Undergraduate Design Team
The Pennsylvania State University – University Park

36th Annual Vertical Flight Society
International Student Design Competition 2019

PSU-73 Cardinal Rescue Helicopter Conceptual Design

Sponsored by Airbus

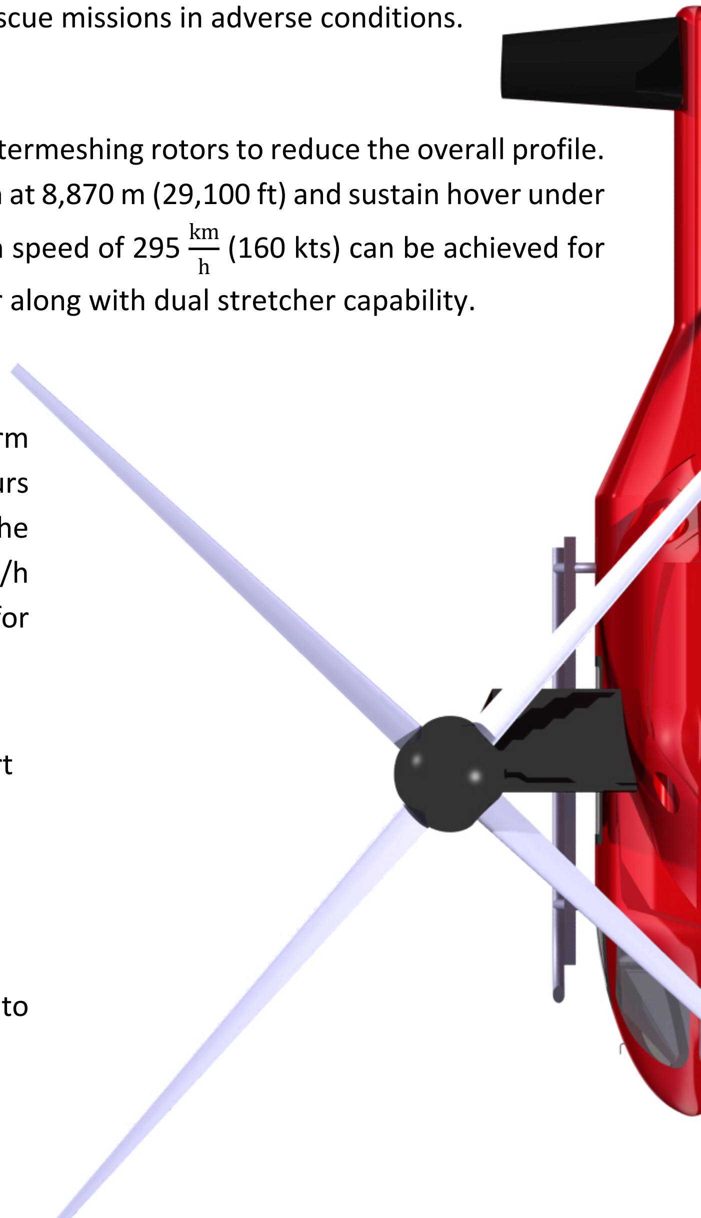
PennState College of Engineering | AEROSPACE ENGINEERING

Introduction

The Pennsylvania State University Undergraduate Student Design Team presents *The Cardinal-73 Search and Rescue Helicopter* to the 36th Annual VFS International Student Design Competition Board and Airbus. The design illustrates an innovative approach to high altitude search and rescue missions in adverse conditions.

Design Capabilities

The Cardinal is a side-by-side helicopter that features canted intermeshing rotors to reduce the overall profile. The vehicle can complete high altitude search and rescue mission at 8,870 m (29,100 ft) and sustain hover under single pilot day or night IFR conditions. Additionally, a maximum speed of 295 $\frac{\text{km}}{\text{h}}$ (160 kts) can be achieved for forward flight. The cabin features a pilot, co-pilot, EMT Operator along with dual stretcher capability.



The Mission

The mission is split into three legs designed to efficiently preform a rescue mission. The mission is required to be completed 3 hours including the 30-minute hover rescue. In order to complete the mission within the time frame, a level cruise speed of 259 km/h (140 kts). Additionally, a fuel margin of 10 percent is required for each leg.

Leg 1

- Take off from international airport and land at smaller airport
- Climb: 2,378 m (7,800 ft)
- Level Cruise: 135 km (73 nautical miles)
- Refueling for 20 min

Leg 2

- Take off from smaller airport, preform rescue, then return to smaller airport
- Climb: 2378 m (16,700 ft)
- Level Cruise: 28 km (15 nautical miles)
- Hover out of ground effect and preform rescue at 2378 m

Leg 3

- Refueling for 20 min
- Take off from smaller airport and return to international airport
- Descent: 2478 m (7,800 ft)
- Level Cruise: 135 km (73 nautical miles)

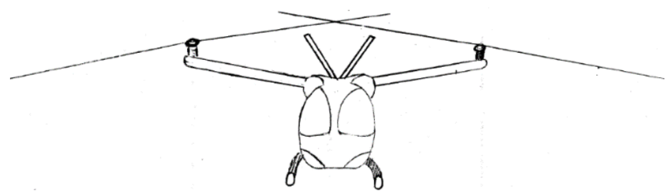
Design Process

STEP 1: Configuration Selection

- Mission requirements were evaluated
- Initial configuration selection was determined by a criteria matrix

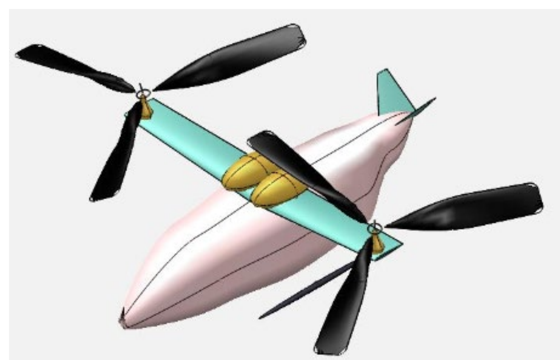
Configuration		Traditional	Tandem	Coaxial	Side-by-side
Total		34	45	39	46
Criteria	Score Weight				
Rotor Radius	2	3	2	3	3
Safety	3	2	3	4	3
Power required at Sea Level	3	2	4	3	3
Cost	1	4	2	2	2
Cross wind stability	2	2	3	2	4
CG Limit	2	1	3	1	3
Cruising speed	2	3	3	2	3

*score weights from 3 (highest) to 1 (lowest) *4 is the highest, 1 is the lowest



STEP 2: Rotorcraft Optimization

- Gross weight was calculated
- Interior was designed for rotorcraft size
- Minimum rotor cant and separation distance was found
- Engine and proper power margins were found
- Optimal rotor for hover at altitude was designed
- VSP model was generated

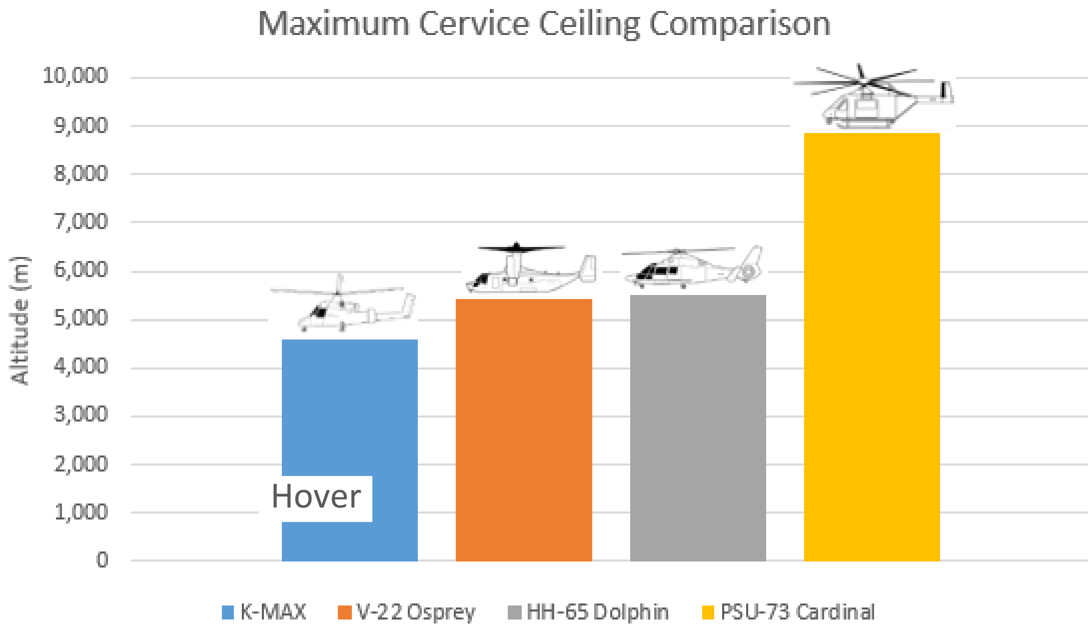


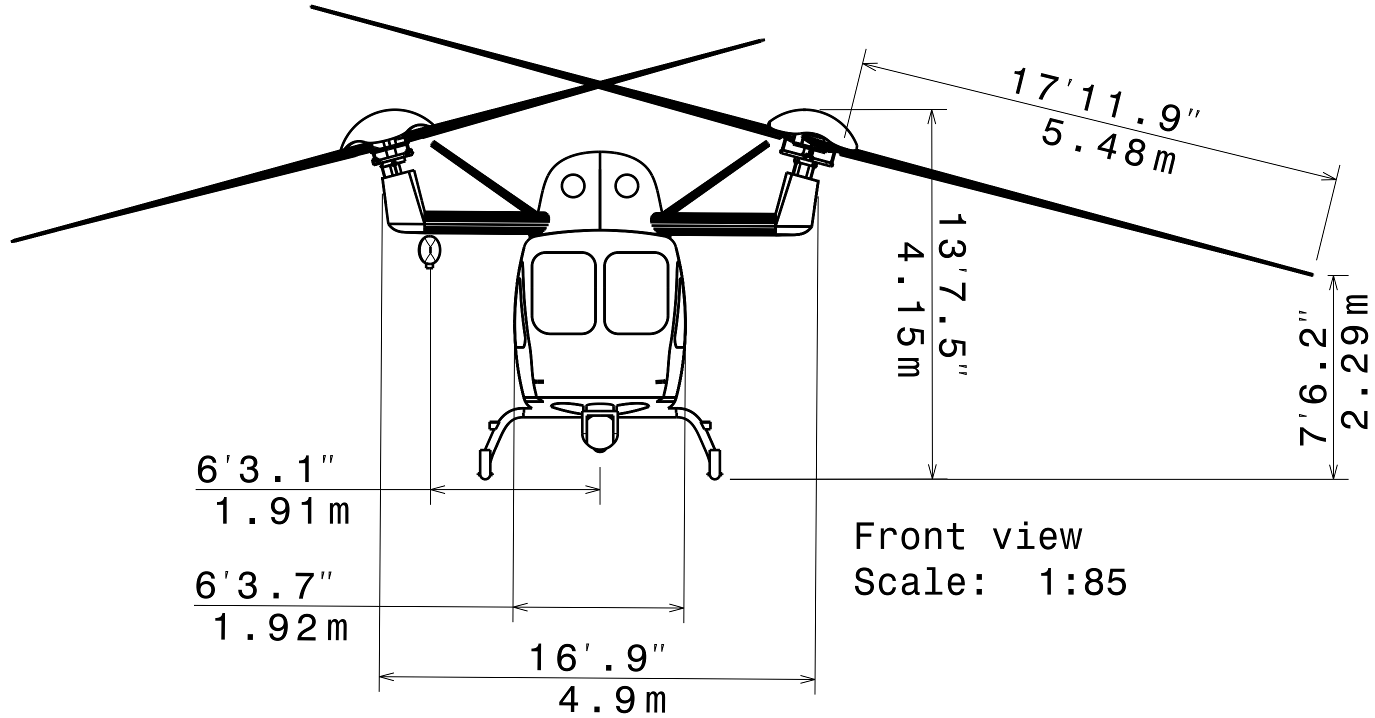
STEP 3: Fully Developed Rotorcraft

- CATIA model generated using information from step 2
- Avionics suite was chosen
- Rescue capabilities were integrated
- ECS systems were integrated
- Rotorcraft simulation was preformed
- Mission requirements were verified
- Rotorcraft performance was developed

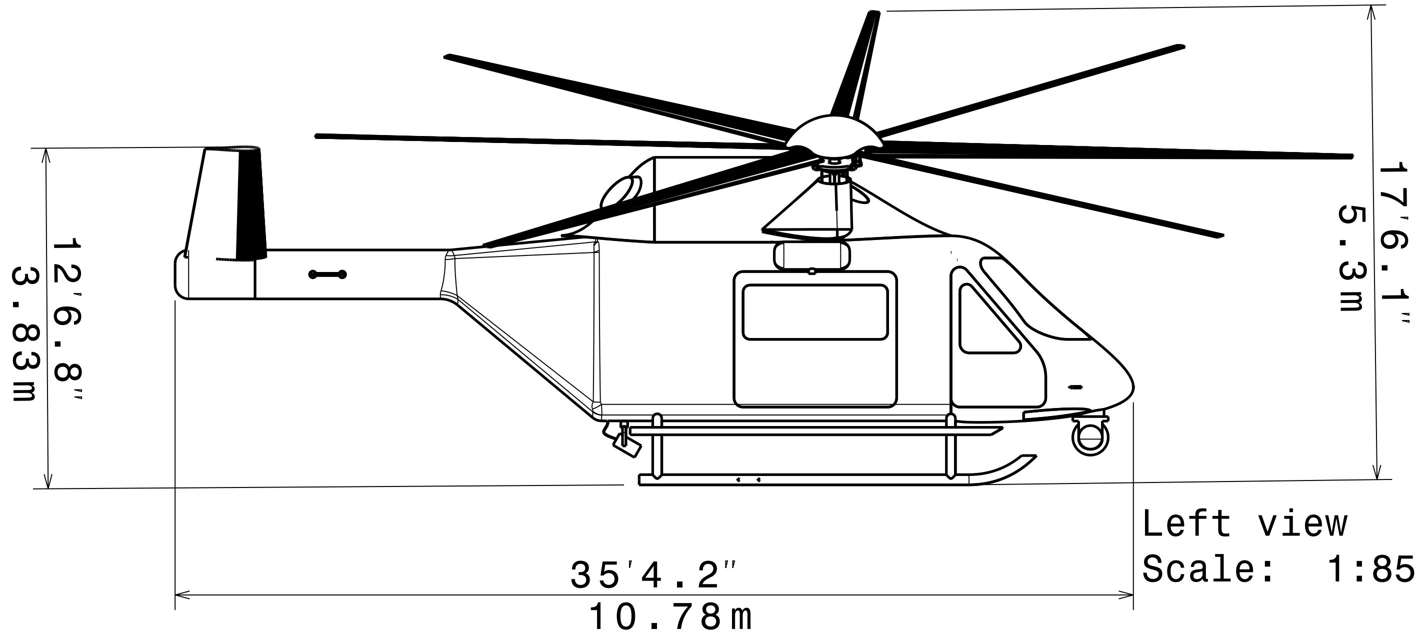
PSU-73 Cardinal Design Specifications

The Cardinal was design was around Leg 2's hover segment due to the particular difficulties of hovering at high altitude out of ground effect (HOGE). In order to achieve this, a high power of installed was required with low disk loading. When this is done, a ceiling can be achieved. When comparing the hover ceiling of rotorcraft used as design bases, The Cardinal has nearly twice the hover ceiling as the K-Max and a substantial margin on the V-22 Osprey and HH-45 Dolphin. The Cardinal also has very similar stats compared to the dolphin in length and max speed.

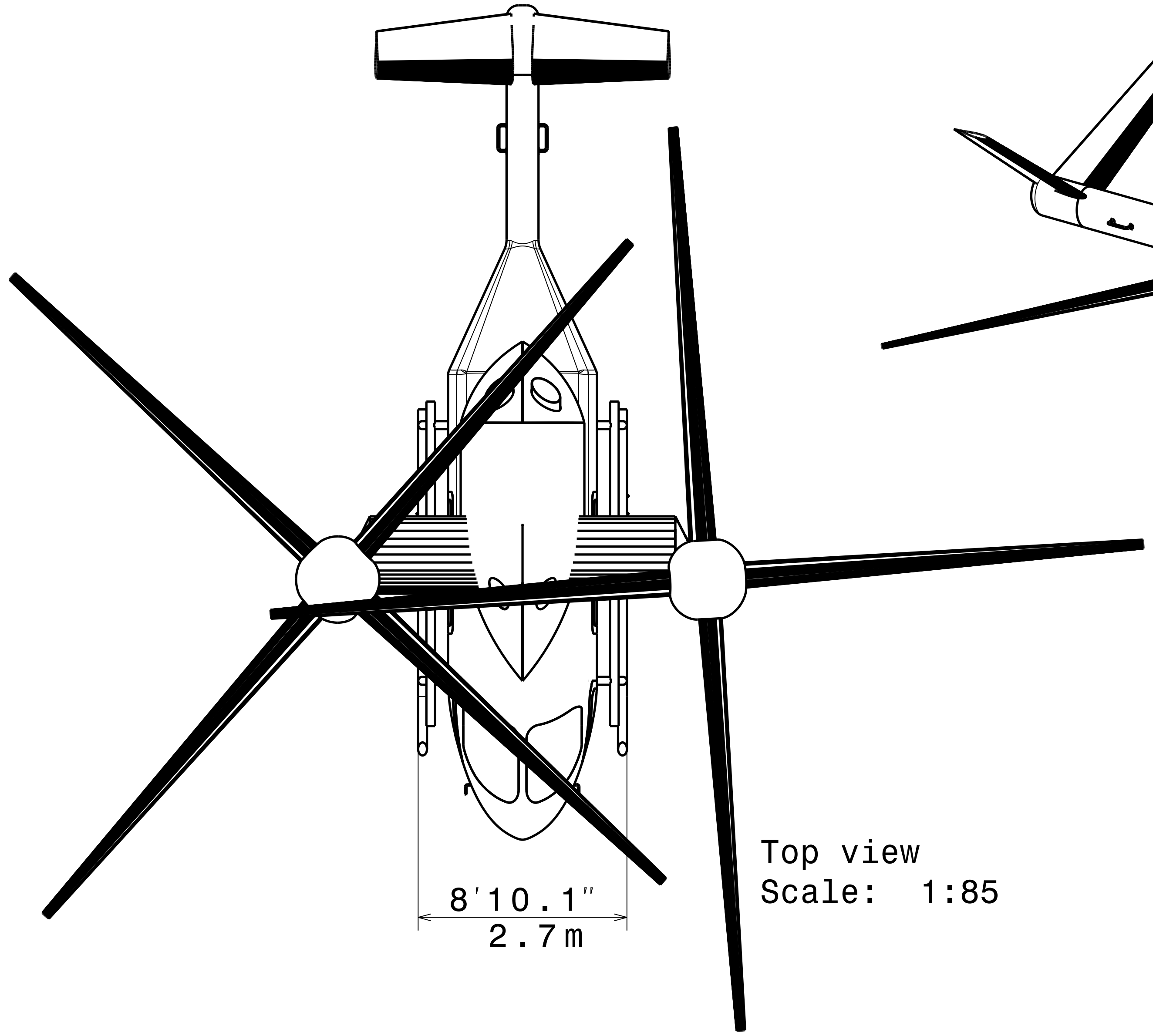




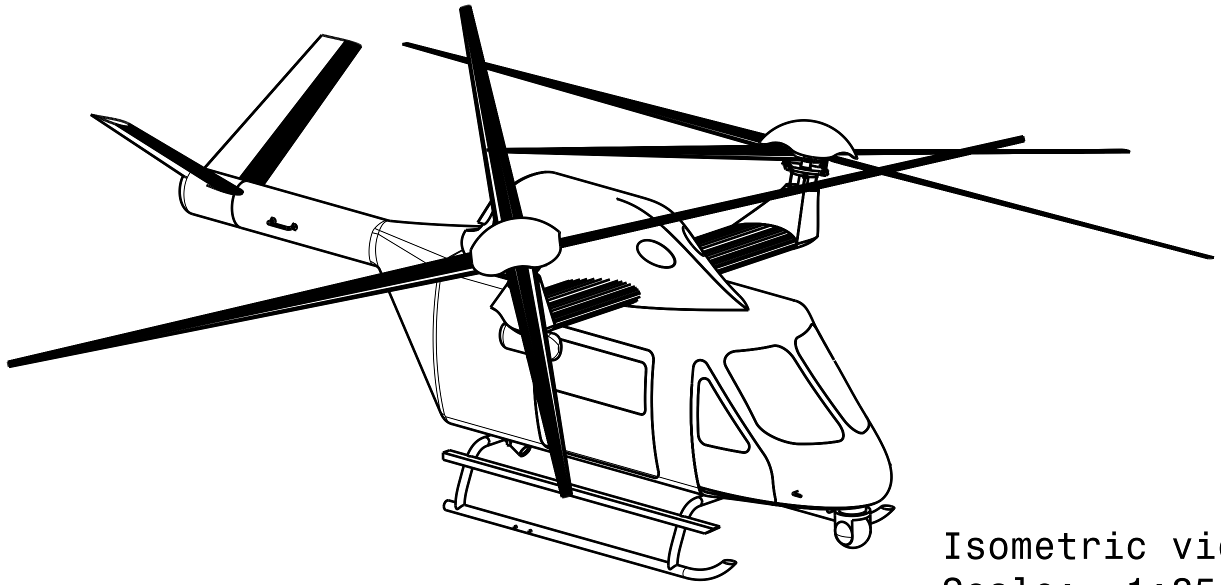
Front view
Scale: 1:85



Left view
Scale: 1:85



Top view
Scale: 1:85



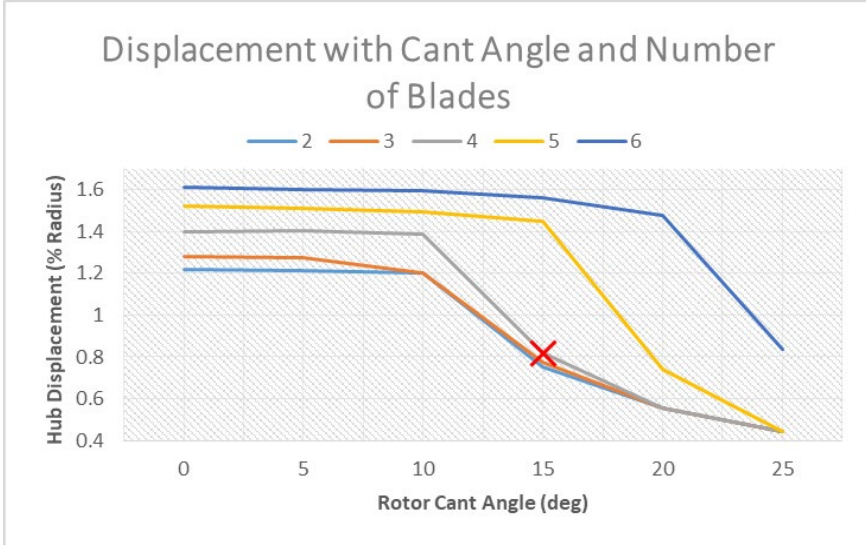
Isometric view
Scale: 1:85

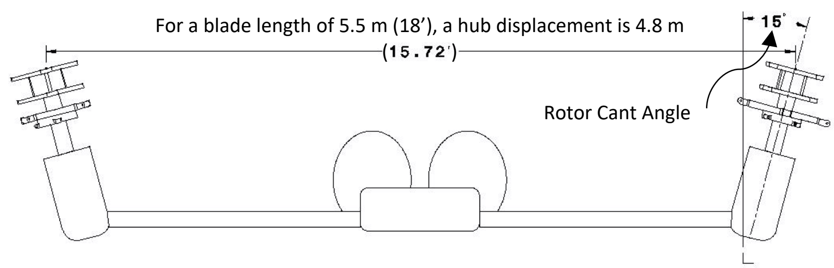
PENN STATE UNIVERSITY					
DRAWING TITLE	PSU-73 CARDINAL				
DRAWN BY	RED8091	DATE	4/18/2019		
CHECKED BY	XXX	DATE	XXX		
DESIGNED BY	XXX	DATE	XXX		
SIZE	A3	DRAWING NUMBER	FD-1	REV	A
SCALE	1:85	WEIGHT(lb)	5700	SHEET	1/1

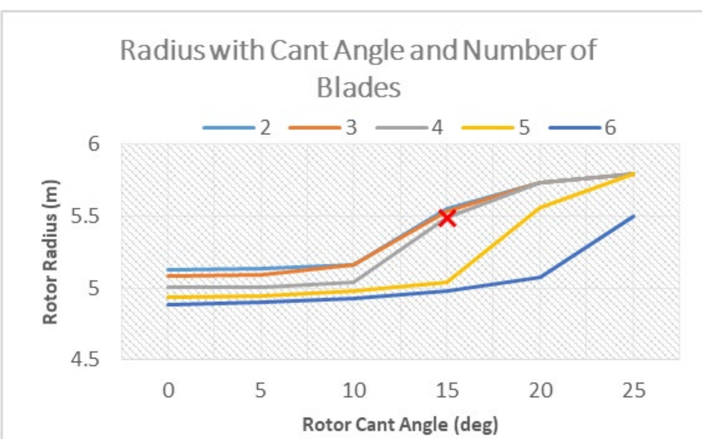
PSU-73 Cardinal Optimization

1. Rotor Layout Analysis

In order to optimize the rotor, it was necessary to compare rotor configurations with varying number of blades and increasing cant angle. This analysis determined how close the rotor hubs could be placed together without causing contact between the blades, taking into consideration worst case lead and lag scenarios. The graph to the right shows the results of this analysis, mapping the hub displacement in terms of percent rotor radius against the rotor cant angle. Each color represents a different number of blades. One can observe the convergence of hub displacement found with increasing cant angle. The final layout selection is marked with a red "X" for reference.

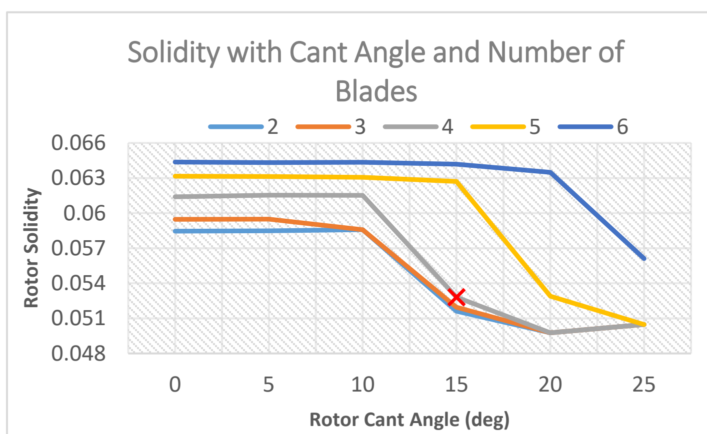


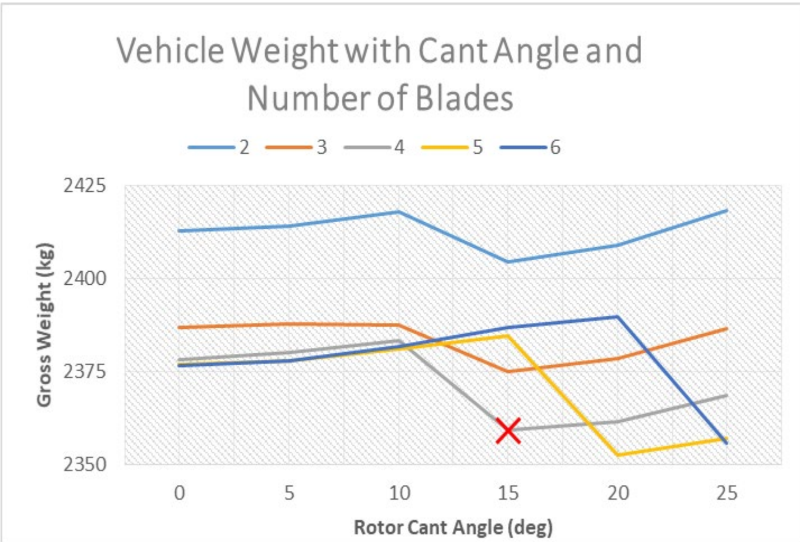




2. Blade Dimension Calculation

The next step in optimizing the rotorcraft involved calculating the required blade dimensions for each layout, based on the hub displacement found in the previous analysis. The rotor radius, solidity, average chord, and dimensional hub displacement were determined in order to sustain hover above 8,870 m (29,100 ft).



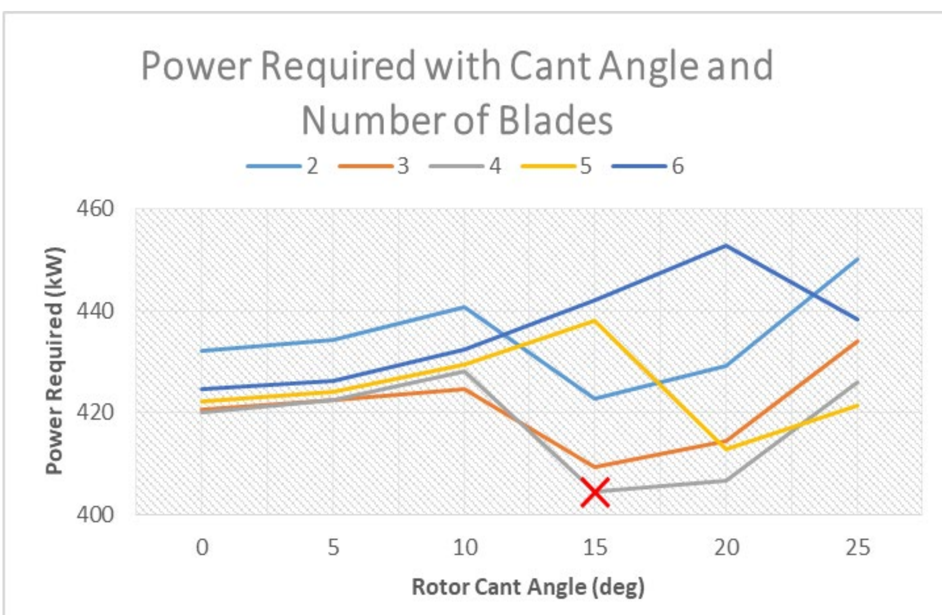


3. Vehicle Weight Comparison

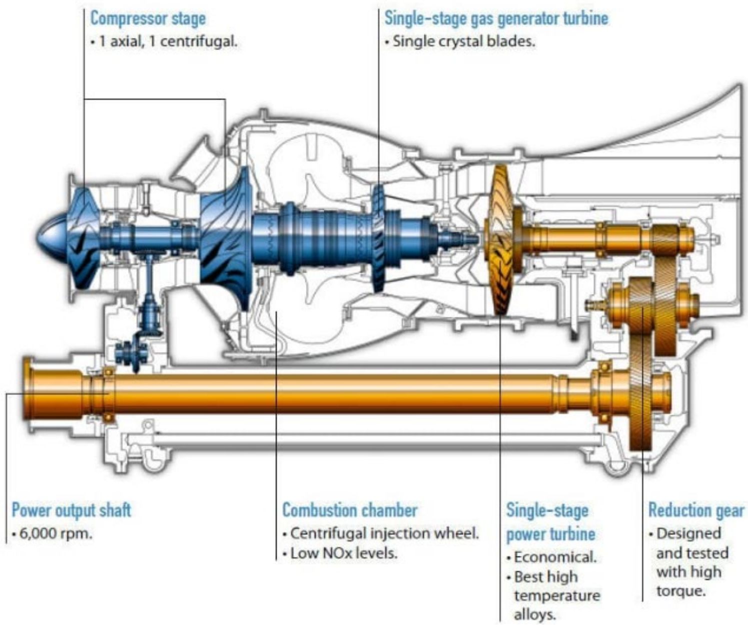
The blade dimensions and hub displacements calculated for each layout were used to conduct a more detailed weight trend analysis, the results of which are shown in the graph to the left, which displays gross weight vs cant angle. Once again the number of blades in each layout are represented by different colors, and the final layout is marked. For each layout, the number of blades and blade dimensions contributed to updated rotor weights, while the varying hub displacements were treated as additional wetted area of the fuselage as well as wing structures, to account for the load bearing nature of the internal spars.

4. Power Analysis and Layout Selection

The limiting factor of vehicle performance for this mission was determined to be the power required to hover at altitude during Leg 2. As a result, the final layout was selected to minimize the power required to hover at 8,870 m (29,100 ft). This parameter was calculated using BEMT. The graph below shows the hover power for each rotor layout at altitude. One can note that the final layout selection coincides with the minimum power level.



Engine Performance



Safran 2N is selected as the engine as it provides required power to the rotorcraft for all the three legs. It’s a turboshaft engine and can provide 735.3 Kw (986 SHP) of power for takeoff at sea-level. As the required power is high during the Hover period during second leg (30 minutes), two engines are needed to fulfil the requirements.

Altitude (m) (ft)	Ambient Temperature (°C) (°F)	Ambient Pressure (Pa) (psi)	Take-off Power(Kw) (shp)
4600	25 (77)	85577 (12.4)	595.8 (799)
12400	10 (50)	63428 (9.2)	469.8 (630)
29100	-23 (-9.4)	31341 (4.6)	230 (308)

Three fuel tanks are used to provide enough fuel for the rotorcraft throughout the mission. Fuel used is Kerosene and is refueled twice during the whole mission. The whole volume of fuel system (including fuel tanks and pipeline) is 132.6 gallons.

Weight and Center of Gravity

Component	Weight (kg/lb)	Longitudinal Position (m/ft)
Main Rotor Blades	115.30/254.2	0/0
Main Rotor Hub	99.24/218.8	0/0
V-Tail Stabilizer	17.78/39.2	-7.31/-24
Fuselage	286.33/631.25	-1.67/-5.5
Landing Gear	106.45/234.7	-.60/-2
Nacelles	90.00/198.4	0/0
Engine Installation	273.51/603	0/0
Propulsion Subsystems	68.49/151	0/0
Fuel Systems	11.47/25.3	0/0
Drive System	203.29/448.2	0/0
Cockpit Controls	10.56/23.3	3.04/10
System Controls	14.01/30.9	1.52/5
Instruments	15.55/34.3	3.35/11
Hydraulics	14.74/32.5	0/0
Electrical Subsystems	175.49/386.9	0/0
Avionics	68.03/150	3.65/12
Furnishings/Equipment	57.78/127.4	0/0
Air Conditioning/Anti-ice	21.00/46.3	0/0
Manufacturing Variation	10.47/23.1	0/0
Fuel Weight (Wings)	272.15/600	0/0
Fuel Weight (Rear Tank)	167/368.9	2.93/-9.625
Pilots	170.00/374.8	1.28/4.22
EMS Equipment	150.00/330.7	0/0
Hoist	41.73/92	.25/-.83
FLIR Camera	29.93/66	2.87/9.44
Night Sun Spotlight	11.33/25	-2.36/-7.75
Patients/Stretchers	170.00/374.8	-.92/-3.04
Flight EMT	85.00/187.4	-2.5/-8.20
Total	**2589.76/5709.45**	**-.35/-1.15**

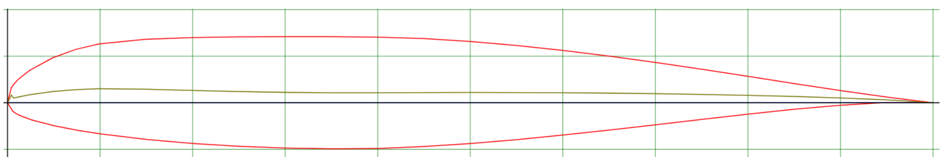
- The *Cardinal* is designed to perform at a GTOW of **2590 kg (5710 lb)**
  - Without Payload -2420 kg (5335 lb)
  - Empty Weight -2148 kg (4735 lb)

CG Location			
	X_{CG}	Y_{CG}	Z_{CG}
Centimeters	-35.05	2.62	142.95
Inches	-13.8	1.032	56.28

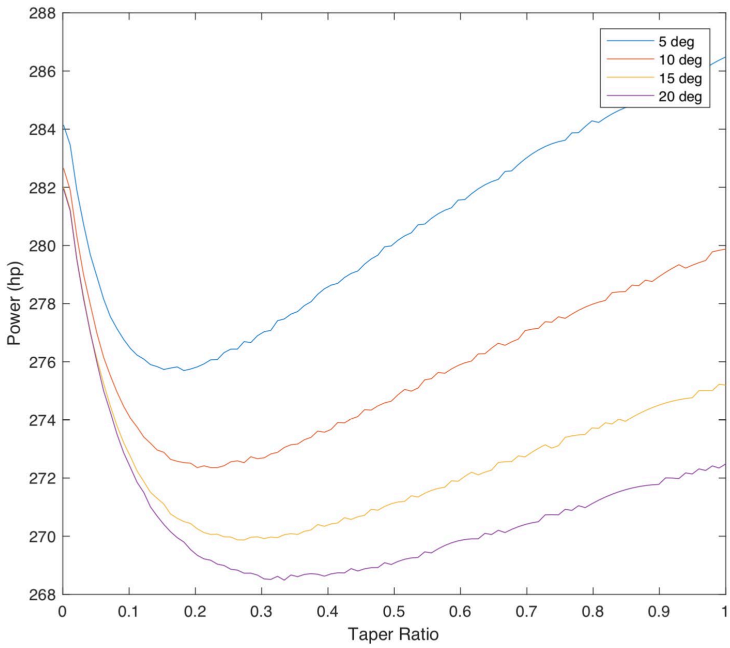
- Center of Gravity calculations are measured from the center of the rotor hubs.

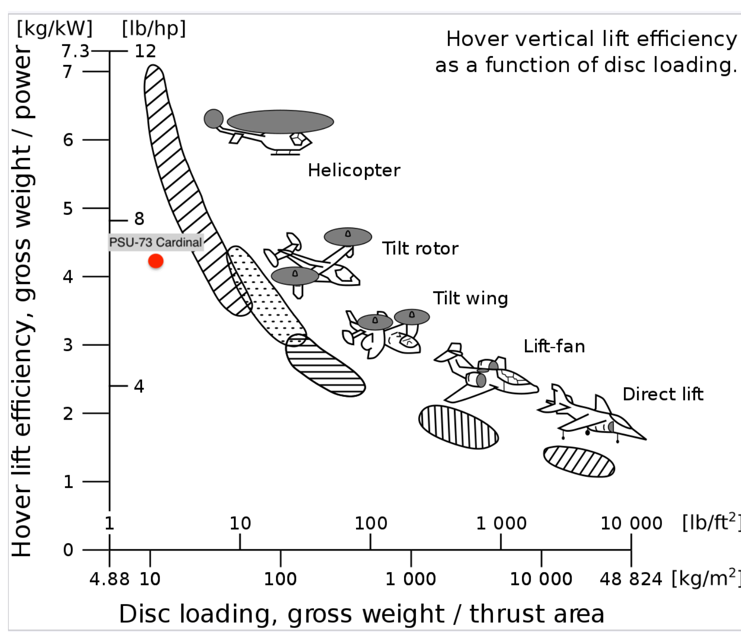
Rotor Blade Design

The *Cardinal's* rotors have been optimized to be able to perform the rescue mission at 29,000 feet. To do this, optimum taper and twist and an airfoil with a high lift to drag ratio was used.



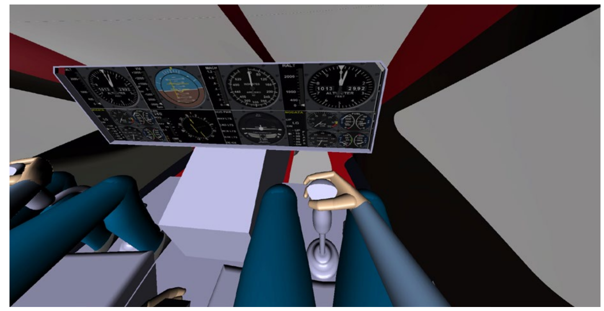
Blade Specs	
Airfoil	NACA 64(1)-212 MOD B
Taper	1:3
Twist Rate	15 degrees





Avionics Suite

Fly-By-Wire



The avionics suite will encompass different systems to help making the rescue mission easier on the pilots and the rescue team. The helicopter will have a **Fly-by-wire** system to help all the different systems used onboard have full authority on the helicopter. Also, controlling the helicopter in a degraded visual environment and bad weather conditions such as the peak of Mount Everest will be very difficult on pilots without the aid of the FBW system.

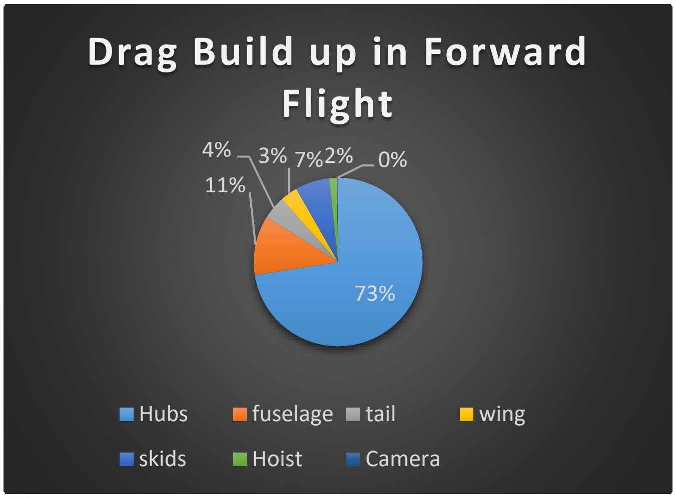
TrakkaBeam & TrakkaCam

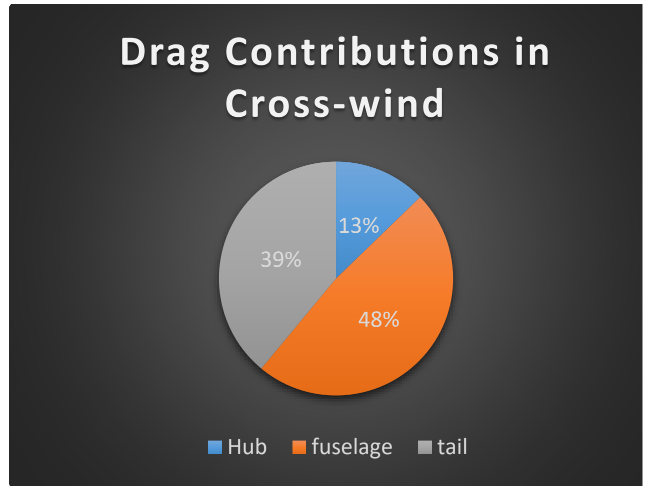
Consuming **800 Watts** and weighing less than **18kg** makes the TrakkaBeam TLX a great choice because of its efficient power consumption and light weight compared to other choices available in the market. It also works greatly with the TrakkaCam SWE-400LE, as shown in the picture, which is equipped with cooled thermal sensors and **video target tracking** on a 4-axis gyro-stabilized platform providing 360-degree flexibility. **Thermal imaging** is essential in the rescuing mission since it will help the pilots distinguishing the location of the people especially in a whiteout since in these conditions the pilots will not be able to distinguish the people by the naked eye.

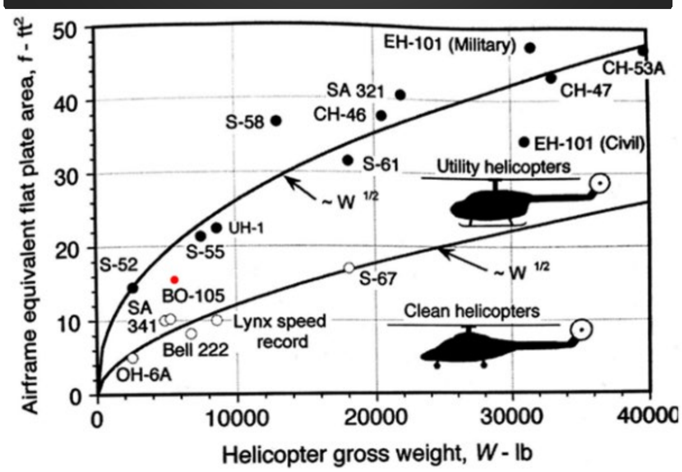
Communications, Displays & Controls

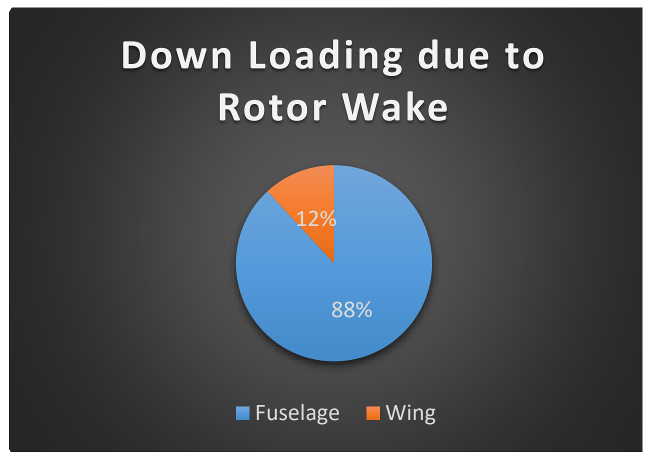
Having the Garmin GSR 56 on top of the regular radio transceiver will enable the rescuing team to have **satellite communication** with the nearest hospitals explaining the incoming cases and might be also used to guide the paramedics onboard to perform certain procedures depending on how critical the case is. The helicopter will also be equiped with 4 multifunction EFI-1040 displays helping the pilots aiding the pilots in easily planning the flight and displaying all the important data. The **Multi-Mission Management System (MMMS)** offered by Universal Avionics helping pilots choose between six different search patterns facilitating the job of the pilot in finding the target easily especially when accompanied with the TrakkaCam and the FBW system which can make the search pattern automated with no input from the pilot.

Drag Reduction and Crosswind Capability







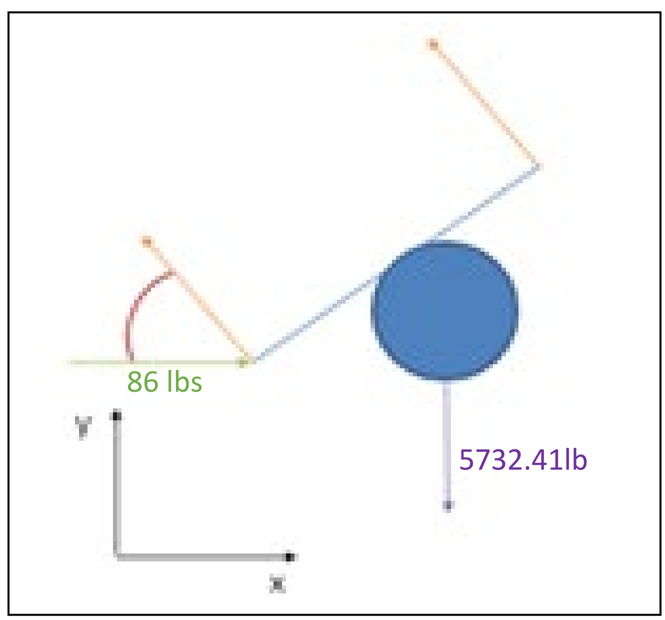


- The Cardinal’s calculated Flat-plate area is 15.78.
- In the Chart above the Cardinal is labeled with a red dot.
- This shows that the cardinal follows the trend shown by the historical data.

- The Cardinal can hover in a 40 kts crosswind and execute its mission safely.
- To prove this, we used the equation below.
-

  $\phi = \tan^{-1}(\text{Side force}/(\text{Weight}+\text{Down Force})$

- Using this equation, it shows that the helicopter will have to bank into the wind by 1° to maintain stationary hover.



ECS and Rescue Capabilities

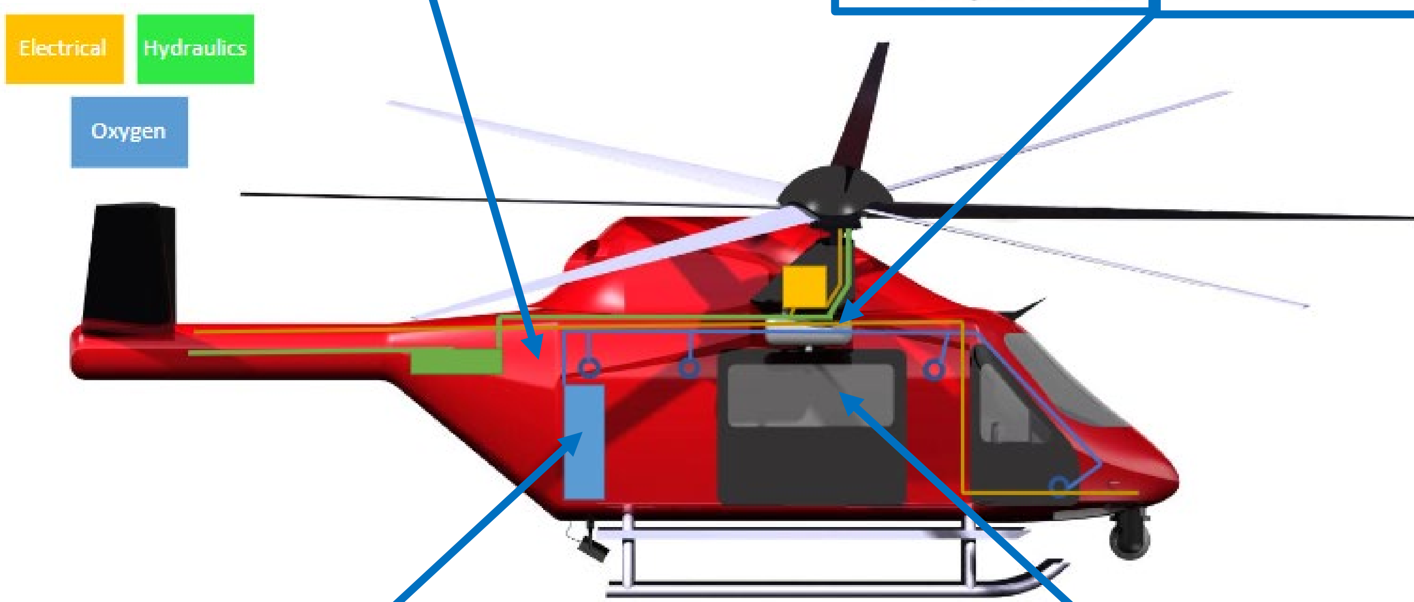
In order to accommodate a long-line rescue, the rotorcraft was fitted with two hoist compatible stretchers and a stretcher compatible hoist. Additionally, all the medical equipment required is allotted for in the cabin, reference H145 medical equipment for a full list. The cabin will also include a central heating and oxygen system with individual oxygen ports throughout the cabin for increased mission capabilities; the oxygen lines are indicated in blue. Additionally, the electrical and hydraulic lines are indicated in yellow and green respectively.

<u>Leibherr Type 12</u>

- Full cabin electric heating system
- Range: 15-30°C (59-86°F)

<u>Goodrich 44311 Hoist</u>

- Stretcher compatible
- Lifting load: 272 kg (600 lbs)
- Cable length: 61 m (200 ft)



<u>Essex 10 LITER LOX READY TO INSTALL (RTI)</u>

- Full cabin LOX system with ports throughout
- Supplementary gaseous oxygen will be on-board

<u>Cobham Mobile Aircrew Restraint System (MARS)</u>

- Operator will be attached to MARS system in the case of a fallout event

Rescue Procedure

1. Receiving in the PAX

The cabin door will be opened after the helicopter is stable in hover. A stretcher will be sent down and the PAX will be secured on the stretcher. The PAX will be raised up and stabilized outside of the helicopter by the operator making contact.

2. Pulling in the PAX

The operator rotates and pulls in the PAX. The PAX should be pulled in feet first in order to secure properly within the helicopter.

3. Securing the PAX

The operator secures the PAX by locking in the stretcher. In the case where two PAX would be rescued, the first PAX would be placed on the top and the second PAX on the bottom. The cabin door will then be closed, and return can begin.

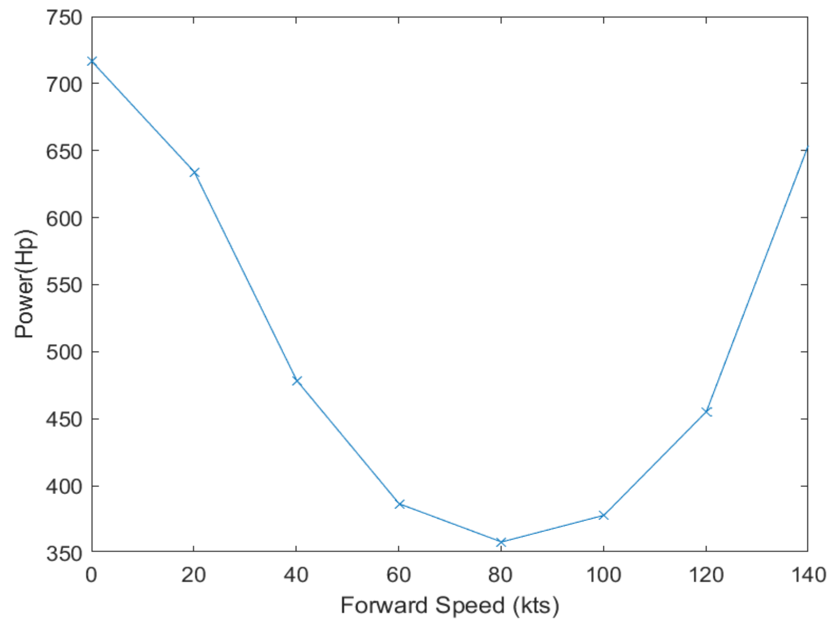
PSU-73 Cardinal Simulation

Modifying the Code

The simulation code used was developed by modifying PSUHeloSimUH60 which was a simulation code developed by Horn et al to simulate the performance of the UH-60 (Blackhawk). The code was modified to simulate the performance of The Cardinal in different scenarios that are useful to analyze and help in reassuring that it is capable to meet the requirements and more. The tail, fuselage, rotor and blades were all modified to match that found on the Cardinal design.

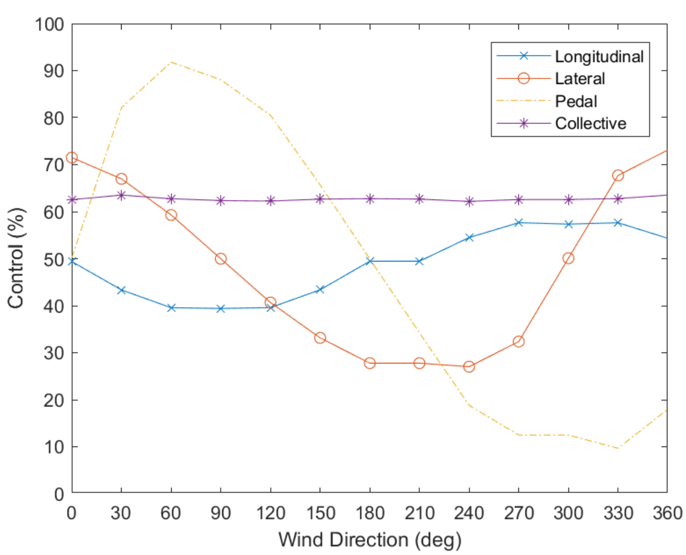
Forward Flight

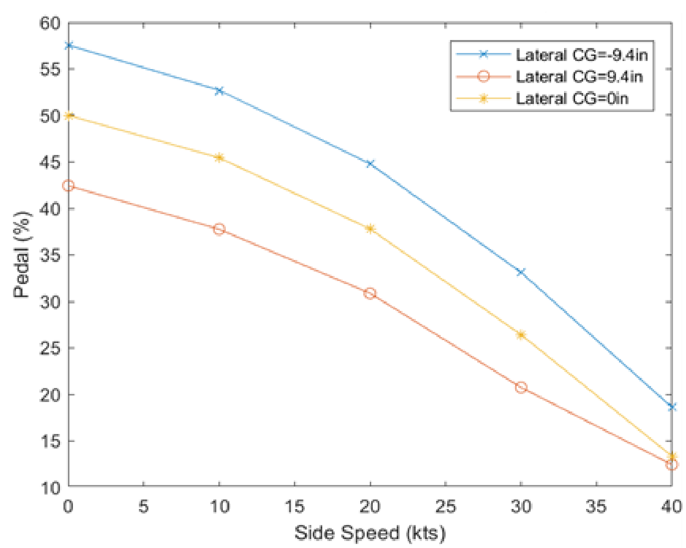
The forward flight scenario is used to test the performance of the helicopter in the first leg. The helicopter is required to cruise in at 140kts or more. The values are calculated at an altitude of 8,800m (29,000ft) which is considered as the most critical altitude for this helicopter's mission. The following graph displays the amount of power required for hover and different cruise speeds. The results show that the power available by the engines will be sufficient for the mission. Also, flapping and the helicopter attitude were tested and analyzed in the full report.



Hover in 40kts Windspeed & Lateral CG Alteration

The below graphs show the controls needed to maintain the stability of the helicopter in these conditions. The controls maintain a 10% control margin because of tuning the control gearing to accommodate these cases.





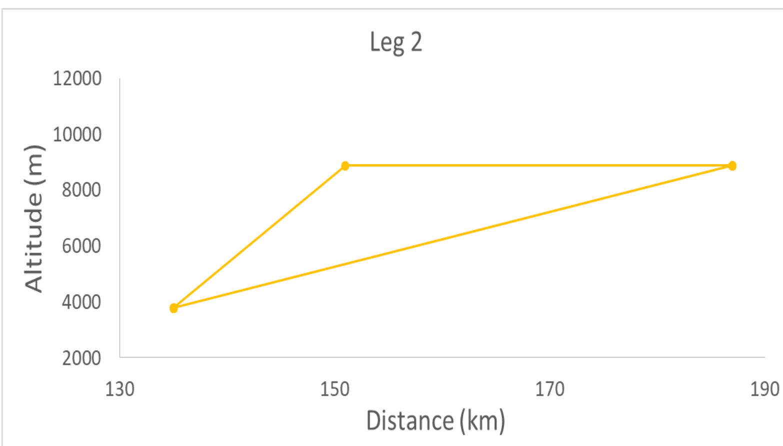
PSU-73 Mission Performance

Leg	1				
Altitude (m)	1402	1402	3780	3780	3780
Time (min)	0	2	3.5	31	33
Distance (km)	0	0	3.4	135	135
Fuel Flow (kg/hr)	151	336	320	162	149
Fuel Burned (kg)	5	0	8	74.4	5
Fuel Available (kg)	204	199	191	116.6	111.6
Payload (kg)	405	405	405	405	405
Weight (kg)	2415	2342	2334	2260	2255
Power Required (kW)	418	1044	1005	471	407
Power Available (kW)	1306	1306	1109	1109	1109
Airspeed (km/hr)	0	128	144.5	287	0
Rate of Climb (m/min)	0	1628	1555	0	0
Notes	hover	climb		cruise	hover

Leg 1 is completed with a 55% fuel margin in 33 minutes. The high installed power of the aircraft allows a cruise speed of 287 km/hr (155 kts) in the transfer portion of Leg 1.

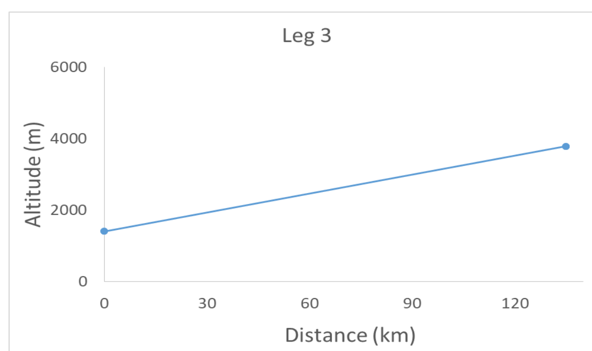
PSU-73 Mission Performance

Leg	2							
Altitude (m)	3780	3780	8870	8870	8870	8870	3780	3780
Time (min)	53	55	60.5	70	100	100	110	112
Distance (km)	135	135	151	187	187	187	135	135
Fuel Flow (kg/hr)	160	320	169	129	172	127	116	153
Fuel Burned (kg)	5.2	0	22.2	20.6	86	0	20	5.2
Fuel Available (kg)	204	198.8	176.6	156	70	70	50	44.8
Payload (kg)	575	575	575	575	575	575	575	575
Weight (kg)	2586	2512	2490	2469	2383	2383	2363	2358
Power Required (kW)	459	1005	501	294	518	280	209	428
Power Available (kW)	1109	1109	590	590	590	590	1109	1109
Airspeed (km/hr)	0	144.5	198	228	0	-228	-287	0
Rate of Climb (m/min)	0	1445	421	0	0	-512	-512	0
Notes	hover	climb		cruise	hover	descend		hover



Leg 2 is completed with a 22% fuel margin in 79 min. The vehicle performance at the critical leg of the mission exceeds expectations. The excess power at 8,870 m (29,100 ft) provides a respectable rate of climb of 421 m/min (1,380 ft/min) and maximum forward speed of 228 km/hr (123 kts) at that altitude.

Leg	3			
Altitude (m)	3780	3780	1402	1402
Time (min)	132	134	161	163
Distance (km)	135	135	0	0
Fuel Flow (kg/hr)	159	151	148	155
Fuel Burned (kg)	5.2	0	67	5.2
Fuel Available (kg)	204	198.8	131.8	126.6
Payload (kg)	575	575	575	575
Weight (kg)	2586	2512	2445	2440
Power Required (kW)	459	413	402	435
Power Available (kW)	1109	1109	1306	1306
Airspeed (km/hr)	0	-287	-315	0
Rate of Climb (m/min)	0	-88.3	-88.3	0
Notes	hover	descend		hover



Leg 3 is completed with a 62% fuel margin in 51 minutes, for a total mission time of 163 minutes. Mission time is crucial for a rescue vehicle, and the Cardinal performs this mission 17 minutes under the allotted three hours.

Summary

The PSU-73 Cardinal is The Pennsylvania State University’s novel approach to high-altitude search and rescue missions. The rotorcraft combines optimum rotor cant and separation distance to minimize profile. Additionally, advanced avionics are implemented to perform missions in adverse weather conditions.

RFP specific requirements that were fulfilled:

- Cruise speed: 315 km/h (170 kts)
- Hover ceiling (HOGE): 8870 m (29,100 ft)
- Hoist rating: 272 kg (600 lbs)
- State of the art avionics system (single pilot day/night IFR certified)
- Fuel reserve after each leg (10% required): 22%
- Maximum crosswind: ????-mina
- Stretcher compatible hoist
- Fully stocked medical equipment (comparable to H145)