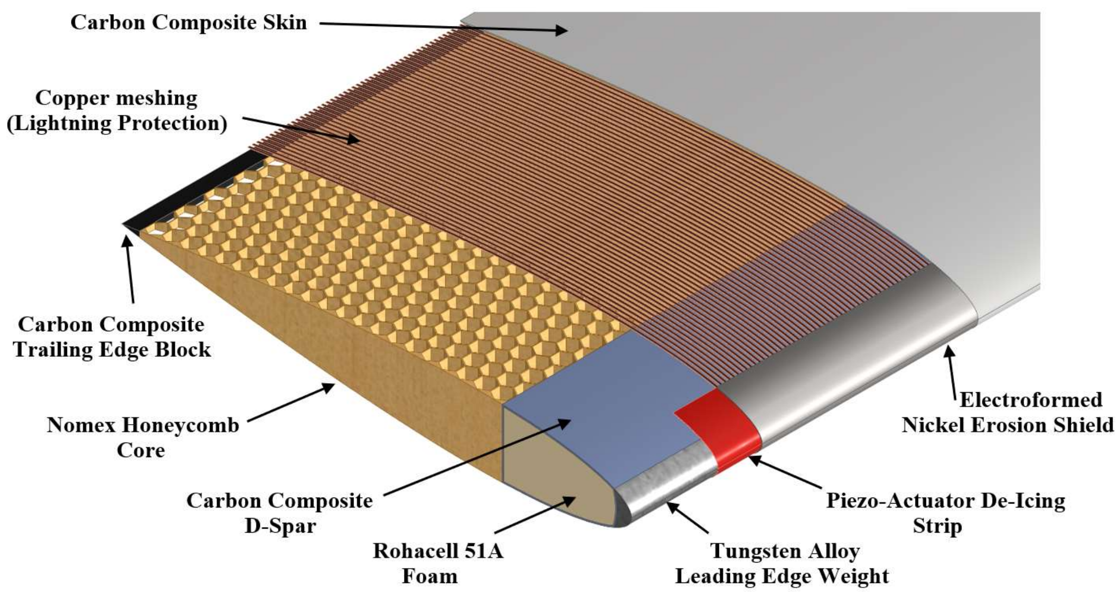
UNIVERSITY OF MARYLAND

KARFI

Main Rotor Blade Design



Airfoil	RC3-8
C_T/σ (Hover)	.1596
C_T/σ (Cruise)	.042
RPM (Hover)	346
RPM (Cruise)	170
FM (Hover)	.85
η_P (Cruise)	.51

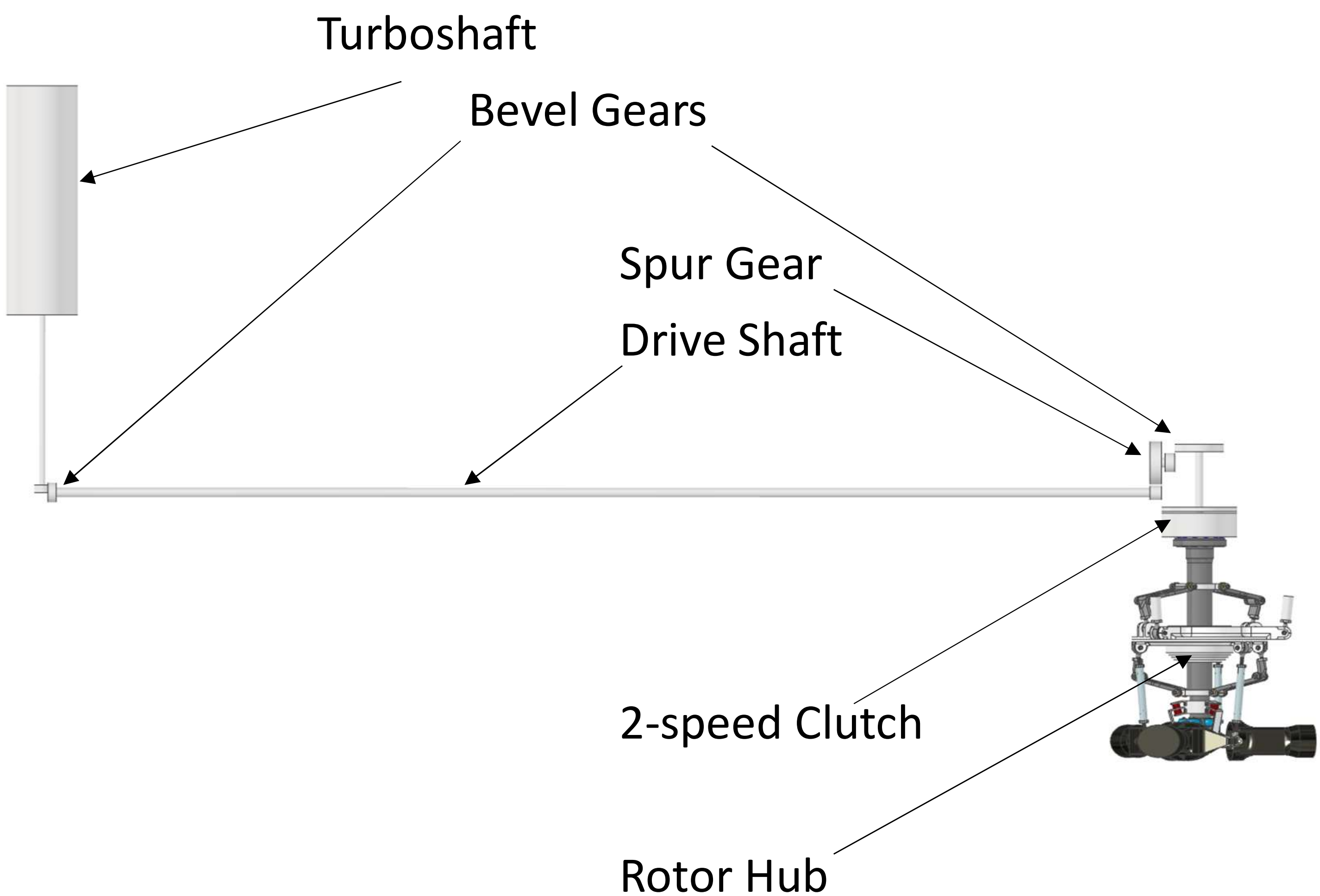


The proprotor blades were designed using Blade Element Momentum Theory (BEMT) and optimized for Figure of Merit. The rotor structure was designed for high stiffness to resist large flap deflection.

UNIVERSITY OF MARYLAND

KARFI

Dynamic System Schematic

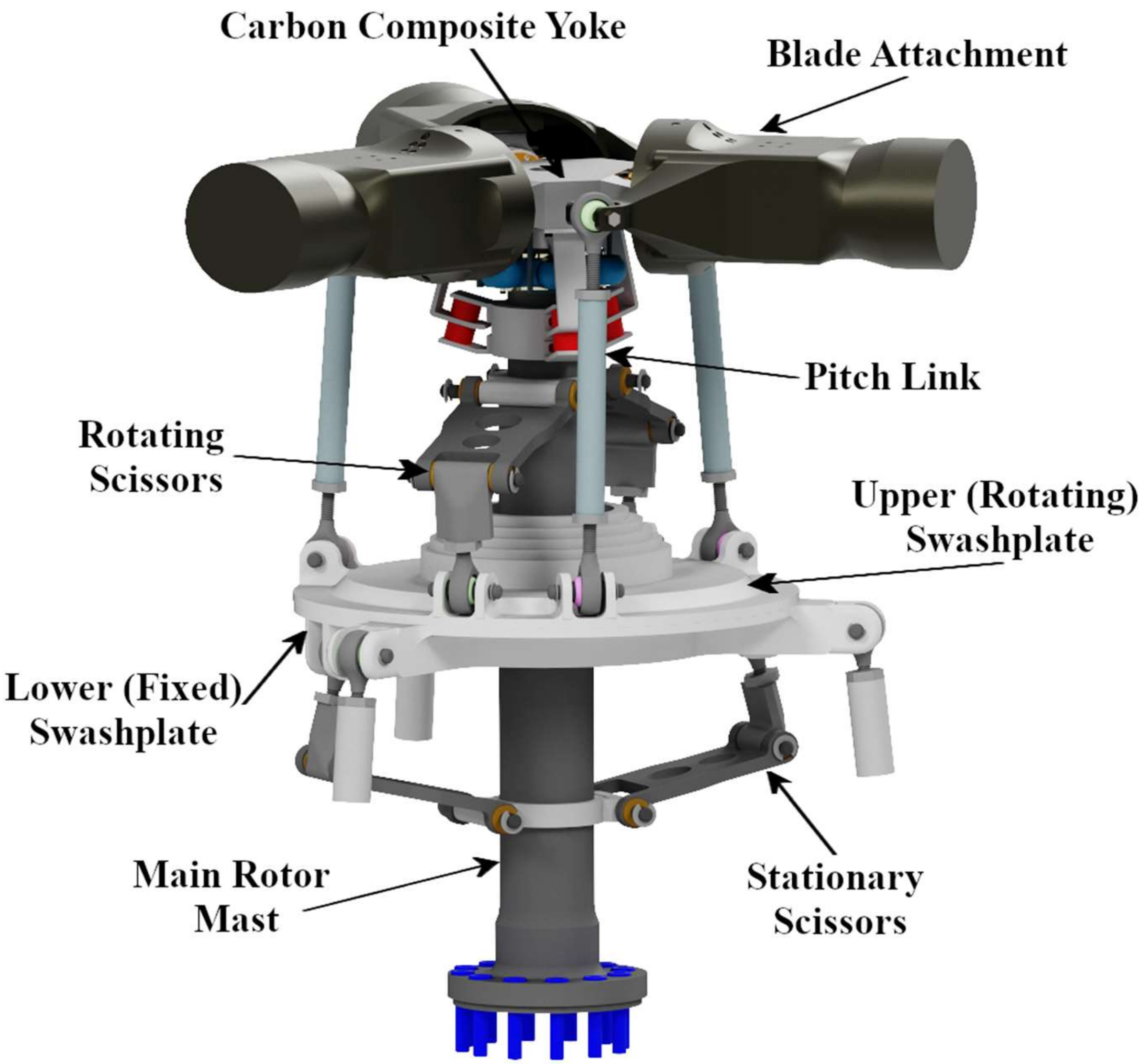


UNIVERSITY OF MARYLAND

KARFI

Rotor Hub

A gimballed hub was chosen for the Karfi because they provide relief for the one-per-rev blade flapping loads and severely reduce the blade acceleration and deceleration induced by blade flapping. Also, the CV joint allows gimballed hubs to not transmit the moments produced by the rotor to the rest of the aircraft.

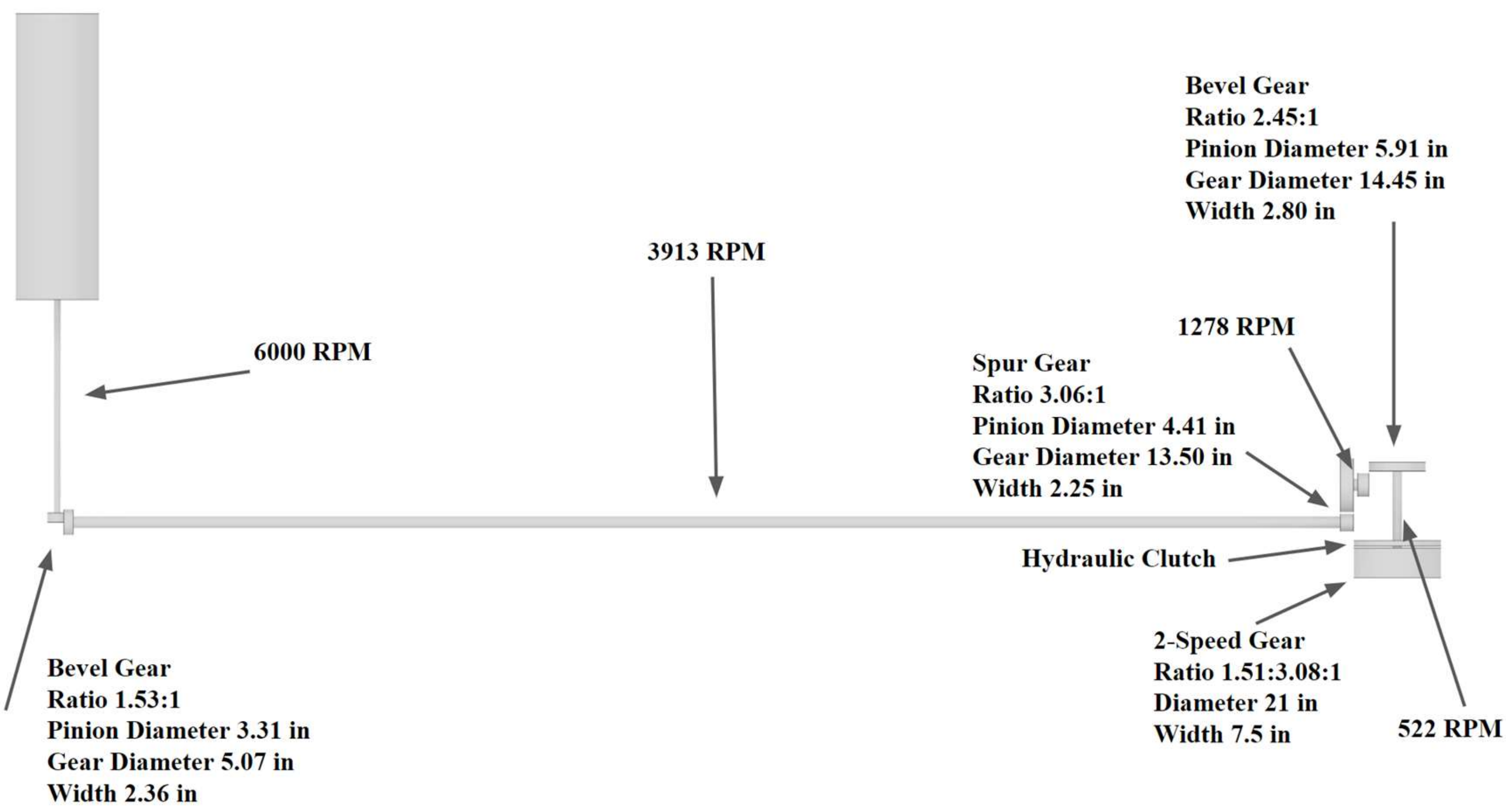


UNIVERSITY OF MARYLAND

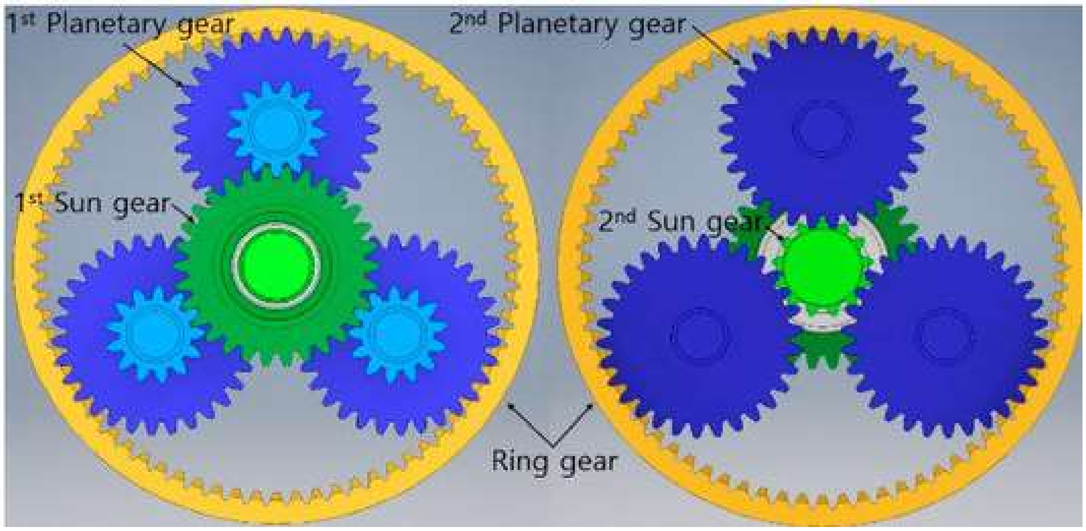
KARFI

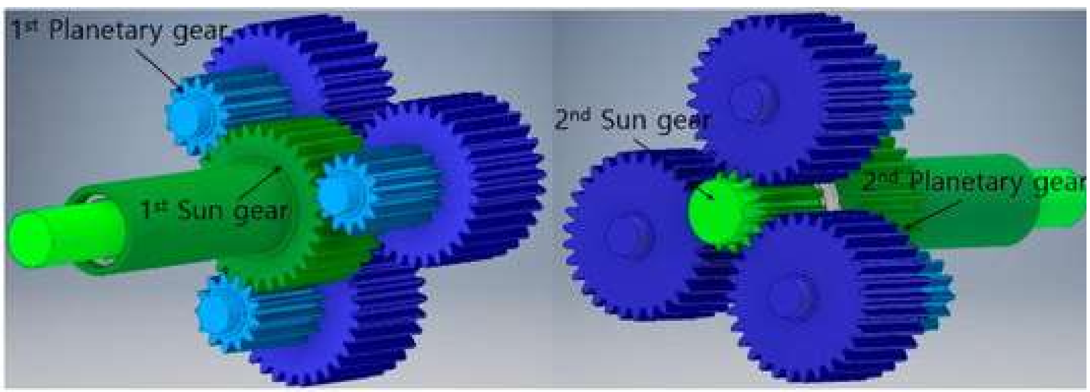
Drive System

With the turboshaft engines in the fuselage, it is necessary to transfer the power to the wingtip nacelles through the driveshaft. Keeping a high RPM through the drive shaft reduces the torque load on it, thus allowing for a smaller drive shaft and a large weight reduction.



2-Speed Planetary Clutch





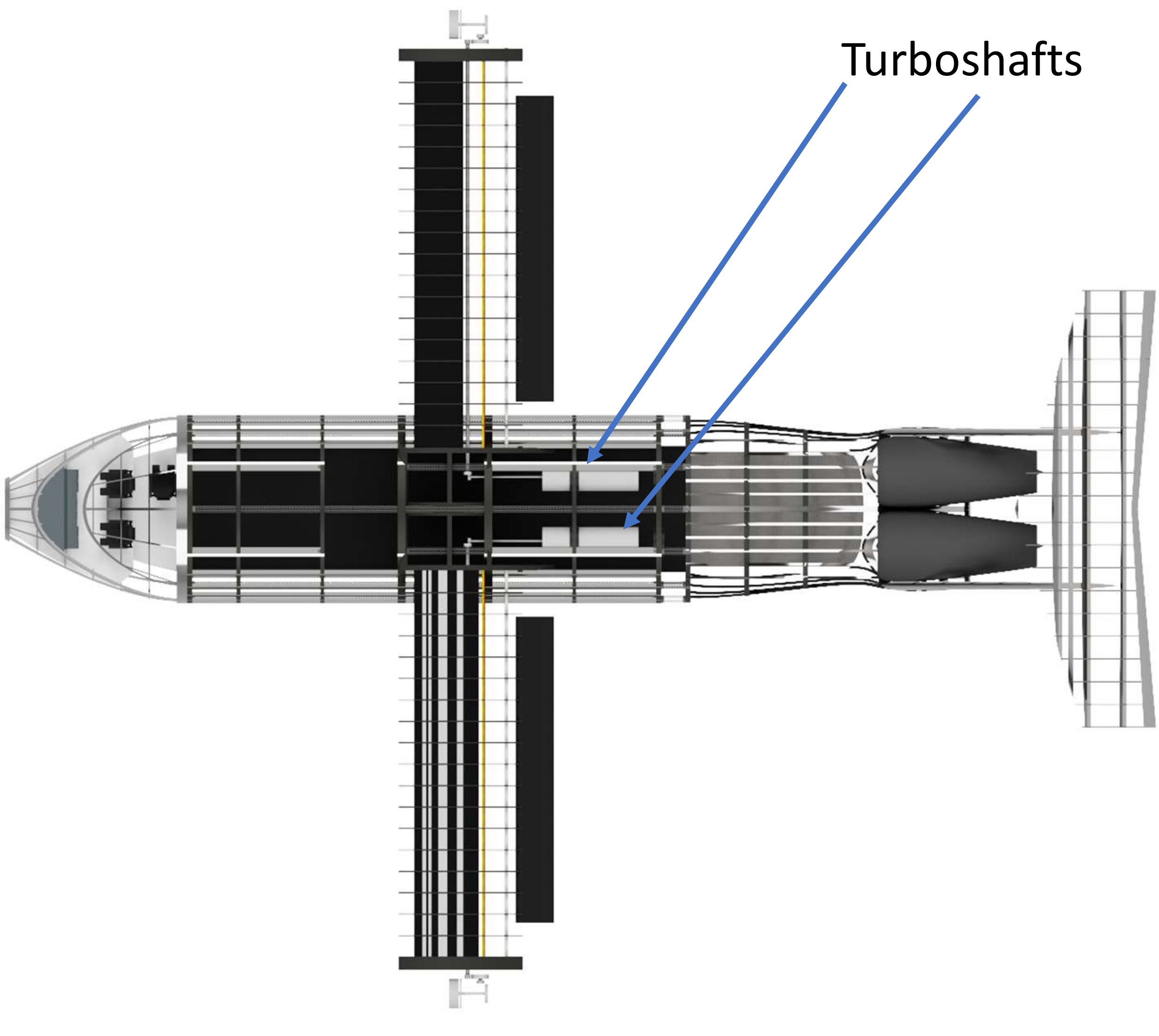
The gears were sized such that the planetary gears for the engaged and disengaged states rotate on the same axis. The planetary gears are combined into one gear. The larger planetary gears and the smaller sun gear make up the engaged clutch state; the smaller planet gears and larger sun gear make up the disengaged state. The engaged planetary gears will always remain in contact with the ring gear, but when the clutch is disengaged, they will be driven through the smaller planet gears. When engaged, the clutch provides a 50% rpm reduction.

UNIVERSITY OF MARYLAND

KARFI

Turboshaft Engines

Judicious use of the turboshaft engines allows for efficient VTOL flight and a reduced power required in forward flight.



Turbofan Engines

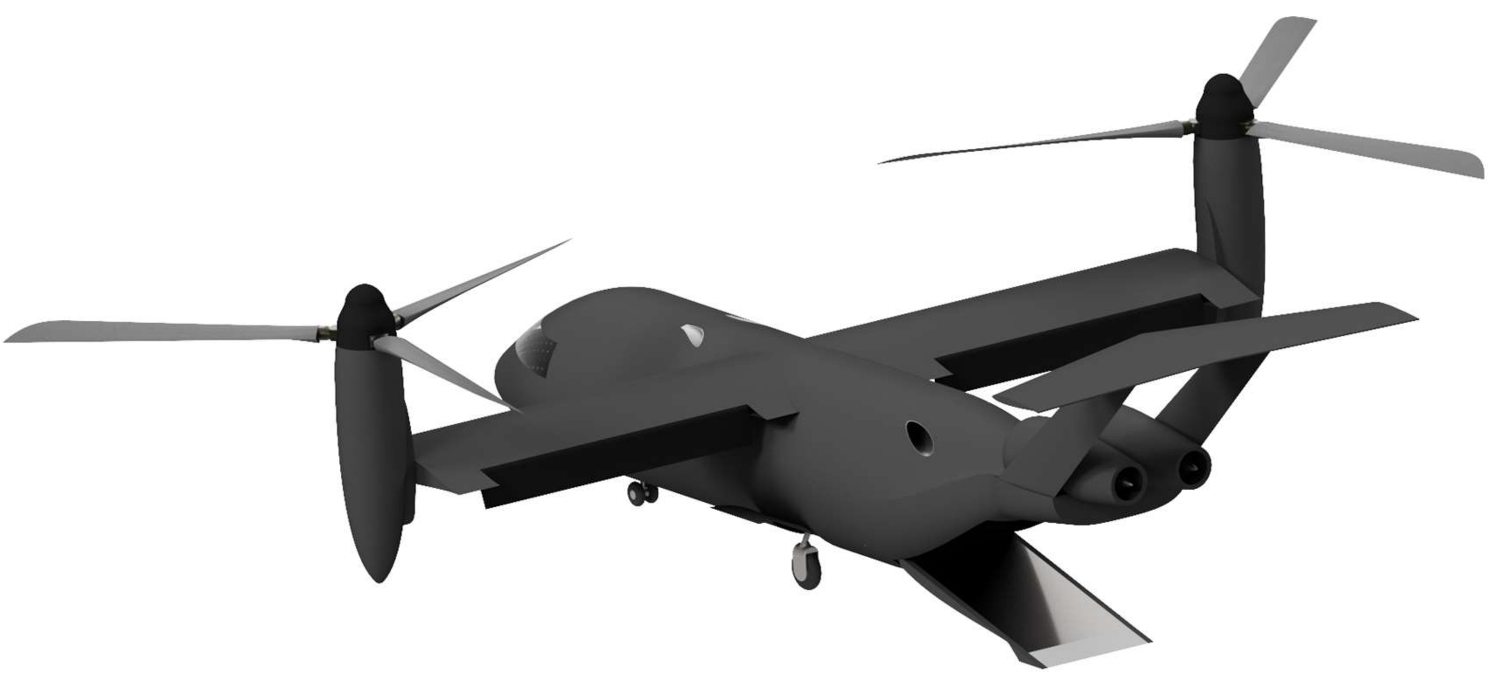
Integrating Karfi's turbofan engines into the Π-tail design reduces the frontal area of the engines, thus reducing drag. This design has the added benefit of the turbofans ingesting up to 40% of the boundary layer of the fuselage which can result in up to a 4% increase in thrust efficiency.

UNIVERSITY OF MARYLAND

KARFI

Cargo Door

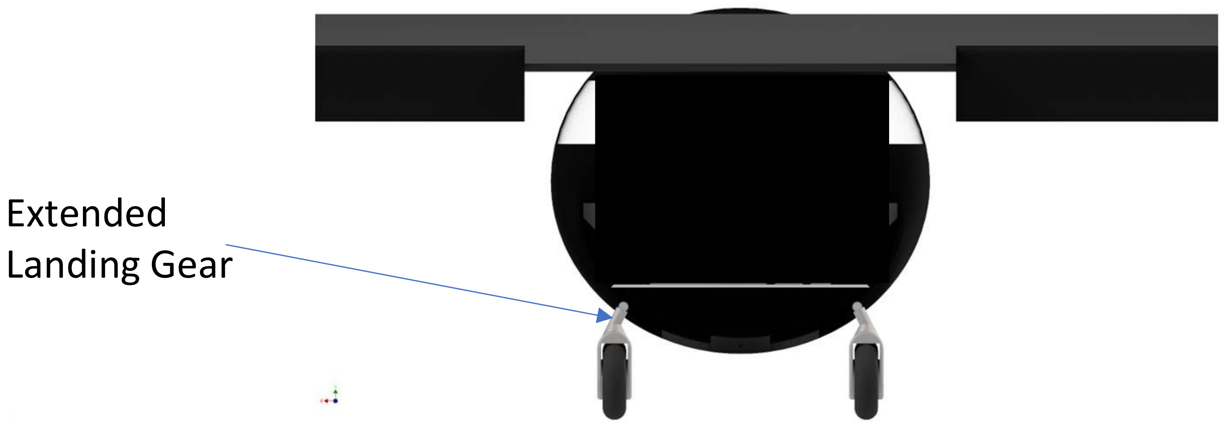
The rear cargo door smoothly integrates into the empennage to facilitate smooth airflow in flight. When landed, the cargo door extends out to make a ramp for easy loading and unloading of the payload. The ramp rests at 13 degrees below the horizontal.

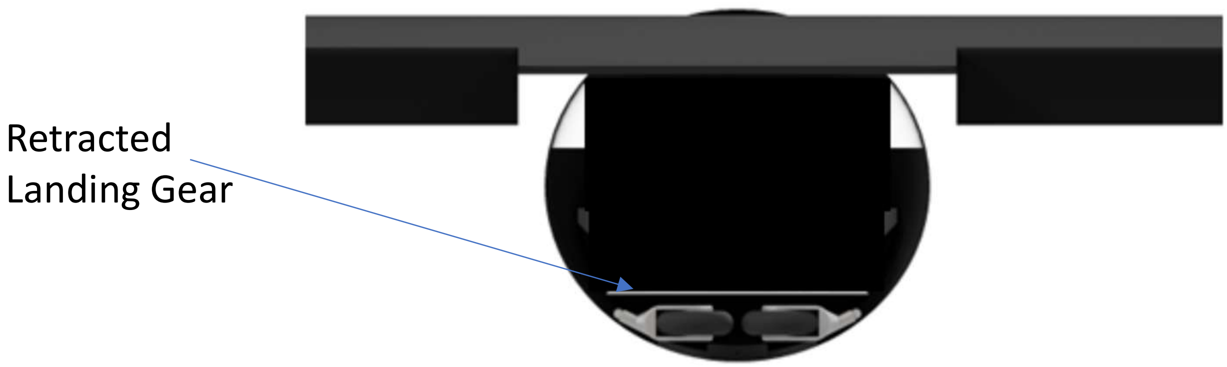


University of Maryland

KARFI

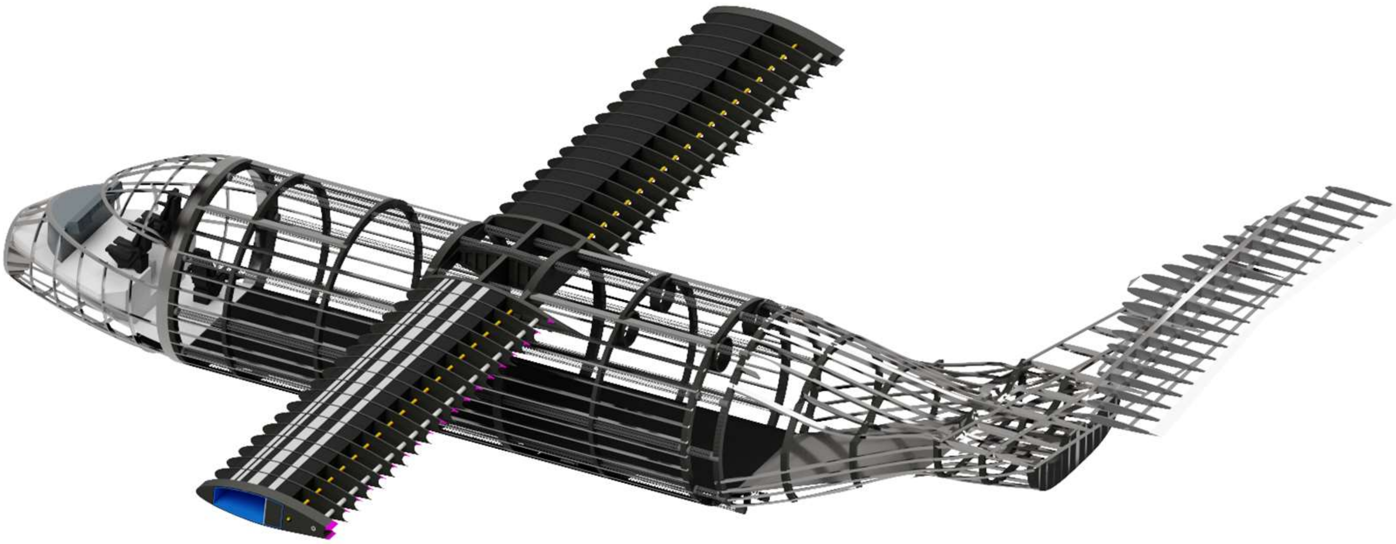
Landing Gear

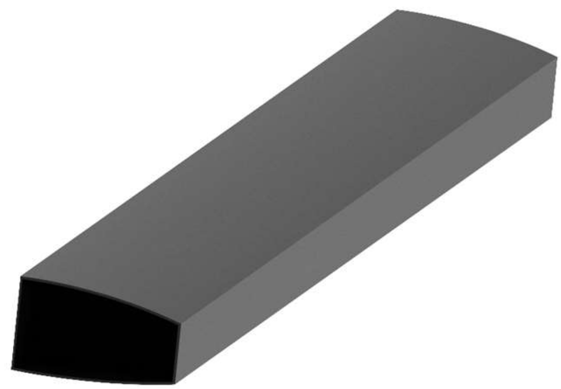




The landing gears conveniently retract into the fuselage during flight without the need for sponsons to store them. This reduces drag and keeps the fuselage aerodynamic for high-speed flight.

Airframe and Wing





Karfi's isotruss longerons provide a strong and lightweight structure. The fuselage can handle all the required loads of the aircraft with a 15% empty weight reduction.

Karfi's rigid graphite-epoxy composite torque box provides the necessary strength and stiffness to achieve high speed flight with a relatively thin wing. This provides an important drag reduction in forward flight.

Cost and Weight Breakdown

Component	Weight (lb)	Weight (kg)
Wing Group	**2,634.15**	1,1194.9
Rotor Group	**2,790.82**	1,265.97
Proprotors (Total)	**1,443.31**	654.69
Rotor Hub	**1,111.18**	504.03
Spinner	**236.44**	107.25
Empennage Group	**1,066.66**	483.85
Horizontal Tail	**533.35**	241.93
Vertical Tail	**533.35**	241.93
Fuselage Group	**6,981.95**	3,167.13
Primary Structure	**6,099.07**	2,766.54
Pressurization	**487.93**	221.32
Crashworthiness	**395.22**	179.27
Landing Gear Group	**1,500.24**	680.53
Engine Gear Group	**5,649.15**	2,562.41
Turboshaft Engines (Total)	**2,111.18**	957.62
Turbofan Engines (Total)	**3,248.58**	1,473.56
Fluids	**289.39**	131.27
Air Induction Group	**1,086.71**	492.95
Nacelles (Total)	**974.41**	442.01
Air Induction	**112.29**	50.94
Fuel System Group	**582.62**	264.28
Drive System Group	**2,534.66**	1,149.70
Gearboxes (Total)	**1,712.34**	776.72
Rotor Shafts (Total)	**255.87**	116.06
Drive Shafts (Total)	**153.37**	69.57
Two-Speed Gearboxes (Total)	**342.47**	155.34
Flight Control Group	**1,417.05**	642.80
Hydraulic Group	**261.52**	118.63
Anti-Icing Group	**421.17**	191.05
Common Equipment Group	**1,458.60**	616.28
Avionics	**458.6**	208.017
Mission Equipment Package	**1,000**	453.59
Miscellaneous	**988.67**	448.45
Empty Weight	**29,373.95**	13,323.80
Crew (Total)	**750**	340.20
Payload	**5,000**	2,267.96
Fuel	**10,234.93**	4,642.56
Gross Weight (w/o 5% Margin of Empty Weight)	**45,358.88**	20,574.44
Gross Weight (w/ 5% Margin of Empty Weight)	**46,827.58**	21,240.99

Component	Cost ($)
Wing	9,156,721
Rotor Systems	1,727,327
Fuselage	113,519,630
Turboshaft Engines	5,820,000
Turbofan Engines	6,500,000
Drive System	374,535
Avionics	993,279
Empennage, Nacelle and Landing Gear	2,250,255
Auxiliary Power System, Fuel and Propulsion Systems	25,781
Environmental Group	493,000
Armament, Furnishings, Loading and Handling	13,623,330
Aircraft Manufacturing Cost	154,483,858
Maintenance Cost per Hour	3,456

UNIVERSITY OF MARYLAND

KARFI

Summary

In response to the RFP for the 2022-2023 VFS Student Design Competition, sponsored by Sikorsky, the University of Maryland undergraduate design team presents *Karfi.* The team was tasked with designing a HSVTOL cargo aircraft for use in highly contested environments and using unprepared landing surfaces.

Karfi's thrust-compounding tiltrotor design contains many novel technologies and improvements on current concepts. Fuselage-mounted turboshaft engines increase wing bending frequency and whirl flutter onset speed. *Karfi*'s two-speed transmission reduces the proprotor RPM in forward flight; most of the rpm reduction takes place in the wingtip nacelle to reduce the driveshaft weight. In forward flight the proprotor thrust is compounded with empennage-embedded turbofan engines. *Karfi* has a lightweight fuselage structure which handles the loads of a high-speed vehicle while minimizing the weight of the aircraft. The cabin houses a large cargo bay with a rear loading ramp for convenient loading and unloading of the payload. *Karfi*'s wings are thinner than other tiltrotor aircraft to reduce drag in high-speed flight. The thin wing is supported by a graphite-epoxy composite torque box. The RFP emphasized the importance of controlling the downwash and outwash effects that often result from HSVTOL vehicles, and the *Karfi* successfully limits its disk loading to 19.5 lb/ft ^{2}.

UNIVERSITY OF MARYLAND

KARFI