36th VFS Annual Student Design Competition

EXTREME ALTITUDE MOUNTAIN RESCUE VEHICLE

Sponsored by AIRBUS

SNU Graduate Design Team Executive Summary in collaboration with KU

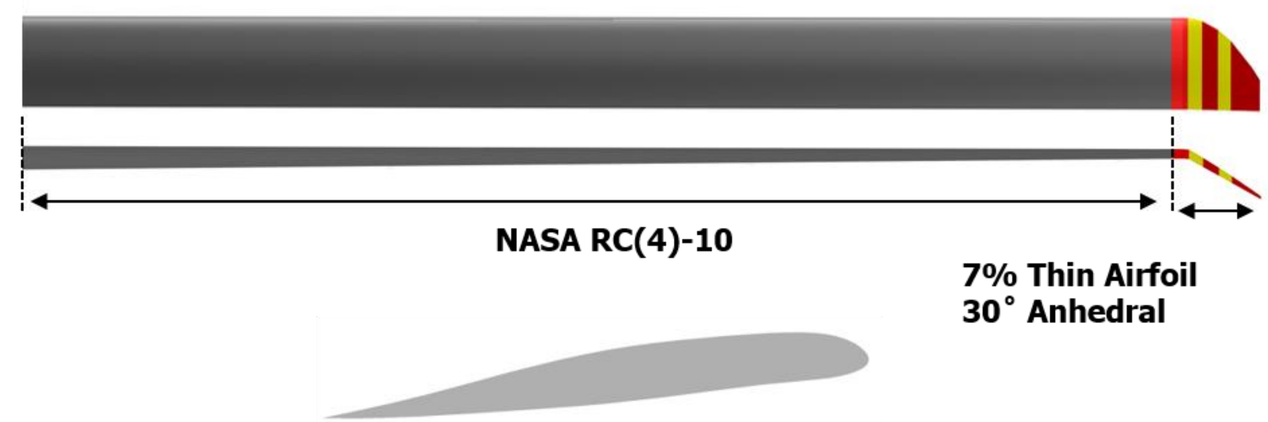
EH-291

Designed for the most demanding SAR mission at Mt. Everest

The EH-291, also known as the CRANE, is designed specifically for extreme altitude mountain rescue vehicle and other versatile missions. A true successor of a compound winged helicopter, CRANE's reliability and safety have been demonstrated through rigorous optimizations of the rotor group.

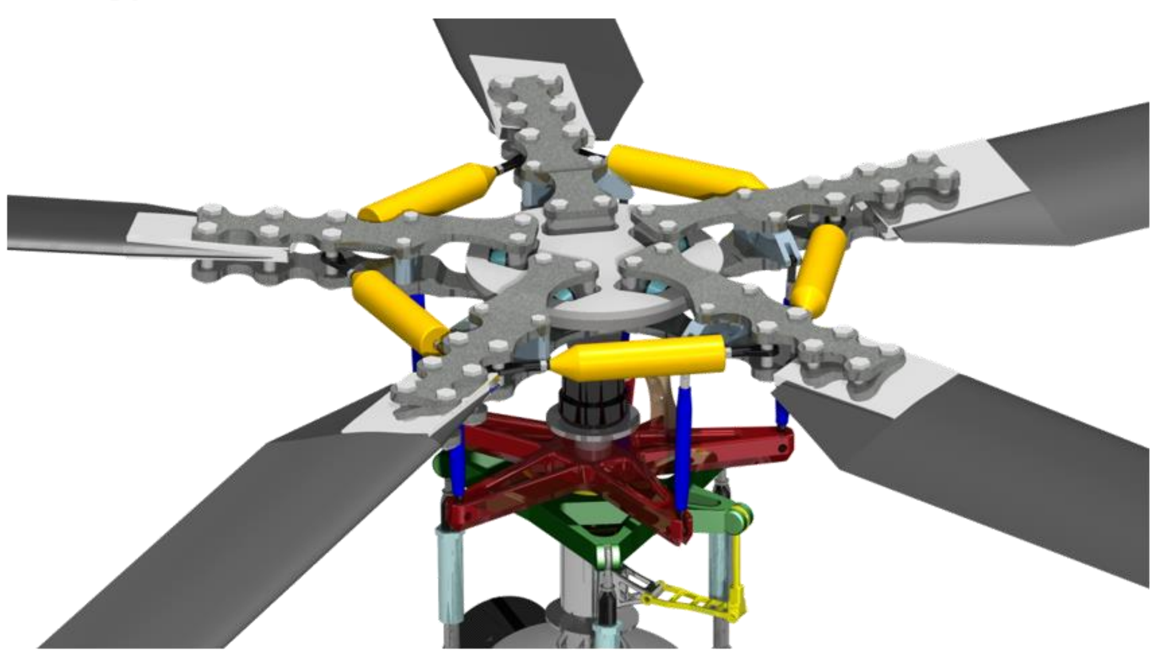
1. Main Rotor Blade

Highly optimized blade planform design provides unmatched hover capability at extreme altitude. Simple, yet powerful rotor blade design allows SAR mission at extreme altitude to be reliable and safe while providing efficient high-speed cruise mission



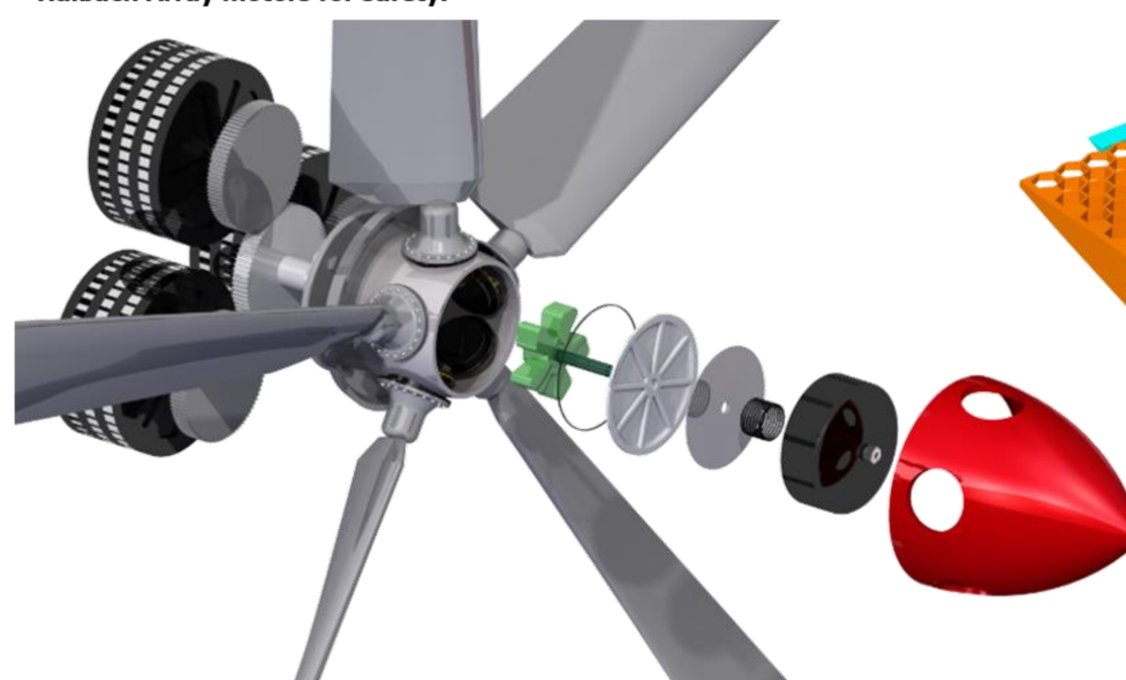
2. Interblade-Damper Hub

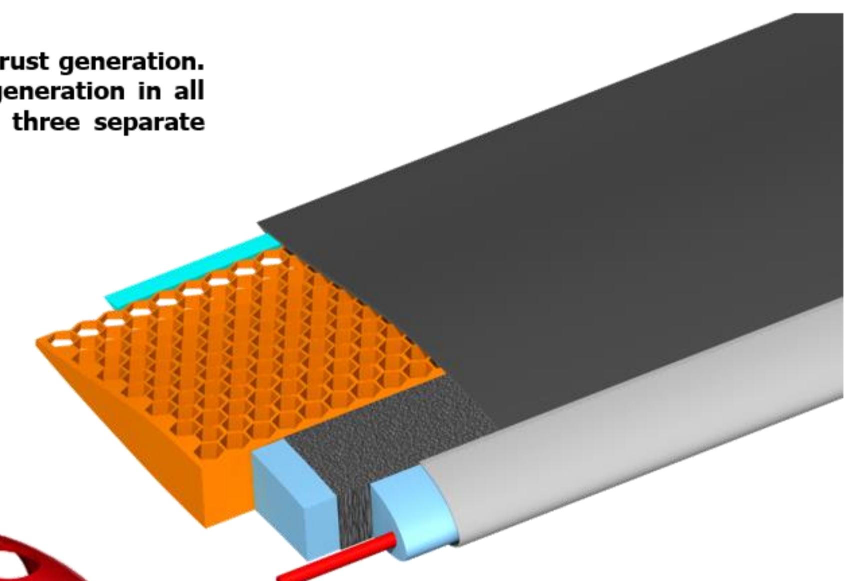
The interblade hub employs unique elastomeric bearing for the flap, lead-lag, pitch motion and provides necessary rotor dynamics making it simple and provide low drag profile.



3. Electrified Propeller Hub

The CRANE employs four wing-mounted propellers for anti-torque and thrust generation. Variable pitch provides responsiveness of thrust and optimized thrust generation in all flight condition. Each of the wing-mounted propellers are powered by three separate Halbach Array motors for safety.





Light weight composites provide all the necessary support in all flight operations

SEOUL NATIONAL UNIVERSITY

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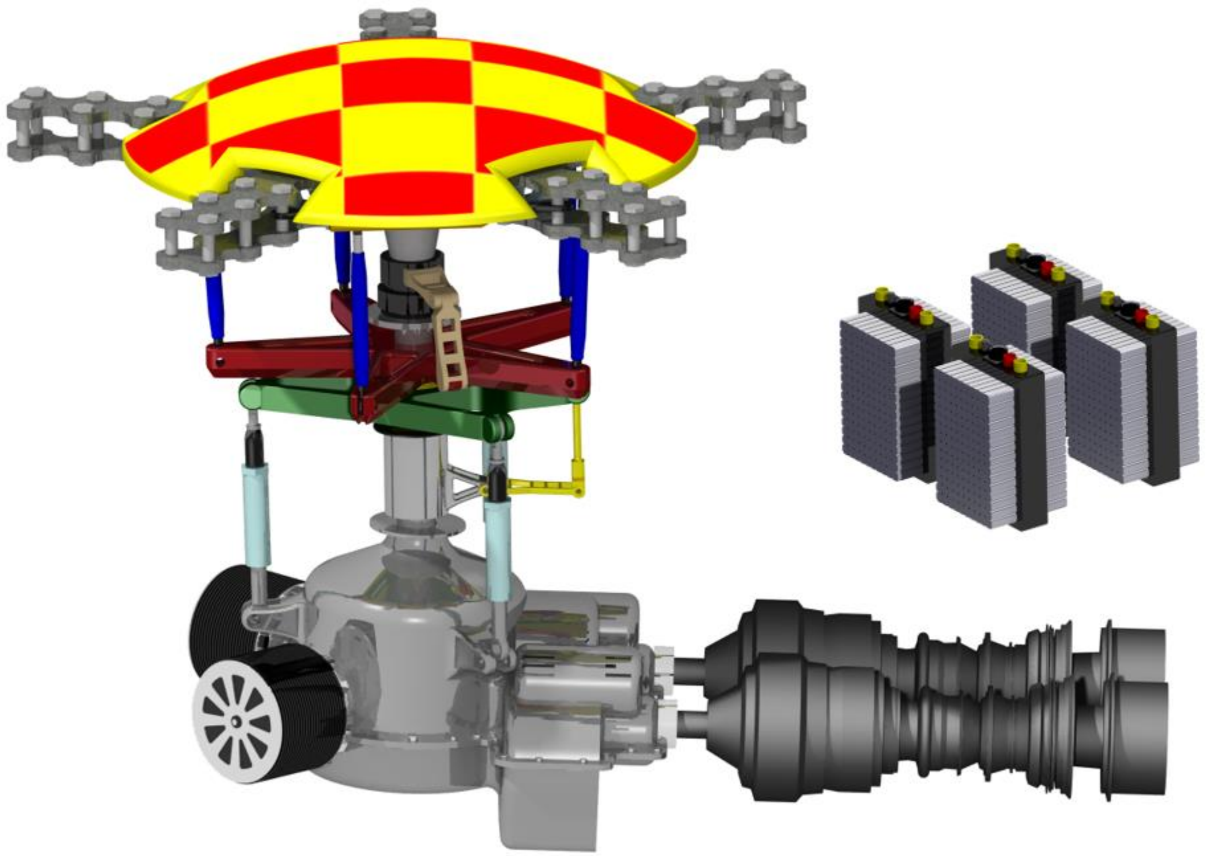
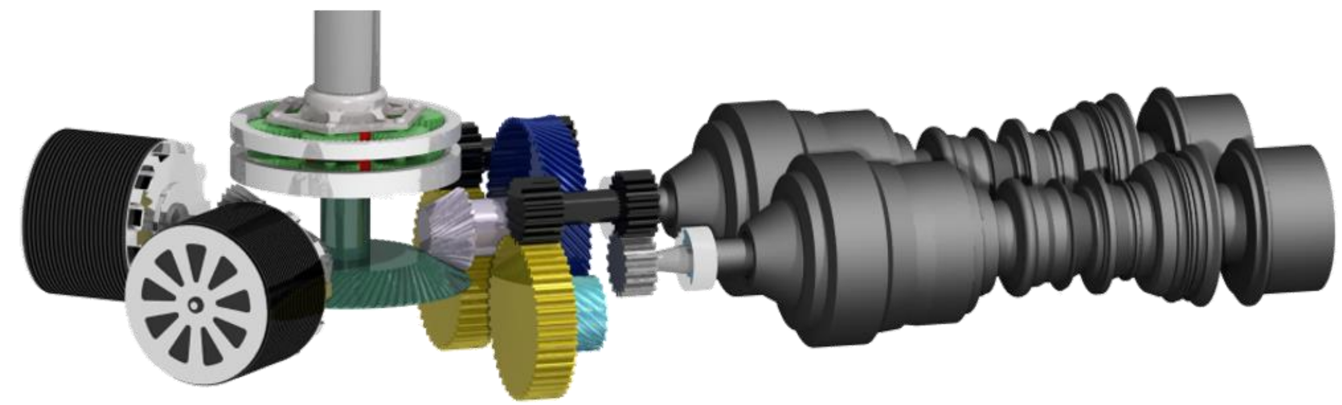


1. Serial-Partial Hybrid Propulsion

With potential improvements in the battery technology, hybridized propulsion system is designed to provide power at extreme altitude efficiently. With current technology, 200Wh/kg battery was adopted. Battery supplements deficient hover power at extreme altitude



2. Variable Speed Transmission Design

Dual-speed transmission design is adopted by placing two planetary gear sets stacked on top of each other that is controlled by a clutch controller. When airspeed reaches 110 knots, main rotor is slowed down by 9%.

3. Cabin Layout

CRANE's internal layout accommodate for sufficient room for 2 litter with internal hoist system for hoist rescue. The cockpit incorporated anthropometric design to accommodate 25th to 90th percentile male/female. All the fuselage are carefully designed for crashworthiness.

SEOUL NATIONAL UNIVERSITY

The *CRANE*, Extreme Altitude Mountain Rescue Vehicle

In Asian mythology, the crane is a majestic bird that symbolizes longevity and immortality. The *CRANE* is also known as one of the highest flying birds in the world and has been sighted flying at an altitude of 10,000 meters while crossing the Himalayas. Inspired by the symbolism of the mythical bird, Phoenix, the color of *CRANE*'s logo adapted its color symbolizing immortality, resurrection, healing, and longevity. Integrating these symbolisms, the extreme altitude mountain rescue vehicle was named as the *CRANE* with technical name, EH-291, which stands for Emergency Helicopter 29,100 ft.

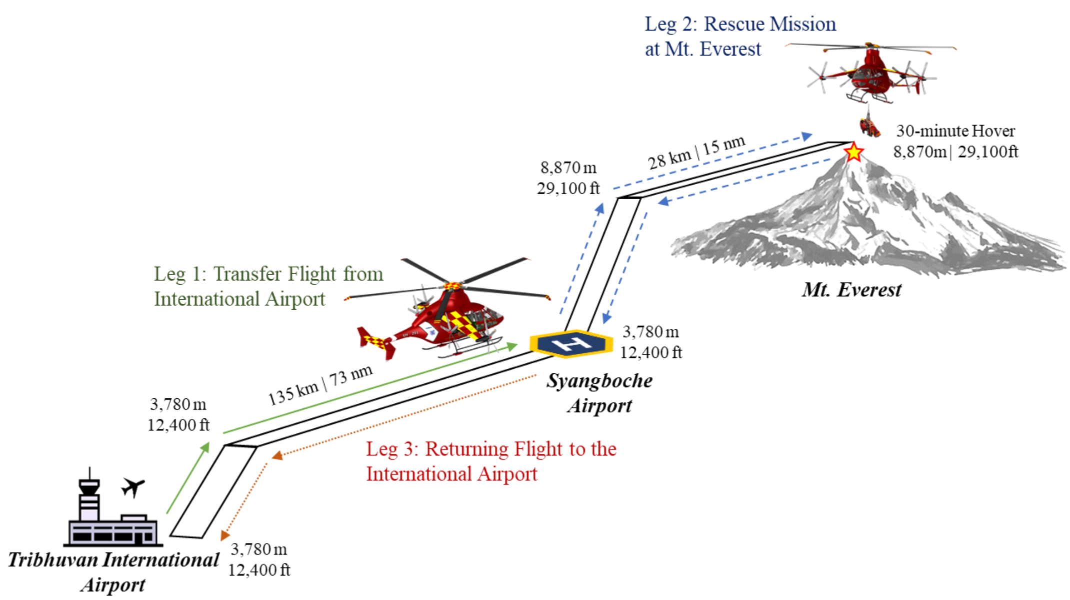
In response to the 36th Vertical Flight Society (VFS) Annual Student Design Competition Request for Proposal (RFP), Seoul National University collaborated with Konkuk University design team presents *CRANE*, an Extreme Altitude Mountain Rescue Vehicle. As an innovative solution for the extreme altitude operation, the CRANE represents a true successor of the compound helicopter to be the unparalleled highly efficient rotorcraft specifically adapted for the Search and Rescue (SAR) mission.

The success of the CRANE can be attributed to the optimized systems as well as to the implementation of innovative solutions including:

- ✓ Unique design configuration
- ✓ Optimized rotating elements (rotor blade and propellers)
- ✓ Serial-partial hybrid powertrain
- ✓ Variable speed transmission

Mission Requirements & Capabilities

The RFP defined a mountain rescue mission starting from a larger international airport, with possible refuel stopover at a smaller airport close to the mountain peak with three crew and 150 kg of EMS equipment. A simple search has identified that the international airport and the smaller airport referred in the RFP were Tribhuvan International Airport and Syangboche Airport respectively.



The 150 kg EMS equipment consists of EMS interior with one cabin seat and two stretchers, medical floor, oxygen system, and medical kit. Upon refueling at the smaller airport, the vehicle will need to climb and perform 30 min hover at 8,870m (29,100 ft) with an additional 2 PAX onboard. Due to strong winds at 8,870 m (29,100 ft), the RFP also specified that the vehicle's control system must be able to maintain its heading in hover with wind from any azimuth up to 74 km/h (40 knots). Moreover, the rotorcraft must include an internal or external hoist system rated for a 300 kg load. Upon returning and refueling at the nearby smaller airport, the vehicle must takeoff and cruise descent to the international airport for medical treatments.

Rapid Response

Mount Everest, also known as the highest peak of the planet, is located in the Mahalagur Himal sub-range of the Himalayas, running across the international border between Nepal and China. Its summit measures at 8,848 meters (29,029 feet) and such height attracts many experienced mountaineers for many reasons. Regardless of its popularity, statistical evidence showed that climbing the Everest is something that should not be overlooked. Everest has been summited 8,306 times (by 4,833 mountaineers), and 288 people have died trying up to June 2017 – a ratio of nearly 29 successful summits for every death.

CRANE is capable of carrying out the overall mission in less than 2.9hr

Cruising at 185 knots, the *CRANE* completes the SAR mission including 30minute hover at 8,870 m, (29,100 ft) within 3 hours. Equipped with Terrain Awareness and Warning System (TAWS), infrared camera sensors, and other avionics to comply with FAA single pilot day/night IFR operation, *CRANE* has enabled SAR mission in Mt. Everest possible even in the low visibility environment. The *CRANE* is the proven vehicle to be able to maintain its heading even at the worst possible weather conditions at extreme altitude.

With the internal hoist system, the *CRANE* enables rescue mission that was beyond the bounds of possibility with commercially available rotorcraft at an unparalleled speed and safety of the overall mission.

Design Philosophy

For any multi-attribute problem, the selection of the "best" alternative is inherently subjective with no single answer that fulfills all requirements of the design space. Throughout the design process of the *CRANE*, a process of establishing design requirements and system-engineering-based requirement analysis techniques commonly known as the Quality Function Deployment (QFD) was carried out. The most important questions addressed were: What are the customer's needs and how do an engineer meet those needs with necessary design choices. The final outcomes of the design have exhibited all features to meet mission objectives while exceeding the requirements set forth by the RFP.

Simplicity, low maximum gross weight, installed power and payload ratio

As an excellent and innovative demonstrator of state-of-the-art rotorcraft, *CRANE* represents a new paradigm shift to the rotorcraft community to achieve unmatched hover and forward flight efficiency while minimizing the complexity, total gross weight, and installed power. Furthermore, safety driven design throughout the design of the *CRANE* has been carried out. To this end, a rigorous optimization process using the comprehensive sizing code coupled with the Evolutionary Algorithm (EA) during the initial sizing phase was carried out to obtain an optimal solution for the given mission. This process was cross-validated with Computational Fluid Dynamics (CFD) analysis of the rotating elements (main rotor and propellers) of the *CRANE*.

Safety Driven: Design Configuration

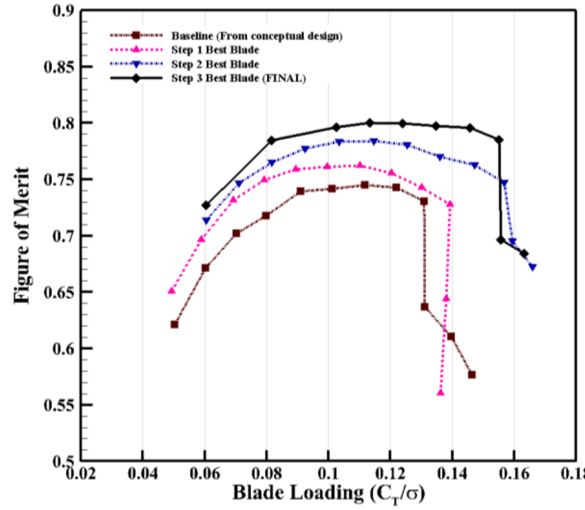
The main purpose of the initial sizing was to provide the most realistic design through detailed analysis, attempting to cover all aspects of aerodynamics, structure, propulsion system, weight, and stability controls. By adopting the QFD analysis and detailed analysis, a compound winged helicopter with distributed wing-mounted propulsion system was proposed for the safest platform to carry out extreme altitude mountain rescue mission. The House of Quality (HOQ) has identified the following parameters that must be extensively studied to meet various requirements.

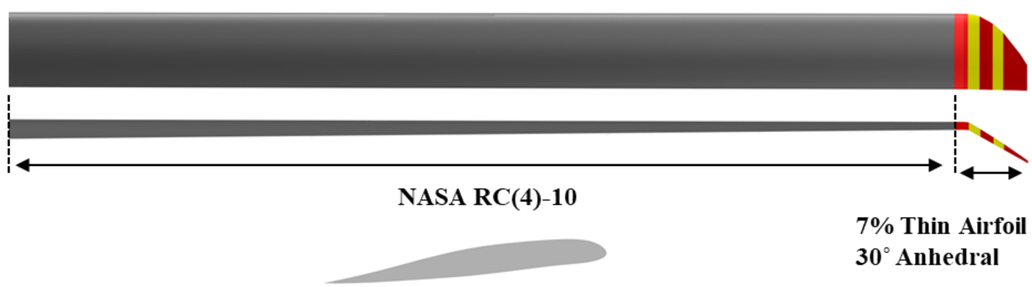
1	2	3	4	5
TOGW	Rotor Aerodynamics Design	Installed Power	Disk Loading	# of Engines
6	**7**	**8**	**9**	**10**
Blade Stall Margin	Figure of Merit	Anti-deicing	Avionics Capability	Blade Structural Design

The final outcome of the design configuration is obtained through the rigorous sizing process, with a total of 3 baseline prototypes designed while carrying out a detailed analysis of the major systems. The final configuration is a **thrust augmented winged helicopter** with four propellers mounted on the wing to provide thrust required for anti-torque at extreme altitude.

The SNU design team has proposed the quad-propeller winged helicopter based on the requirements of the RFP. Not only is this configuration provides utmost hover efficiency at extreme altitude, but also provides simplicity by adopting electric counterparts of the serial-partial hybrid system.

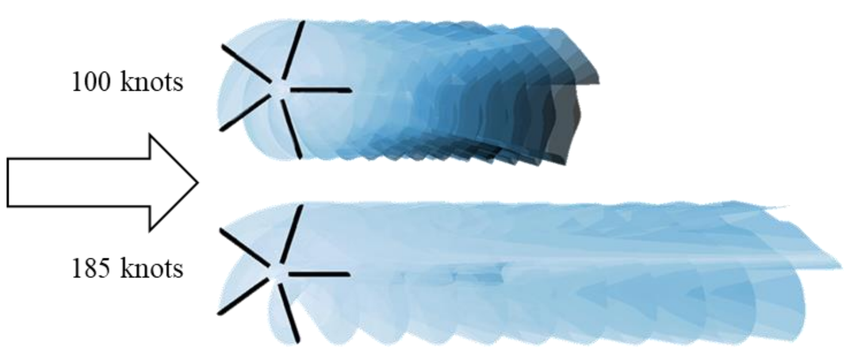
Designing a rotor blade planform requires multi-disciplinary analysis as the parameter attributes of a rotor efficiency in hover and rotor in forward flight are contradictory. These contradictory design requirements often result in a design that is efficient in neither hover nor forward flight. *CRANE*'s proposed design of the main rotor and the propellers offer excellent propulsive efficiency for a wide range of operating conditions but most importantly at the extreme altitude.





The optimized result of the *CRANE*'s blade planform from CFD analysis has achieved **7% increase in the hover Figure of Merit** at 8,870 m (29,100 ft) and up to **6.4% improvements at cruise flight**.

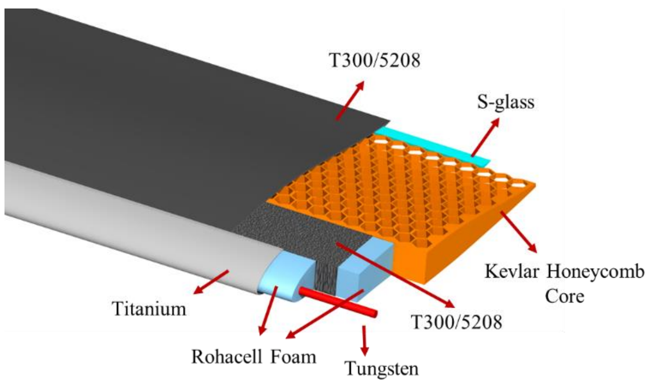
C_Q (Torque Coefficient)	100kts	185kts
Baseline blade	0.0008686	0.000409
Final blade	0.0008131 (6.4% decrease)	0.0003947 (3.5% decrease)

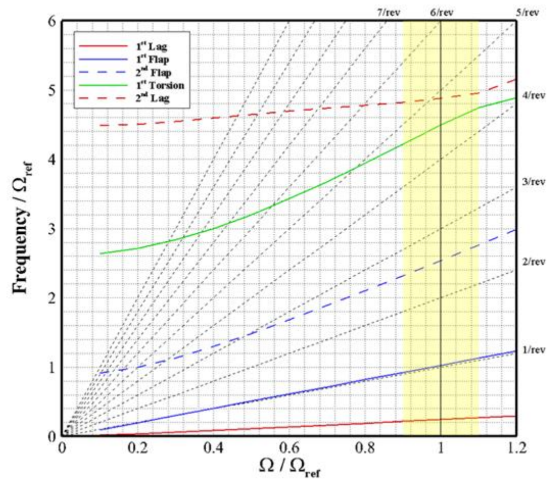


30,000 Sizing Iterations → **17** Airfoils Analysis → **70** CFD Planform Design → **1** Optimized Solution

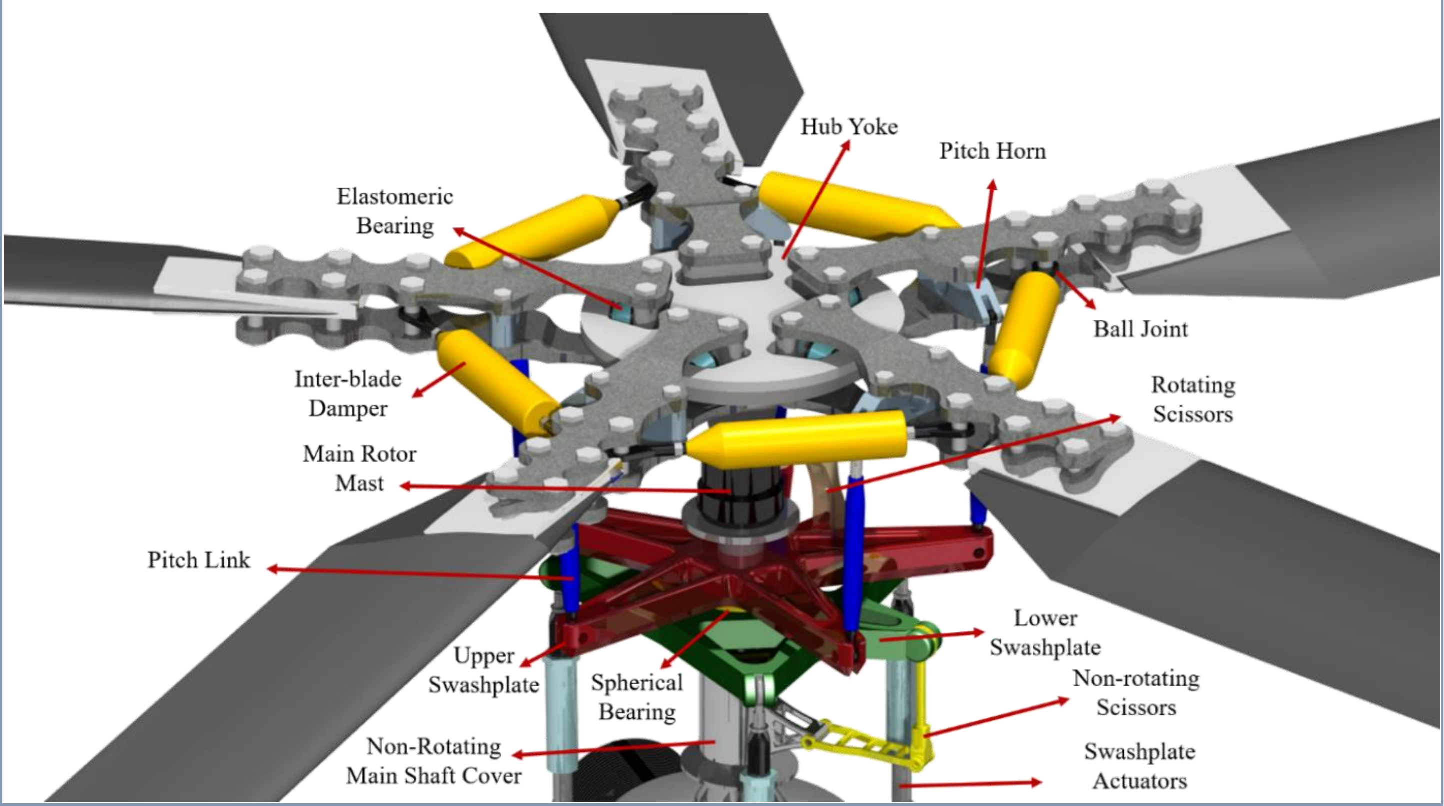
Safety Driven: Main Rotor Group Design

A robust structural design of the main rotor is employed consisting of mainly composite material due to their physical properties. Comprehensive Analytical Model of Rotorcraft Aerodynamic and Dynamics II (CAMRAD II) and KSEC-2D code are utilized for the design of the rotor blade performing all the required analysis such as aerodynamics, structural dynamics, vibration, and finite element cross-sectional analysis of the rotor blade during hover and cruise flight.



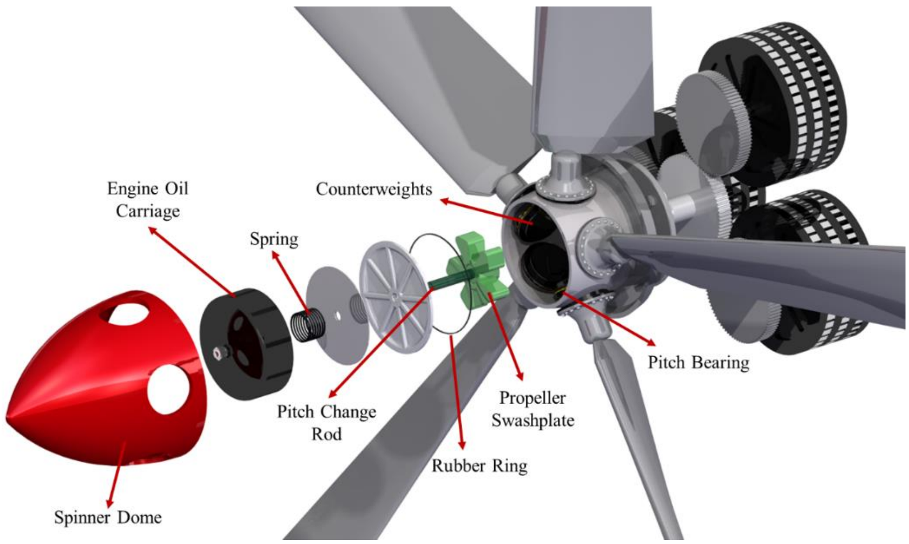


The 5-bladed rotor of the *CRANE* also utilizes the **inter-blade elastomeric bearing hub** for the main rotor. This unique design, compared with a conventional configuration such as articulated which dampers are interposed between each blade and the rotor hub, increases the lever arm between the dampers and drag axes. This also serves to cause two dampers to act on each blade and thereby reducing the ground resonance. The uniqueness of the rotor hub is therefore favorable for combating the ground resonance.

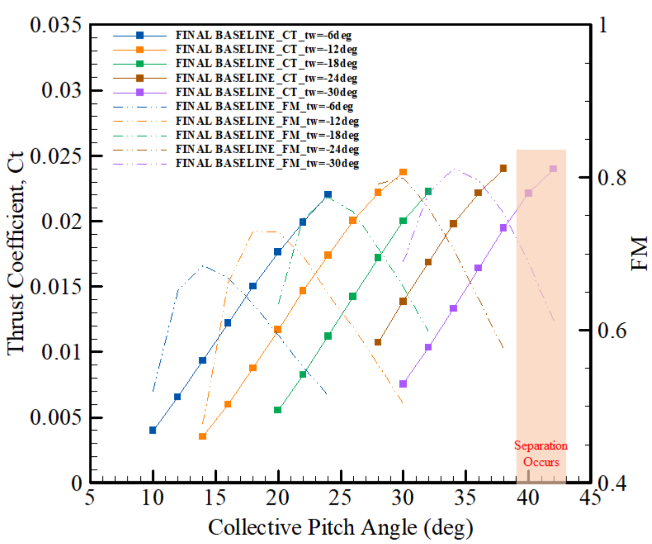


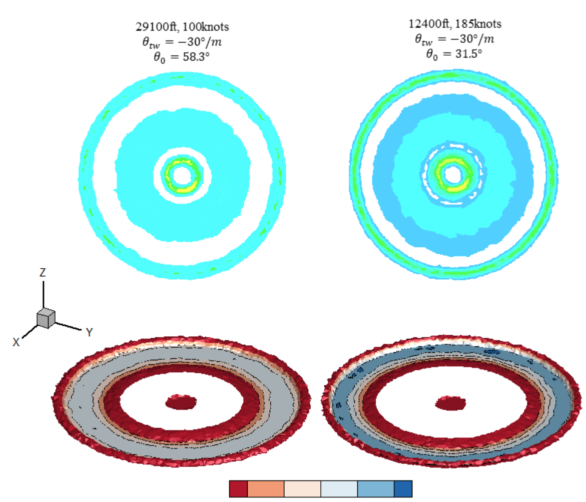
Safety Driven: Propeller Group Design

The anti-torque requirement at the extreme altitude has led to the unique design of the *CRANE* adopting four wing-mounted propellers. These propellers are designed to be powered by three electric motors connected in parallel to the power source, which further expands the safety of the aircraft with the redundant system. In case of a motor failure, deficient power can be redistributed to the two operating motors, giving ample time for the pilot to take necessary actions.



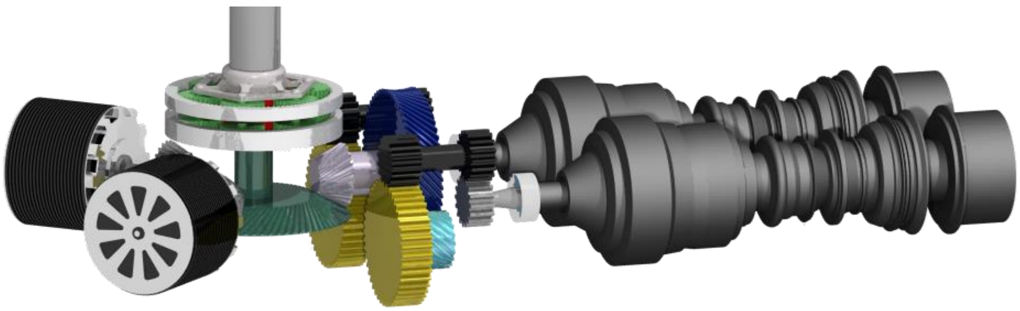
By adopting the **variable pitch propeller**, constant propeller efficiency was achieved throughout the mission profile. The propeller blade twist was optimized for hovering at 8,870 m (29,100 ft). Together with the main rotor blade performance, the *CRANE* was designed to meet the requirement of the RFP and serve as the safest platform for extreme attitude mountain SAR mission.



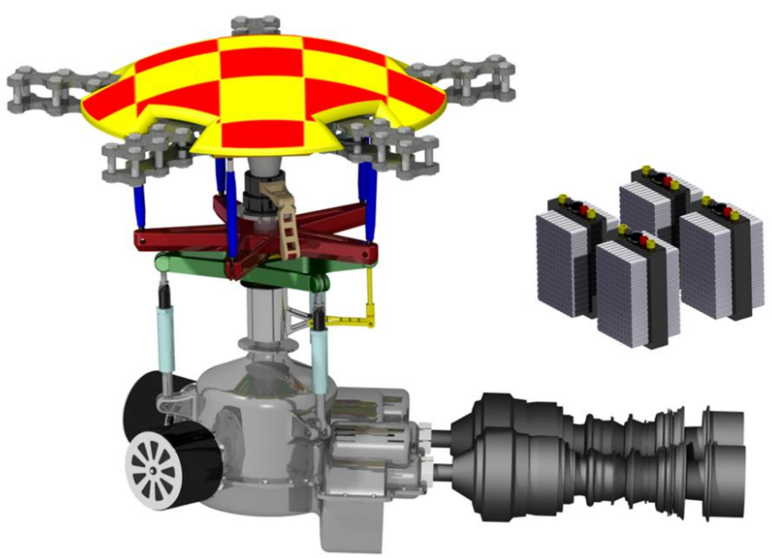


Safety Driven: Propulsion Group Design

One of the features that separate the *CRANE* from past winged helicopter design is the integration of the hybridized powertrains used for simplicity and efficiency. Traditionally, propeller shafts are mounted through the wing structures to provide shaft power to the wing-mounted propeller, but this leads to an increase in the structural weights and transmission complexity. For the propulsion system design, GE T700 “rubberized engine” was sized for increased reliability.



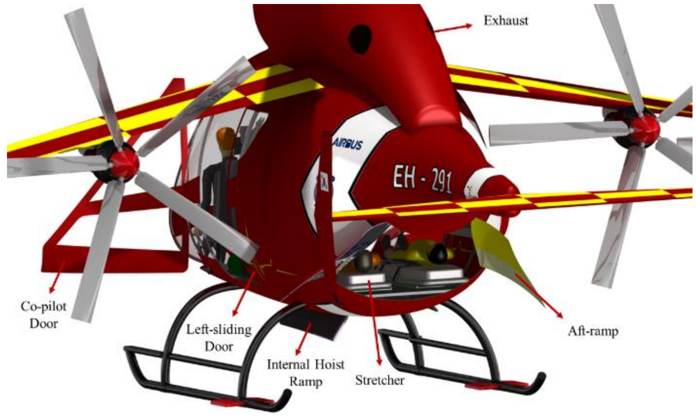
- ✓ **Dual Speed Transmission** — Highly efficient dual-speed transmission design is adopted by placing two planetary gear sets stacked on top of each other that is controlled by a clutch controller. When airspeed reaches 110 knots, the main rotor is slowed down by 9% enabling *CRANE* to cruise at 185 knots.
- ✓ **Serial-Partial Hybrid** — *CRANE*’s powertrain is designed to achieve OGE hover ceiling of 8,870m (29,100 ft) at ISA+20. With battery packs providing deficient power only at the extreme altitude, the *CRANE* exceeded performance requirements even with the current technology level.

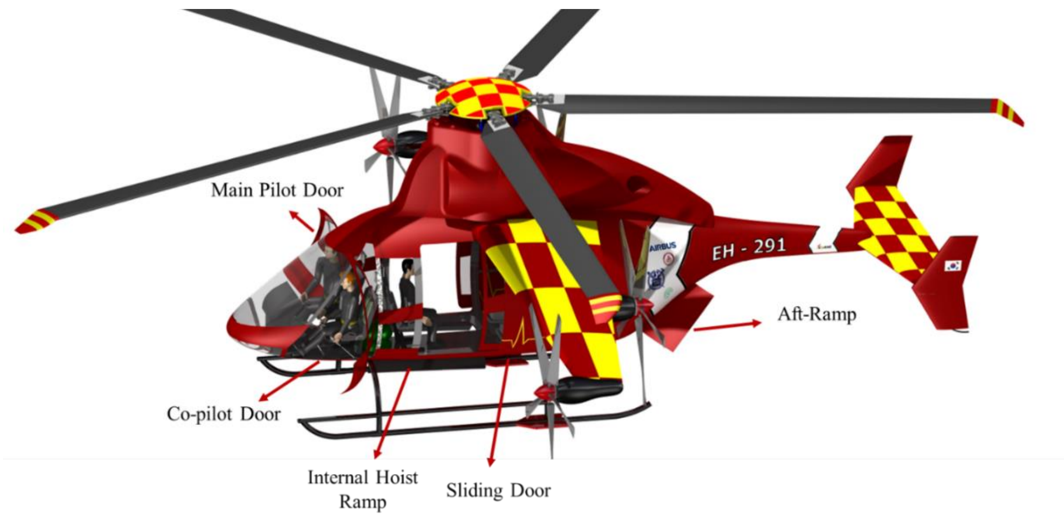


Aerodynamically designed engine cowling and the hub cap provides a significant decrease in profile drag.

Safety Driven: Airframe Group Design

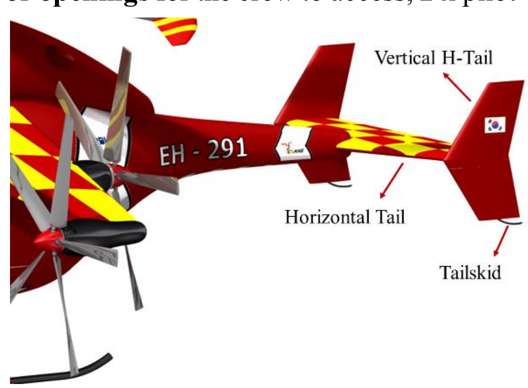
One of the unique selling points is that *CRANE*'s fuselage is designed to accommodate three crews and two litters with an internal hoist system. The cabin is an unpressurized cabin for weight minimization. Instead, oxygen supply is carried in a light Kevlar fiber container for each flight personnel. The hoist system adopted is commercially available GOODRICH Pegasus rescue hoist rated at **273.16kg (600lb)**. An internal ramp is sufficient to accommodate for the non-ambulatory patient stretcher. The *CRANE* also benefits from a high wing design to keep propeller blades clearances. Other accessory features include partially retractable landing skid, settling protector, and cabin steps designed for crashworthiness.





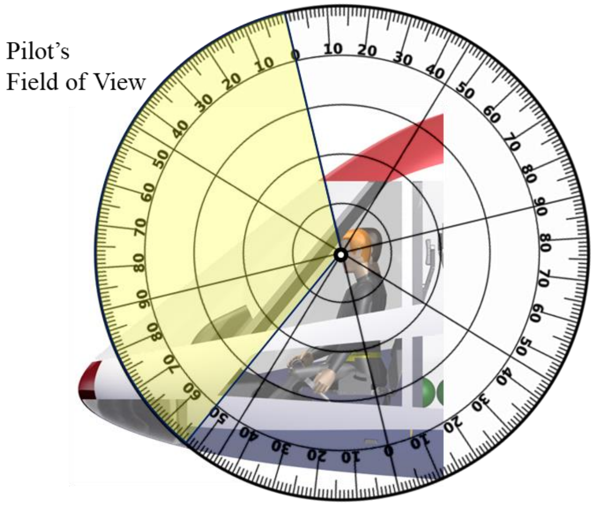
As a rescue vehicle, the unloading and loading of the litter similar to a typical ambulance was accommodated by an aft-ramp. The *CRANE* has a total of **6 door openings** for the crew to access; 2 x pilot doors, 2 x side sliding doors, aft-ramp, and hoist ramp.

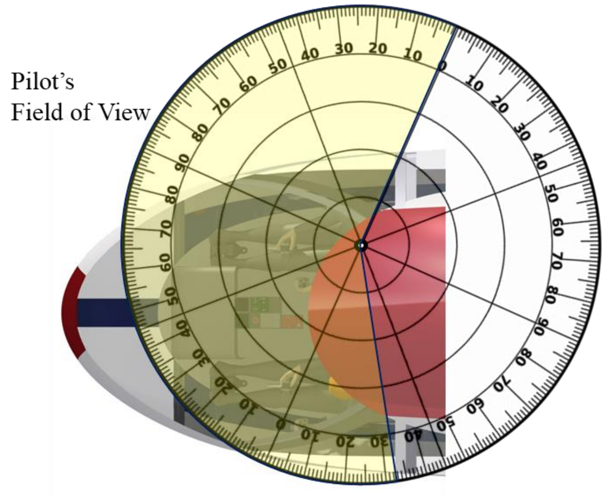
The **H-tail empennage** configuration provides a larger surface area for a lower span, decreasing the possibility of a tail-strike and minimizes the wake impact. The sizing of the empennage ensures weathercock stability and other dynamic stability. **Tail skid** on the vertical tail provides protection against a possible tail strike.



Safety Driven: Airframe Group Design

The *CRANE* incorporated an anthropometric design to accommodate 25th to 90th percentile male/female flight crew with ergonomically designed cyclic and collective controls. For SAR operation, when the pilot workloads are at the highest point, it was necessary to design the cockpit that is intuitive and has wide unobstructed field of view. The *CRANE*'s cockpit canopy provides more than unobstructed 125˚ vertical and 210˚ horizontal field of view for the pilot/co-pilot.



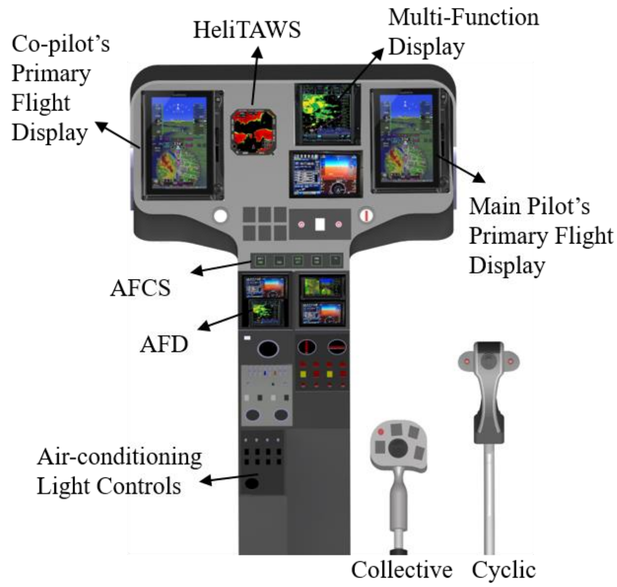


With the wing providing a significant portion of the lift during forward flight, the airframe of the *CRANE* is specifically designed considering the load paths of the major components.

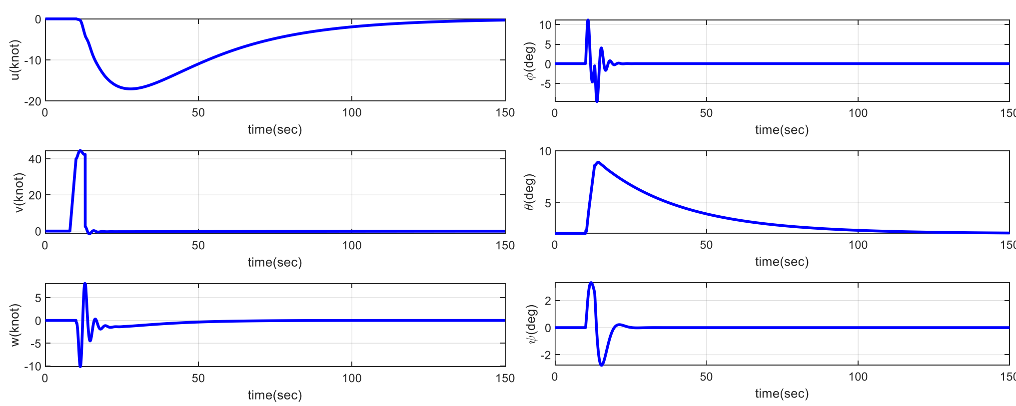
Safety Driven: Avionics

Specifically designed to operate as an extreme altitude mountain rescue vehicle, the *CRANE* is equipped with various avionics to handle degraded visual flight conditions. The *CRANE* is also equipped with Health Usage Monitoring System (HUMS) providing comprehensive monitoring and data recording of airframe, rotor, engine, and drive system. It is designed to conduct routing vibratory assessment to make discretionary rotor and balance adjustments without pilot interface during flight.

For the safety of the flight personnel, the *CRANE* features a variety of flight safety system to indicate and relay all the critical information to the pilot. This information can be monitored with an intuitive design of the multi-function display while minimizing the workload of the pilot by providing automated pilot controls such as the altitude hold, hover hold, and other trim push button annunciators that are ergonomically designed.

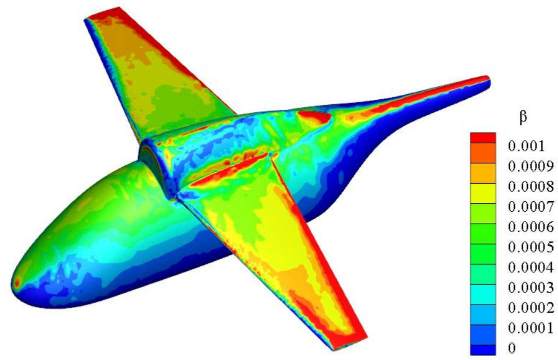


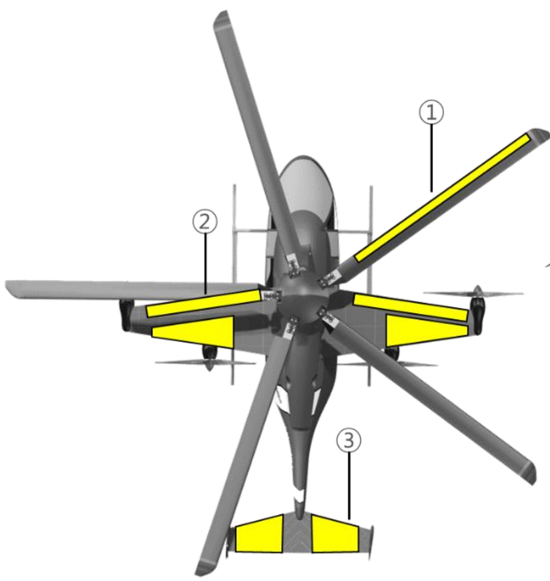
A digital fly-by-wire is also designed to reduce pilot workload and fatigue with increased reliability and safety. Specifically, AFCS enables an overview of the system by gathering information from the HUMS and flight management system. The AFCS of the *CRANE* is designed to enable rate command attitude hold, airspeed hold, hover hold, altitude hold and provide inherent stability augmentation and gust rejection of up to 40knots side wind.

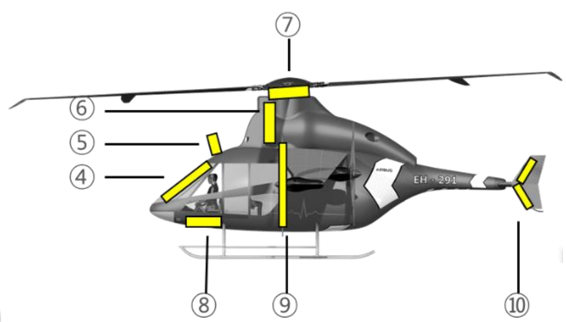


Safety Driven: Ice Protection System (IPS) Design

Freezing is a meteorological phenomenon that can occur anywhere on the structure exposed to the outside, which is a serious threat to flight safety as well as the performance of aircraft. Due to the nature of the mountainous climatic conditions, unpredictable and extreme weather conditions at the summit of Everest place the *CRANE* in the inevitable freezing conditions. Therefore, *CRANE* is equipped with all the essential anti/de-icing equipment







Position ID	Location	Anti/de	Type	Description
1	Rotor Blade	De	Electro-thermal	
2	Main Wing	Anti	Air-bleed	Forward Flight
	Control Surface	De	Electro-thermal	
3	Horizontal Tail	Anti	Electro-thermal	Forward Flight
4	Wind Shield	Anti	Electro-thermal	
5	Wire Cutter	Anti	Electro-thermal	
6	Engine Intake	Anti	Air-bleed	
7	Rotor Mast	Anti	Electro-thermal	Forward Flight
8	Pitot Tube & Sensors	Anti	Electro-thermal	
9	Propeller	De	Electro-thermal	
10	Vertical Tail	Anti	Electro-thermal	Forward Flight

Multi-mission Capability

Another design feature of the *CRANE* is the reconfigurability of the cabin for multi-mission capability. With low disk loadings, optimized rotor planform, large cabin volume, and sufficient power for heavy lifting, *CRANE* can be configured to fly as other purpose rotorcraft. The interior of fuselage is designed for easy and rapid integration, everything from cargo, seats, and universal attachment fittings that can be easily removed or added to ensure reconfigurability of the cabin.

SAR and MEDEVAC/CASEVAC Mission

- ✓ *CRANE*'s high cruise speed and long range capability make it even more ideal for a conventional SAR mission.
- ✓ Equipped with the 300kg load hoist system enables naval rescue. An additional floating device can be installed prior to a naval rescue mission
- ✓ The cabin area for the *CRANE* can be reconfigured to transport 6 non-ambulatory patients.
- ✓ IR camera also provides significant SAR capability to assist in locating the target victims.

Urban Transportation (Air-taxi operation)

- ✓ The *CRANE* can provide a new perspective for the door-to-door PAX transport
- ✓ Low disk loading and tip speed ensuring low acoustic profile reduces acoustic signature concerns in urban areas
- ✓ Maximum cruise speed of 185knots makes it ideal for inter/intra-city air-taxi operation

CRANE's SPECIFICATION

	Value
Empty Weight	2882.9kg | 6355.6lb
Gross Weight	3521.5kg | 7766.2lb
Fuel Weight (leg 1)	120.2kg | 265.1lb
Fuel Weight (leg 2)	214.1kg | 471.9lb
Fuel Weight (leg 3)	100.9kg | 222.5lb

	Value
Engine Type	GE T-700 Turboshaft
# of Engine	2
MCP per engine	917.7kW | 1230.6hp
IRP per engine	1087.8kW | 1458.7hp
CRP per engine	1220.5kW | 1636.7hp

	Radius	Chord	Airfoil	# of Blade	Twist (r/R)
Main Rotor	7.59m | 24.898ft	1.96m | 6.44ft	NASA RC (4)-10	5	-12.36°
Propeller	1.304m | 4.28ft	0.66m | 2.18ft	NACA0012	5	-39.1°

	Span	Chord	Airfoil
Main Wing	9.04m | 29.65ft	1.96m | 6.44ft	NACA23012
Vertical Stabilizer	1.26m | 4.14ft	0.66m | 2.18ft	Clark Y
Horizontal Stabilizer	3.66m | 12.0ft	1.74m | 5.71ft	NACA2412

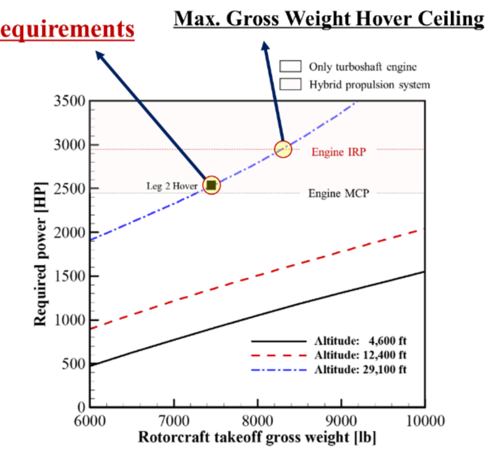
Parameter	Value
Fuselage Capacity	3 crew + 2 Litter
Rotor Solidity	0.099472
Rotor AR	16
Shaft Tilt Angle	2°
Wing Attachment angle	10.25°
Main rotor RPM	241 Normal Operating 220 slowed down
Propeller RPM	1500
# of Generator	2
# of Motor	12
# of Battery Packs	6

Parameter	Value (USD)
Acquisition Cost (Per Unit)	$14.1 million
Direct Operating Cost (Per Flight Hours)	$779.06
Indirect Operating Cost (Per Year)	$1,583,453
Total End of Life Cost	$5.9 million
Lifecycle Cost (Per Unit)	$60 million

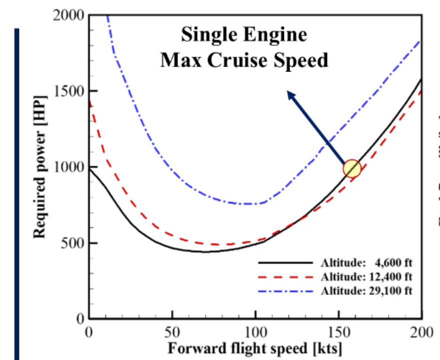
Vehicle Performance

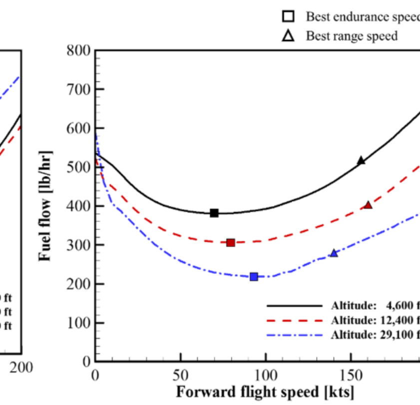
RFP Hover Requirements

Max. Gross Weight Hover Ceiling



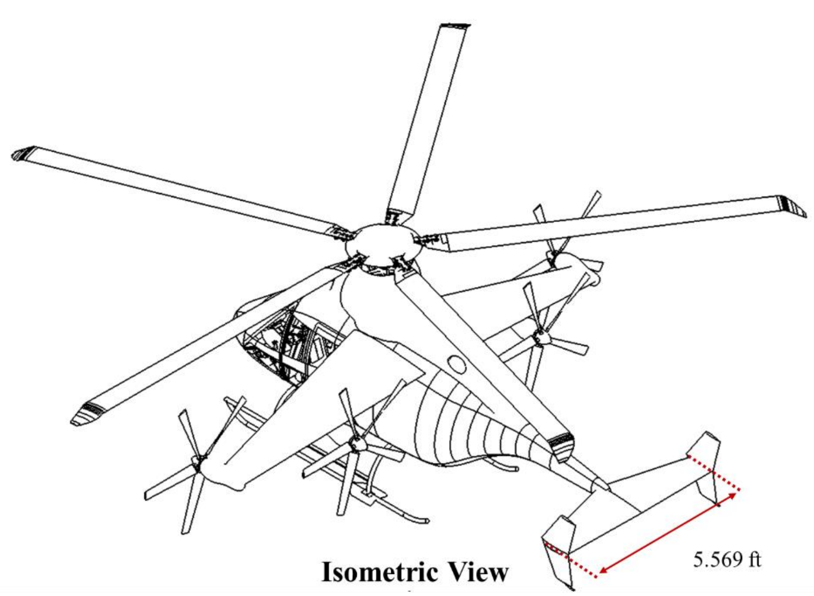
- CRANE combines an advanced series-partial hybridized powertrains with aerodynamically superior rotor blades to achieve unparalleled OGE hover ceiling
  - Battery which is not affected by the lapse rate provides power to operate 4 wing-mounted propellers
- Figure of Merit at 8,870m (29,100ft) ~ 0.8
- Single engine operable @ normal operating condition
- Redundancy system for maximized safety



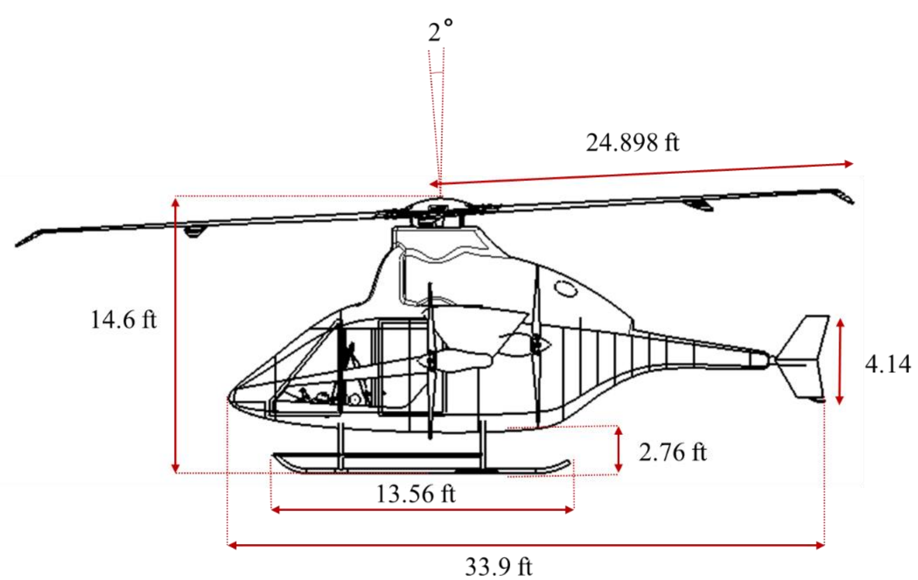


- Efficient rotor blade design at high cruise speed
  - Final blade planform design achieved 6.4% decrease in required power at 100knots cruise flight and 3.5% decrease in 185 knots flight
- Faster than any conventional helicopter
  - 342.62km/h (185knots) cruise speed (design point)
  - Higher speed achievable with corrective measures and anti-vibratory system

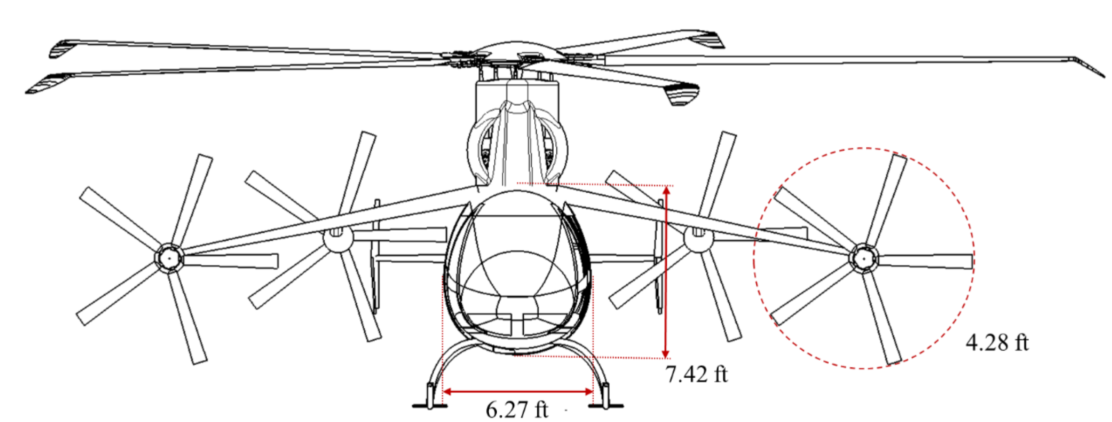
Altitude [ft]	V_{be} [kts]	V_{br} [kts]
4,600	70	155
12,400	80	160
29,100	95	140



Isometric View



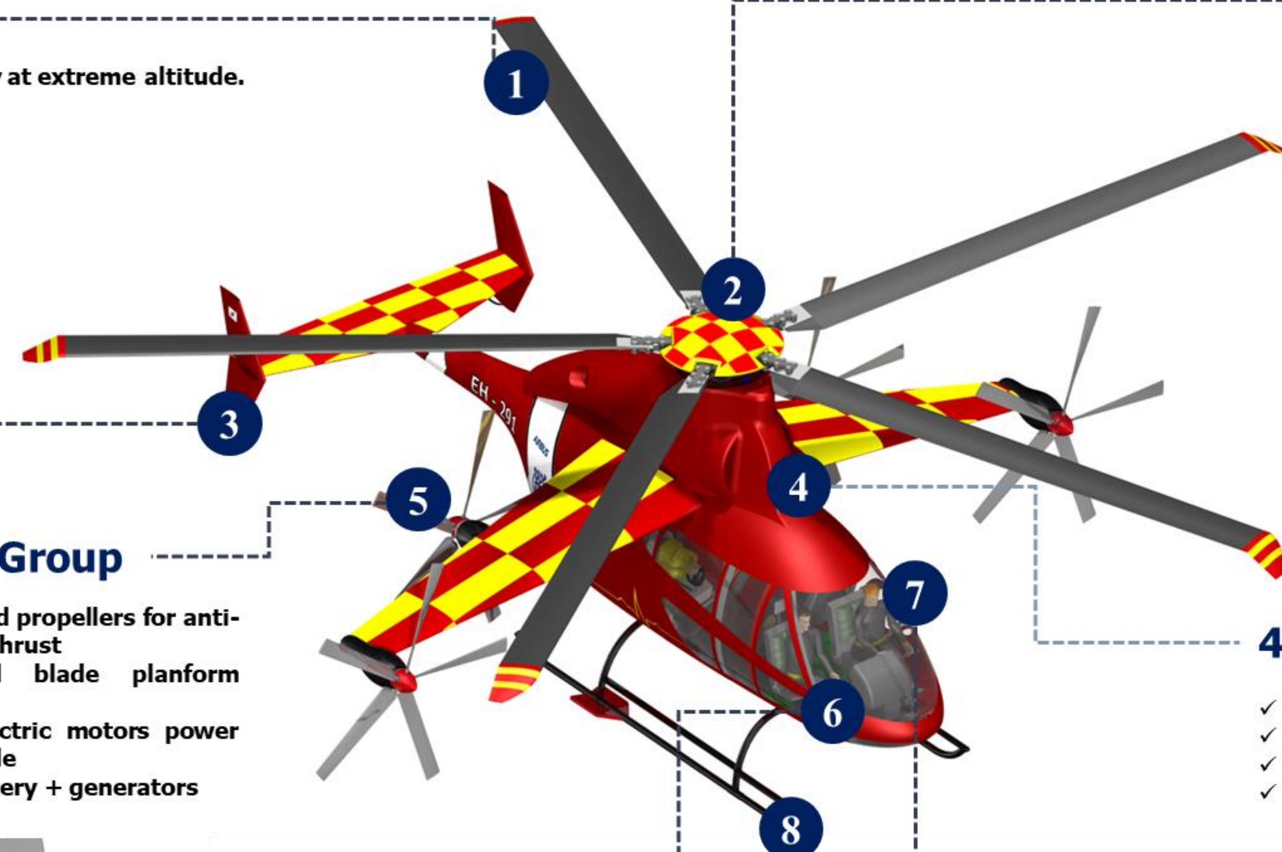
Side View



Front View

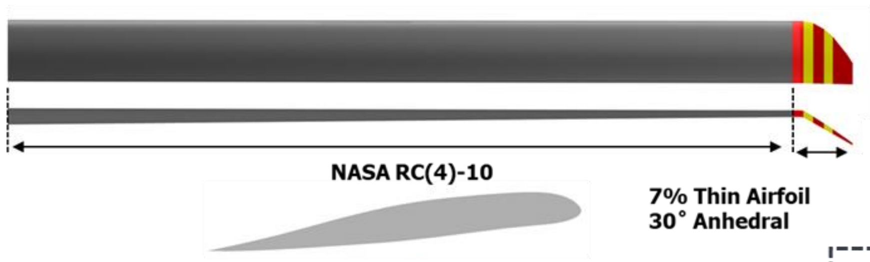
EH-291

Designed for the most demanding SAR mission at Mt. Everest



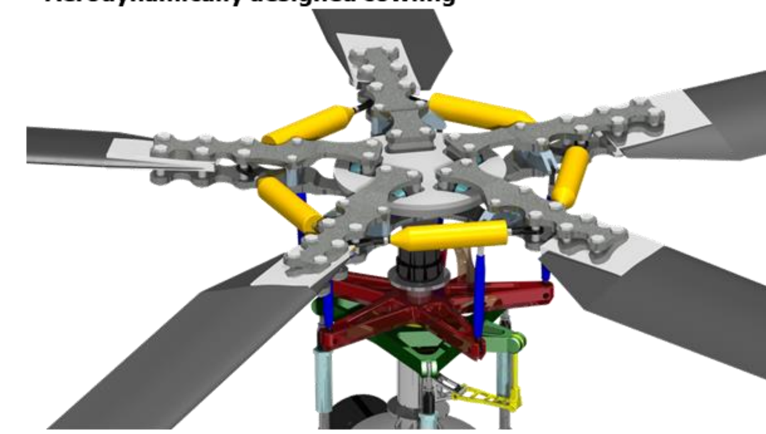
1. Main Rotor Blade

- ✓ Highly optimized blade planform design provides unmatched hover capability at extreme altitude.
- ✓ Efficient cruise flight performance
- ✓ > 3° Stall margin during hover at 8,870m (29,100ft)
- ✓ Lightweight composite material



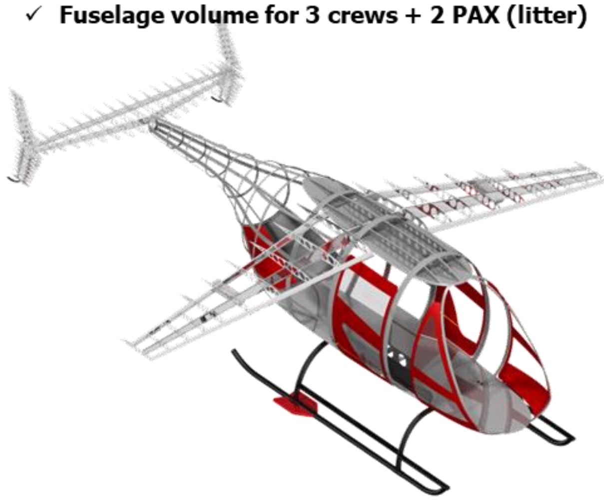
2. Main Rotor Hub

- ✓ Employed Interblade rotor hub for ground resonance
- ✓ Low Drag Profile
- ✓ Highly efficient rotor hub design
- ✓ Aerodynamically designed cowling



3. Airframe Design

- ✓ Airframe Designed for crashworthiness
- ✓ Aerodynamically shaped for high cruise speed
- ✓ Fuselage volume for 3 crews + 2 PAX (litter)

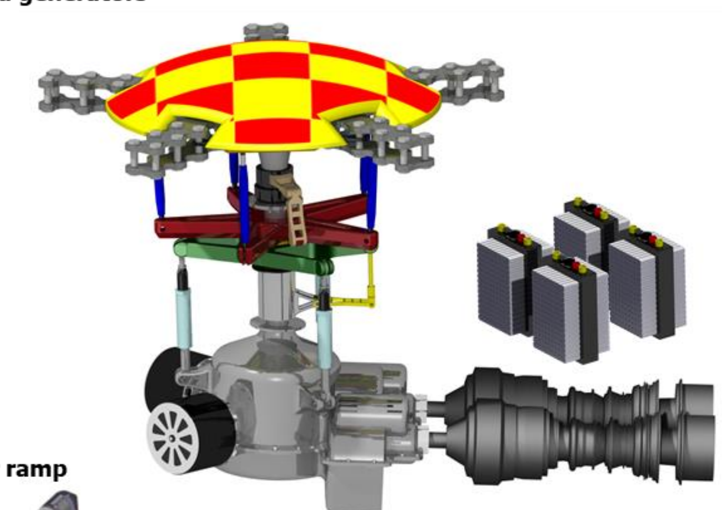


5. Propeller Group

- ✓ Four wing-mounted propellers for anti-torque and cruise thrust
- ✓ Highly optimized blade planform design
- ✓ Three parallel electric motors power each propeller blade
- ✓ Power source: battery + generators

4. Propulsion Group

- ✓ Highly efficient, simple, and compact transmission design
- ✓ Electrified series-partial hybrid turboshaft architecture (GE T700)
- ✓ Variable rotor speed transmission design
- ✓ Wing-mounted propeller powered by a combination of battery and generators



6. Avionics

- ✓ FAA minimum requirements of single pilot day/night IFR operation
- ✓ Intuitive instrumental panel
- ✓ Flight control systems to minimize pilot workload
- ✓ HeliTAWS and infrared camera for SAR mountain rescue operation

8. Retractable Landing Skid

- ✓ Employed partially retractable landing gear for propeller ground clearance
- ✓ Reduced drag profile during forward flight
- ✓ Settling protector for soft ground landing
- ✓ Skid designed to enable 40° slope landing/hover

7. Internal Layouts

- ✓ Internal hoist system rated 600lb
- ✓ Kevlar O_2 tanks for extreme altitude operation
- ✓ Rear unloading ramp with internal hoist system floor ramp
- ✓ Unobstructed field of view

SEOUL NATIONAL UNIVERSITY

Design Summary

In response to the 36th Vertical Flight Society's RFP, *CRANE* is the complete and ultimately the safest platform for the extreme altitude mountain rescue vehicle. For any multi-attribute problem, the selection of the "best" alternative is inherently subjective with no single answer that fulfills all requirements of the design space. However, being the most efficient design it could be, the ultimate design solution proposed by Seoul National University would exceed the requirements set forth by the RFP. The proposed design concludes:

Unmatched Safe Platform

Designed to operate at extreme altitude where flight conditions are unpredictable, *CRANE* is equipped with multiple redundancy systems. With multi highly reliable GE T700 turboshaft engine as part of the hybrid propulsion system, *CRANE* is designed to provide the safest platform for extreme altitude mountain rescue operation. A total of 4 wing-mounted propellers, each of the highly efficient propeller driven by three separate Halbach Array motors, generate thrust and the required counteracting torque. The onboard battery system is able to provide partial power for the propellers to assist the engine in the extreme altitude. The strategic placement of the internal hoist system close to the center of gravity together with the high-performance flight controllers has enabled safe rescue operation of the stranded mountaineers. All the necessary sensors, avionics, anti/de-icing equipment, and highly efficient design have integrated for the design of an unmatched rescue platform.

Superior Performance

Employing the optimized main rotor blade, *CRANE* has demonstrated an outstanding Figure of Merit of 0.8 hovering at 8,870m (29,100 ft). *CRANE*'s serial-partial hybrid drivetrain with variable main rotor speed has attained an unmatched cruising speed of 185knots to reach and perform rescue operation within the "Golden Hour".

Simple and low maintenance

The advanced and highly efficient electrified system has contributed to the simplicity in design and reliability would procure economic viability. Every component is monitored by a central Health Usage Monitoring Systems (HUMS) that support ground crew for maintenance and alert the pilot for a possible issue. By adopting a redundant system that is simple and efficient, enhanced fleet readiness through establishing a systematical rescue procedure can be acquired.