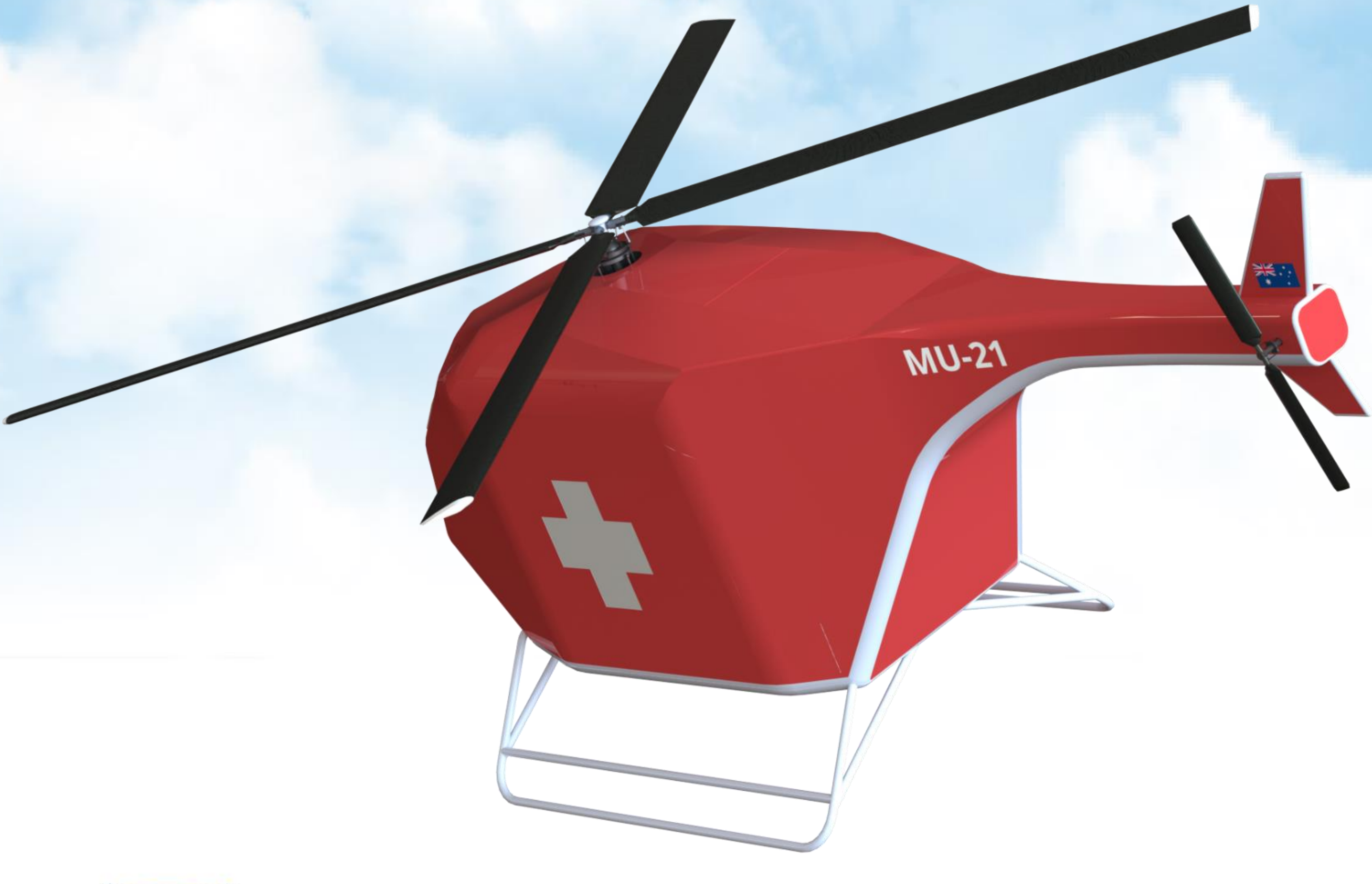
VFS 38TH ANNUAL STUDENT DESIGN COMPETITION

UNIVERSITY OF MELBOURNE GRADUATE DESIGN TEAM

MU-21 JUGGERNAUT

EXECUTIVE SUMMARY



THE UNIVERSITY OF
MELBOURNE

Vertical Flight Society

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Introduction – Executive Summary

The Executive Summary has been structured to provide an overview of the “Design Task-in-Hand” as stipulated by the RFP, followed by the “Methodology Adopted for the Configuration Design Development”.

The Executive Summary also provides a brief insight of the “Design Process and Result Outcomes”. “Limitations” if any in the design is also presented upfront and proposes “Solutions” to address the limitations.

“Vehicle Specifications” and “Design Drawings” are also presented along with a “Poster” that captures the key features of the design.

The Name – MU-21 Juggernaut

The MU-21 craft was designed by Melbourne University students for the 2020-21 competition. A majority of the design team and supervisors are of Indian origin, thus one of the few English words to come from Hindi, ‘Juggernaut’, was selected, symbolising our Australian–Indian connection. ‘Juggernaut’ comes from the Hindu god Jagannath, an abstract from Krishna, the god of protection and compassion. Thus the designated name is most appropriate for a medical supplies delivery vehicle.

The Design Task – Unmanned Aerial Vehicle

With increasing interest in autonomous aerial delivery of supplies, combined with the health crises and lockdowns seen in the past 18 months, The Boeing Company developed a Request-for-Proposal (RFP) for submissions to address both areas. The request required the development of an unmanned vertical lift concept that can deliver a 50 kg medical supplies payload, at high speed, to end-user customer sites up to a 50 km radius, and to logistics centres up to 200 km away. Threshold and target sizes are set, such that the design is a small to medium class UAV. Responses are to include only current year technologies in order to support an initial entry into service in 2025.

The Design Developed – Key Features

The MU-21 Juggernaut is a small to medium class UAV that meets all requirements stipulated in the RFP, and optimised for sizing, system safety, and payload handling. The craft is capable of transporting either of the two 50 kg payloads of two different dimensions well beyond the specified distances. The design considered traditional helicopter configuration (main and tail rotor systems). It is not a fancy configuration, being a well-tested and established configuration, with a composite four-bladed rotor and double-bladed tail rotor. Alternative configurations were considered in the comparative analysis process. The maximum dimensions are within the target sizing of 4.6 x 4.6 m and meets the required block times for both mission profiles.

The MU-21 is powered by the traditional and well-tested internal combustion engine burning Avgas. Alternative propulsion systems were considered in the comparative analysis process. Dual fuel tanks provide redundancy, should one of the tanks or fuel connections malfunction. The key features of the design in brief are:

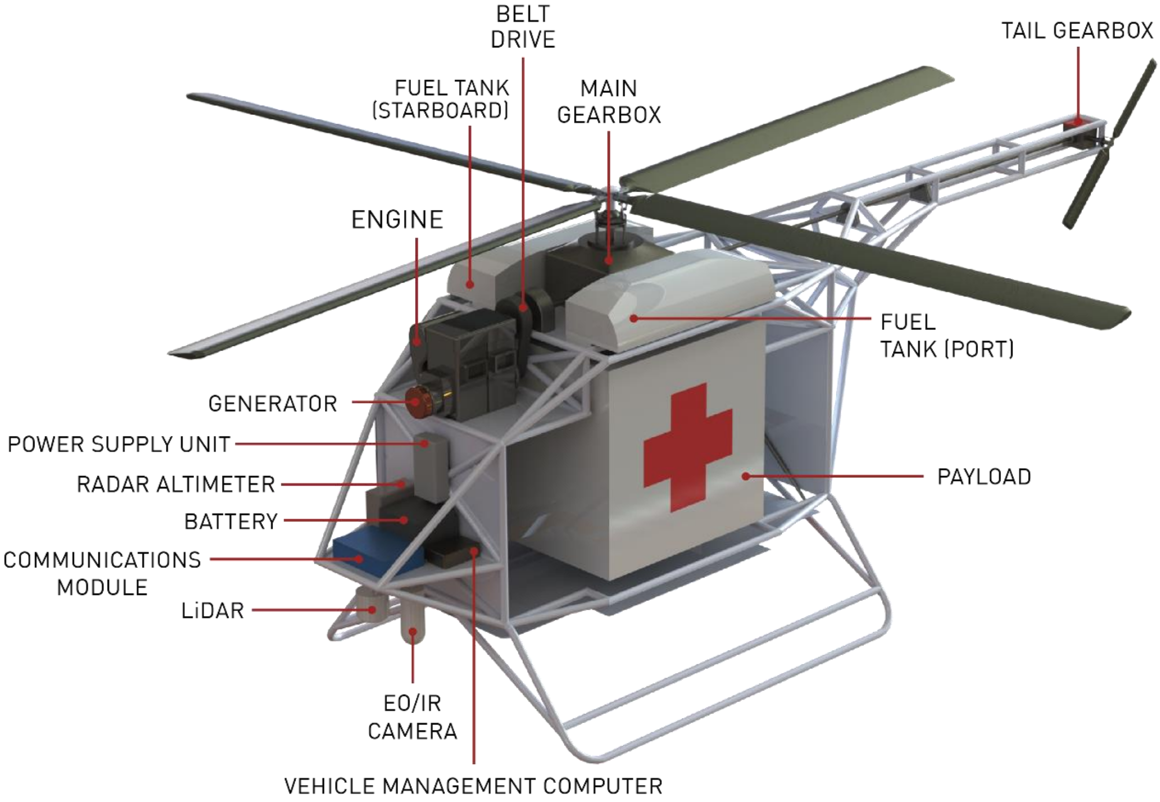
∗ Transmission, Systems and Technologies

The required transmission components, including gears and shafts are selected. A generator unit starts the engine but also harvests electricity to power the flight and mission systems, with excess energy stored in a battery that can power all required systems for the full duration of a mission, as a backup. All necessary systems and technologies to provide autonomous flight under both day and night VFR are incorporated. This includes a LiDAR, radar altimeter, EO/IR camera, and separate HD camera for the sensing systems. A single-package communications module facilitates real-time communication between the vehicle and remote operator. An on-board vehicle management computer receives data from all flight systems and controls the craft appropriately. The placement of the systems and payloads is such that the CG is always less than 100 mm in front of the main rotor axis, and never behind it.

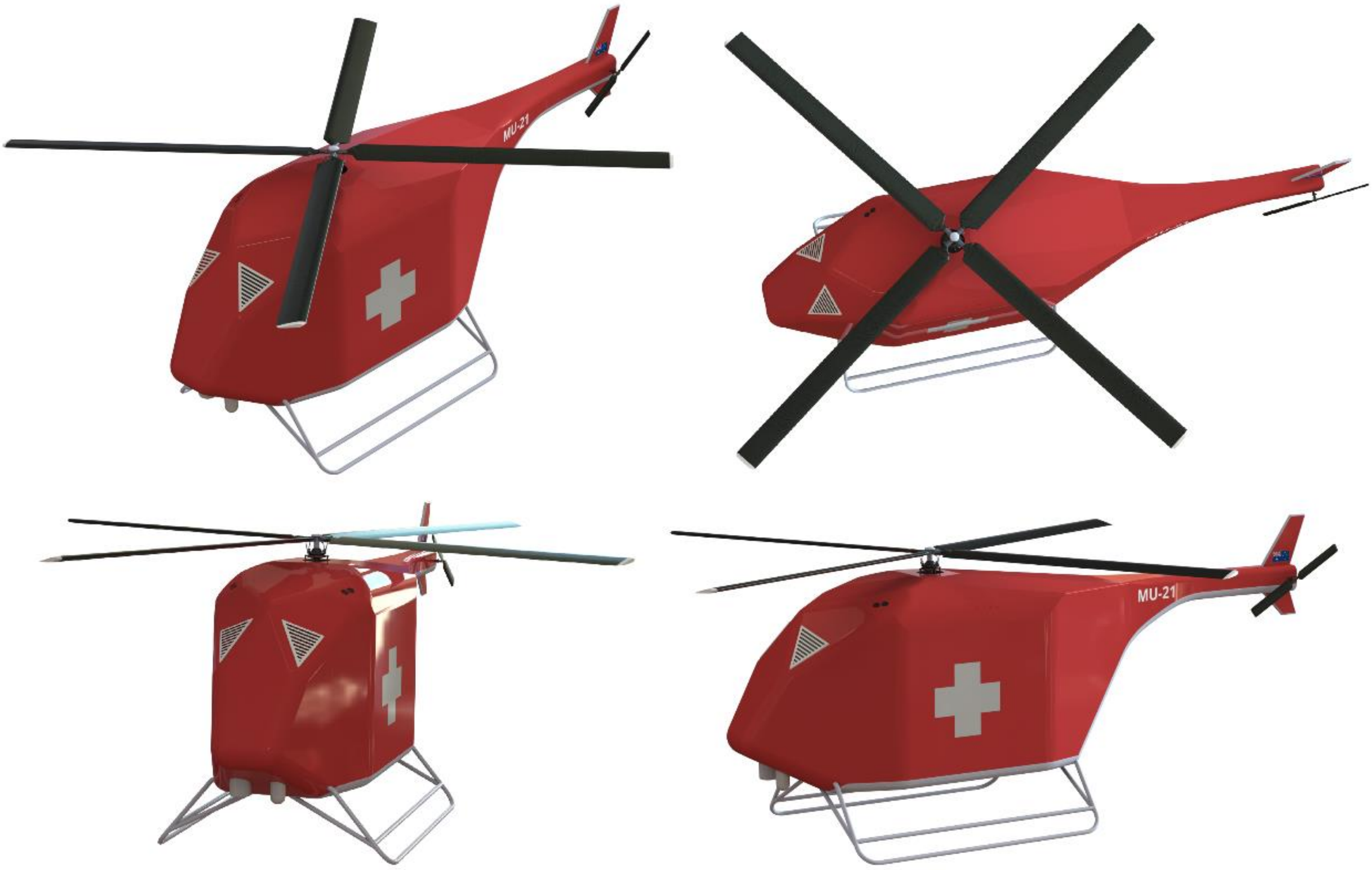
∗ Payload Operations

The payload is manually loaded laterally from either side of the craft, via simple hinged doors. It is secured in place with motorised pegs that attach through four mounting points on the top corners of either payload. Whilst in the payload bay, the container is surrounded and compressed on all four sides by rigid polyurethane foam. This foam provides protection and prevents movement in-flight, but serves its primary purpose while unloading. To unload autonomously, the craft lands (or nearly lands) and the bottom access doors open via hydraulic arms. The pegs are then retracted, allowing the payload to drop slowly due to friction provided by the foam. The foam pads are a simple and cost-effective novel system developed by the team that allows for safe and slowed descent of the payload to the ground.

As stipulated in the RFP, Means-to-Certification was developed for the craft, including a Certification Basis adopted from EASA SC-S100c, a detailed Preliminary System Safety Assessment consisting of Functional Hazard and Fault Tree Analyses, and a Safe Operation analysis that considered the safe flight envelope and emergency procedures for the craft.



Platform and On-board Systems



Vehicle Renders

Design Results – Methodology adopted through to all results achieved

The design results are presented in this executive summary in five sections, covering the objectives, achievements, limitations if any, and viable solutions to address the limitations.

1. Design Method

Design Objectives

There is specific emphasis on conducting appropriate trade studies and the safety of the system, in particular how it impacted the design process. The trades are to direct and support the design process, with the results, description, and accompanying assumptions included for each trade-off conducted. Every trade-off conducted is to consider the safety merits of each alternative, including the impact on the overall system safety. The RFP specifically details that design trades are to be used to determine the powerplant and energy storage selections.

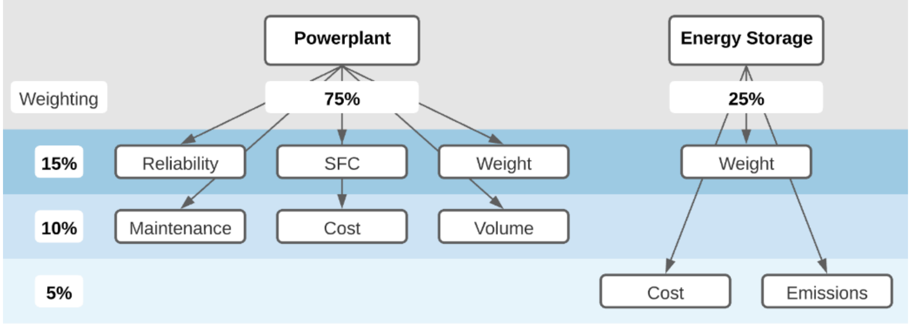
Design Achievements

The adopted design method applied trade studies as the core tool to select the alternatives to progress to design. Firstly, the RFP was translated into operational and design requirements through Operational Analysis. Phrases from the RFP are isolated and condensed down to what will affect the design. A summary of the operational and design requirements is presented in the following table.

Operational and Design Requirements

Operational Requirement	Design Requirement	Specific Explanation
1 Payload Transportation (G, M)	A: Type B: Loading C: Maximum weight D: Fixed dimensions E: Delivery mode	Medical supplies container Easy securement, well inside 5 min. requirement 50kg 140x50x50cm or 70cm cube Landing, Autonomous release of payload (No human action for payload release)
2 Operational Environment (G, FP)	A: All weather, terrain B: Urban & manmade obstacles C: Rural D: Temperature limits E: Altitude	Global use, must handle all conditions Large areas of infrastructure with little open land Large areas of open land with little infrastructure ISA+20C, with takeoff at 35°C, cruise at 26.4°C Cruise at 1350m, with 100% Max. Continuous Power (MCP) for long periods
3 Safety (G)	A: Design process B: Autonomous failure protocol	Inclusion of craft safety, at every stage of design Threshold: Emergency landing after 15 mins Objective: Return to launch site or destination
4 Dimension (G)	A: Length and width limits B: Height limit	Threshold: 6.1 x 6.1m , Objective: 4.6 x 4.6m None
5 Systems (G, M)	A: Sensors B: Communications C: Landing systems	Obstacle detection and avoidance systems on board for autonomous flight, remote piloting Real time, 2-way comms. with acceptable time delay without compromising safety Obstacle/personnel avoidance, delivery site detection, emergency landing site evaluation
6 Regulations (G)	A: VFR	Australian standard for day/night VFR, with required equipment being adapted for a UAV
7 Ground Operations (G, M)	A: Safety B: Landing site C: Landing gear	Crashworthiness design to cover: Emergency Landing on unprepared sites, including no damage to airframe/payload/personnel/structures 15.25m flat, clear square, uneven emergency sites With appropriate sensor systems and landing gear for operation in the stipulated area above
8 Configuration (M)	A: Fixed	No reconfiguration between different mission types
9 Propulsion (FP)	A: Fuel limits B: Power C: Cruise speed limits	95 minutes endurance Climb, cruise, and descent speeds to match flight profiles 170 km/h minimum at 100% MCP

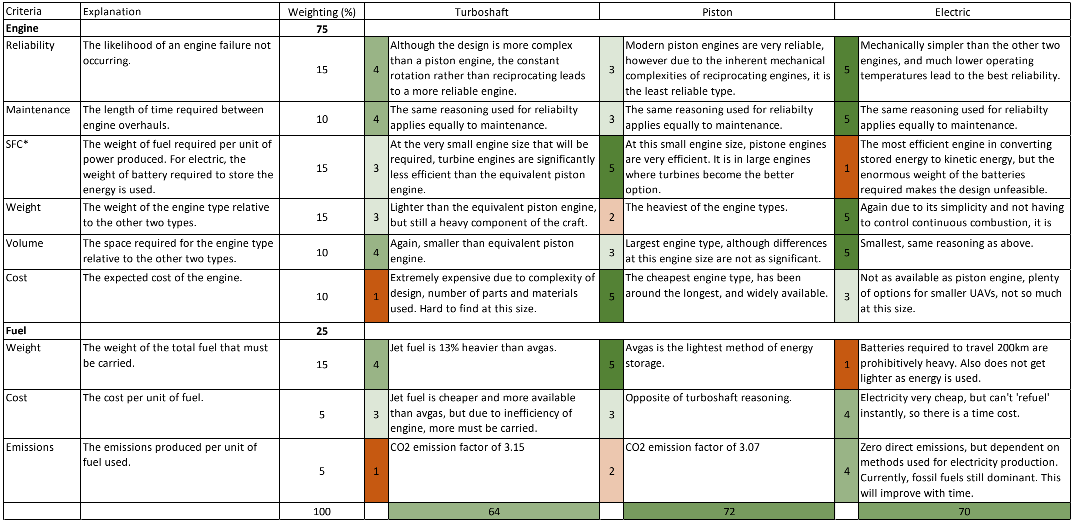
These requirements provided the design trade parameters for selection of flight and mission systems. Multi-criteria analysis (MCA) was selected as the preferred methodology to address the design trades for its concise representation and easy comparison of different alternatives. Two quantitative MCAs were developed for selection of powerplant and energy storage, and rotor configuration. To assess each alternative, relevant criteria were generated and assigned weightings. The following figure illustrates the criteria and weightings used for the powerplant and energy storage MCA.



Criteria with weightings for the powerplant MCA

The following table is the powerplant and energy storage MCA. The full-resolution table is presented in the Final Proposal (Document Number 1 refers). As seen, each option is assigned a score for every criteria and the aggregate is taken to arrive at final scores.

Powerplant and Energy Storage Multi-Criteria Analysis



Criteria	Explanation	Weighting (%)	Turboshaft		Piston		Electric	
Engine		**75**						
Reliability	The likelihood of an engine failure not occurring.	15	4	Although the design is more complex than a piston engine, the constant rotation rather than reciprocating leads to a more reliable engine.	3	Modern piston engines are very reliable, however due to the inherent mechanical complexities of reciprocating engines, it is the least reliable type.	5	Mechanically simpler than the other two engines, and much lower operating temperatures lead to the best reliability.
Maintenance	The length of time required between engine overhauls.	10	4	The same reasoning used for reliabilty applies equally to maintenance.	3	The same reasoning used for reliabilty applies equally to maintenance.	5	The same reasoning used for reliabilty applies equally to maintenance.
SFC*	The weight of fuel required per unit of power produced. For electric, the weight of battery required to store the energy is used.	15	3	At the very small engine size that will be required, turbine engines are significantly less efficient than the equivalent piston engine.	5	At this small engine size, pistone engines are very efficient. It is in large engines where turbines become the better option.	1	The most efficient engine in converting stored energy to kinetic energy, but the enormous weight of the batteries required makes the design unfeasible.
Weight	The weight of the engine type relative to the other two types.	15	3	Lighter than the equivalent piston engine, but still a heavy component of the craft.	2	The heaviest of the engine types.	5	Again due to its simplicity and not having to control continuous combustion, it is
Volume	The space required for the engine type relative to the other two types.	10	4	Again, smaller than equivalent piston engine.	3	Largest engine type, although differences at this engine size are not as significant.	5	Smallest, same reasoning as above.
Cost	The expected cost of the engine.	10	1	Extremely expensive due to complexity of design, number of parts and materials used. Hard to find at this size.	5	The cheapest engine type, has been around the longest, and widely available.	3	Not as available as piston engine, plenty of options for smaller UAVs, not so much at this size.
Fuel		**25**						
Weight	The weight of the total fuel that must be carried.	15	4	Jet fuel is 13% heavier than avgas.	5	Avgas is the lightest method of energy storage.	1	Batteries required to travel 200km are prohibitively heavy. Also does not get lighter as energy is used.
Cost	The cost per unit of fuel.	5	3	Jet fuel is cheaper and more available than avgas, but due to inefficiency of engine, more must be carried.	3	Opposite of turboshaft reasoning.	4	Electricity very cheap, but can't 'refuel' instantly, so there is a time cost.
Emissions	The emissions produced per unit of fuel used.	5	1	CO2 emission factor of 3.15	2	CO2 emission factor of 3.07	4	Zero direct emissions, but dependent on methods used for electricity production. Currently, fossil fuels still dominant. This will improve with time.
		100		64		72		70

Eleven qualitative MCAs were used for various design decisions including loading and unloading systems, and material selections. The qualitative MCA to determine where unloading should take place is presented below. Safety-related criteria were included in every design trade. Hence, the RFP requirement for an emphasis on trade studies and safety impacting the entire design process was addressed.

Mid-Air or On-Land Unloading Analysis

Parameter	On-Land	Mid-Air Controlled	Mid-Air Uncontrolled
Design			
Weight implications	Low	High	Low
Initial cost	Low	High	Low
Ongoing cost	Low	Low	High
Payload attachments required	No	No	Yes
Operational			
Vehicle safety	Average	Average	High
Payload safety	High	Average	Low
Personnel safety	Average	Average	Low
Unloading time	High	High	Low
Fuel burned	High	High	Low
Mid-mission rest and system checks	Yes	No	No

The Design Analysis (presented below) summarises the previous four stages of analysis (Operational, Systems, TRL, and Configuration). The weight, size, and power of the vehicle was then determined by a structured set of evaluations. These led to a reliable set of estimated vehicle specifications. Upon the selection of material and sizing of the rotor, transmission, and structural systems, the design was complete and the three-dimensional model was developed.

Design Analysis Summary

System	Design Req's	Parameters/Capability	Sub-System	Technology
Powerplant	2ADE,3A,**4**,**9**	Reliability, Maintenance, SFC, Weight, Volume, Cost	Internal Combustion Engine	Rotax 582
Energy Storage	2DE,**4**,**9**	Weight, Cost, Emissions	Liquid Fuel	Avgas
Sensors and Cameras	3B,5C,**6**,7AC	Accurate altitude measurement	Radar Altimeter	Honeywell SARA
	2BC,3B,5AC,**6**,7AC	Environment and obstacle detection	LiDAR	Velodyne Lidar Ultra Puck
	2B,3B,5AC,**6**,7AC	Person/animal detection and camera backup	EO/IR Camera	Trillium Orion HD25-LV
	2BC,3B,5AC,**6**,7AC	Clear view for operator and recording	HD Camera	Teledyne Lumenera Lt-C1900
Control and Communications	5B,**6**	Transponder and real-time control for operator	Comm's Module	Cobham Aviator UAV 200
	1E,2,3B,5AC,6A,**7**	Autonomous decision making and control	Vehicle Man. Comp.	MicroPilot MP2128 heli-LRC2
Power Systems	3B,7A	Stores and supplies energy for systems	Battery	B.B. Battery BP26-12
	5	Distributes power to systems	Power Supply Unit	ePropelled iPS750
	5	Converts energy from mechanical to electrical	Generator	ePropelled SG750
Fuel Systems	**9**	Provides reliable fuel flow to engine	Pump	Currawong Triplex Pump CE822
	3B,9A	Determines amount of fuel remaining	Level Sensor	Reventec LS100
Payload (Transportation)	**1**,**2**,3A,7A,8A,9A	Fuselage req's, Weight, Personnel access, Aerodynamics, Payload protection and safety	Payload (Carriage)	Internal
Payload (Unloading)	**1**,2A,3A,4B,7BC	Weight, Cost, Fuselage design, Req'd power, Tail rotor clear., Inflight safety, Ground clear., Personnel access, CG change	Release (Directional Mode)	Vertical
	1,2A,3A,4B,**7**,**8**	Design complexity, Cost, Weight, Fuselage design, Ground clear., Inflight safety, Extra safety req's, convenience, Payload protection	Release (Opening System)	Hinged Doors
Payload (Securement)	**1**,3A,**8**	Prevent payload release due to bay doors malfunction. Keep weight off doors while opening.	Payload Mounting	Motor-driven Pegs
	1,3A,7BC,**8**	Slowly release payload while unloading Parameters: Power req'd, Weight, Design complexity, Malfunction probability.	Safe Release System	Friction Pads
Payload (Loading)	**1**,3A,4B	Weight, Cost, Fuselage design, Req'd power, Tail rotor clear., Ground clear., Loading ease and personnel access, Payload mounting ease, Balance	Insertion (Directional Mode)	Lateral
	1,3A,4B,**8**	Design complexity, Cost, Weight, Fuselage design, Inflight safety, 'Open' convenience, Payload protection, Loading ease	Insertion (Opening System)	Hinged Doors
Platform (Configuration)	2ADE,**3**,**4**,7A,**8**,**9**	Design Complexity, Stability, Power Loss Safety, Rotor Failure Cons., Speed, Efficiency, Weight, Vertical Thrust	Rotors	Single Rotor
	2ADE,3A,**4**,5C,**9**	Cost, Weight, Power Efficiency, Design Complexity, Ease to Manufacture, Safety, Cruise and Hover Effectiveness	Anti-Torque System	Tail Rotor

Design Limitations

Though supported by research, the allocated scores in the MCAs cannot capture every relevant detail when comparing the design alternatives. In addition to each individual score, the importance of each criteria is determined by the analyses' author. Hence the results are subjective. This issue is enhanced in the qualitative analyses, where no criteria importance or exact scores are used, and are hence more dependent on the designer's judgement.

The evaluations are governed by iteration to remain within statistical limits and equations based upon historical design data. These statistical limits and past data are derived from larger helicopters, designed to safely transport a crew in addition to the flight and mission systems, with gross weights heavier than required for this RFP. Hence, amends may be needed based on statistical design limits of RFP class of vehicles.

Proposed Solutions

The design trades carried out with quantitative MCAs are more thorough and robust compared to the qualitative analyses. To improve this design process, more of the analyses need be quantitative, though there is a time-cost associated with this. The alternatives for each analysis were compared based on past results and experiences in the industry; to make the analyses more accurate. The concept for each solution could be developed further, specifically for this RFP. The alternative concepts' performances could then be compared.

The accuracy of design evaluations based on in-service craft and past design data for this class of vehicle will improve with time, as more similar sized vehicles are developed. To validate or refine the assumptions and equations used, extensive simulations and testing need be carried out. Due to the number of variables present in the design evaluations, this may not be a feasible short-term solution.

2. Vehicle Specifications

Design Objectives

The vehicle is to be sized to make a difference within a future pandemic or natural disaster. The threshold size is 6.1m x 6.1m, and an objective of 4.6m x 4.6m, with no limits placed on the height. Vehicle height impacts other design objectives, including gross weight, aerodynamics, CG location and ground operations. Thus there are indirect limits placed on the height.

The powerplant and energy storage for the craft is not specified, and thus is to be determined through trade studies, as mentioned previously. All remaining flight and drive systems are to be selected and described, including their size, weight, and power (SWaP). These details are to be used as the basis for numerous design deliverables, including component level performance data, turn-time procedure description and a detailed weight statement. Only current-year technologies are permitted, to support an initial entry into service in 2025.

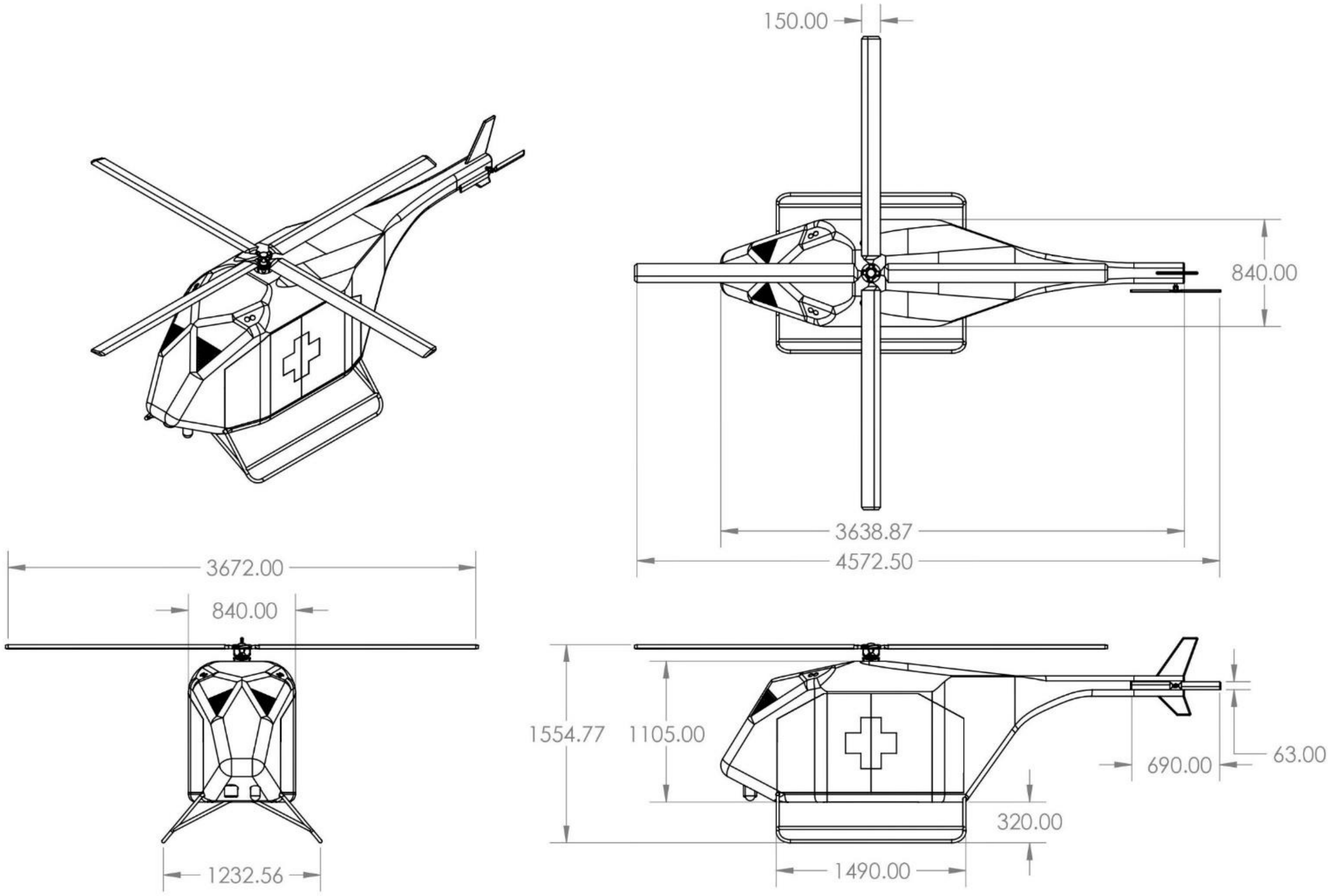
The system is to be autonomous, with an operator "on-the-loop" to be considered. The operator is to be physically located at a remote GCS to monitor the vehicle's status and act by exception to machine decisions. The design of the GCS is not required. All system features that enable autonomous flight including obstacle sensing technologies, are to be described with their SWaP estimated.

Design Achievements

The **objective** target for the sizing was met (4.6 x 4.6 m), with maximum total dimensions:

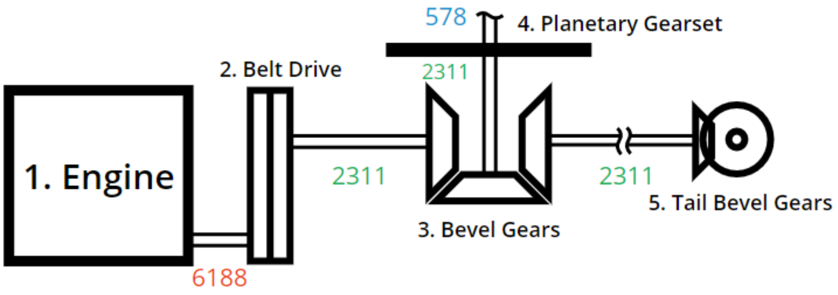
- Vehicle Size: 4.573 x 3.67 x 1.61 m (L x W x H)

The 3-view drawings are presented below.



3-View Vehicle Drawings **Scale - 1:40** **All dimensions in mm**

The specific components required for the transmission were identified and presented below, with the shaft RPMs in colour. Evaluations were carried out to determine the required strengths and sizing of each transmission component, with Off-the-Shelf models then selected.



Side View Representation of Transmission System (Shaft RPM in Colour)

The powerplant, energy storage, and all flight and drive systems were selected and described, including their SWaP. Only current year technologies were used, with every selected technology available in the market and in-service. Hence, an initial entry into service for 2025 is feasible for this design. All necessary on-board systems for safe, autonomous flight and real-time communications with the operator were included and described in the design. A summary of the on-board systems is presented below.

Platform and Systems

System	Sub-System	Technology	Size (L*W*H) (mm)	Weight (kg)	Power (W)
Powerplant	Internal Combustion Engine	Rotax 582	315 x 200 x 280	36	48 kW
Energy Storage	Liquid Fuel	Avgas	-	0.38	(sfc)
	Fuel Storage	Fuel Tanks	700 x 230 x 165	1	-
Sensors & Cameras	Radar Altimeter	Honeywell SARA	155 x 72 x 158	1.9	15
	LiDAR	Velodyne Lidar Ultra Puck	103 (dia) x 86.9	0.925	10
	EO/IR Camera	Trillium Orion HD25-LV	71.1 x 71.1 x 109.2	0.34	100
	HD Camera	Teledyne Lumenera Lt-C1900	45 x 45 x 36.1	0.88	4
Control and Communications	Comm's Module	Cobham Aviator UAV 200	240 x 140 x 60	1.45	28
	Vehicle Man. Comp.	MicroPilot MP2128 heli-LRC2	81.7 x 146 x 46	0.413	4.3
Power Systems	Battery	B.B. Battery BP26-12	175 x 166 x 125	9.4	-
	Power Supply Unit	ePropelled iPS750	201.9 x 99.3 x 54	0.724	-
	Generator	ePropelled SG750	101 (dia) x 28.6	0.44	-
Fuel Systems	Pump	Currawong Triplex CE822	81 x 61 x 54	0.25	8-16 V
	Level Sensor	Reventec LS100	31.5 (dia) x custom	~	0.24
Payload (Trans.)	Payload (Carriage)	Internal	-	50	-
Payload (Unloading)	Release (Directional Mode)	Vertical	-	-	-
	Release (Opening System)	Hinged Doors	1440 x 730	10	-
	Door Actuating Hydraulics	Homend Linear Actuator	260 x 20 x 20	1.13	144
Payload (Securement)	Payload Mounting	Motor-Driven Pegs	54 x 40 x 33	0.055	24
	Safe Release System	Friction Pads	Various	< 1	-
Payload (Loading)	Insertion (Directional Mode)	Lateral	-	-	-
	Insertion (Opening System)	Hinged Doors	1440 x 775	3	-
Platform (Configuration)	Rotors	Single Rotor	3670 (dia) x 150	17.2	-
	Anti-Torque System	Tail Rotor	690 (dia) x 63	0.4	-
	Fuselage	Single Fuselage	3645 x 840 x 1290	17.16	-
Transmission	Belt Drive	Double Banded V-Belt	585.4 (length)	< 1	-
	Main Bevel Gears	MMSG3.5-30RJ30	109.2 (dia) x 35	1.67	-
	Ring Gear (Planetary)	SI2.5-60	210 (dia) x 25	3.33	-
	Sun Gear (Planetary)	SSG2.5-20J22	50 (dia) x 25	0.427	-
	Planet Gears (Planetary)	SSA2.5-20	50 (dia) x 25	0.351	-
	Tail Bevel Gears	MMSG3-20RJ16	64 (dia) x 20	0.42	-
Landing Gear	Skids	Double Rail Tubular Skids	1490 x 1250 x 310	12	-

An eight-stage design evaluations process to estimate the weight, power, and sizing resulted in the following key results:

Design Specifications

System Category	Specification	Value	Unit
Weight	Empty Mass	121.7	kg
	Fuel Weight	29.2	kg
	Useful Weight	105.4	kg
	Gross Weight	227.1	kg
Power	Installed Power	48	kW
	Total Power (Forward Flight)	29.22	kW
	Total Power (Hover)	32.66	kW

Main Rotor	Diameter	3.67	m
	Chord	0.15	m
	Blade Number	4	-
	Angular Velocity	578	RPM
Tail Rotor	Diameter	0.69	m
	Chord	0.063	m
	Blade Number	2	-
	Angular Velocity	2311	RPM

Design Limitations

The aerodynamic properties of the vehicle have not been determined, as consistent with conceptual design. Lateral stability on landing has not been analysed and is a concern due to the high CG. The skids were designed to provide lateral stability, but this requires validation with evaluations or simulation.

The exact placement of the flight systems has not been finalised and has not been optimised for interconnections based on port placements for each avionic. The operating performance of the engine with the designed intakes and exhaust ports has not been estimated. The sizing of these components may require modification.

The sizing of the craft and its structural components were not analysed to determine susceptibility to rotor-induced vibrations at the craft's natural frequencies. Ease of manufacturing was considered for design selections, but details on the manufacturability of each component have not been included.

The gross weight and craft sizing could be optimised further, including the main rotor. The blades are currently NACA 0012 airfoils from root-to-tip, and it is unusual for this class of vehicle to have four blades. This increases hub complexity, drag and weight.

Proposed Solutions

The above limitations of the vehicle would be addressed in preliminary design, including aerodynamic, lateral stability, exact flight system placement, engine performance, vibration, and manufacturing concerns. To reduce the weight and size of the craft, a possible new design with the main rotor blade number fixed as two need be explored, to determine if it is feasible and superior to a four-bladed vehicle for this RFP.

3. Mission Performance

Design Objectives

The overall objective for the vehicle concept was to deliver 50 kg of medical supplies at high speed, with an emphasis on system safety and reliability. The vehicle need be capable of executing both the 'Local Delivery' and 'Logistics' missions in at least the block times of 28 mins and 75 minutes respectively. This is to be achieved in the operating environment specified, at an altitude of 1200 to 1350 m and in ISA+20C conditions. Flight conditions were limited to visual flight rules (VFR) operation, both day and night. The vehicle is not permitted to undergo configuration changes between missions, nor refuel/recharge during either mission.

Design Achievements

The craft is capable of safely and reliably delivering either size of the 50 kg payload, with no reconfiguration or refuelling required. The segment-by-segment performance for both missions was evaluated, confirming that the vehicle will meet the RFP block time requirements. The vehicle's performance for each mission, including time taken, power required, and fuel consumption is presented below for the local delivery and logistics missions, respectively.

Local Delivery Mission Performance

#	Segment	Time (min)	Range (km)	Altitude (m)	Airspeed (km/h)	Power (kW)	Fuel Rate (l/hr)	Fuel Consumption (litres)
1	Load package	5	-	1200	-	-	-	-
2	Warmup	5	-	1200	-	9.396	8.3	0.688
3	Takeoff HOGE	2	-	1200	-	32.466	28.5	0.950
4	Climb	0.51	0.5	1350	56.01	38.391	33.7	0.285
5	Cruise	13.4	49	1350	220	35.287	31.0	6.912
6	Descent	0.5	0.5	1200	56.92	30.432	26.7	0.223
7	Land HOGE	1	-	1200	-	32.466	28.5	0.475
8	Unload Package	0.2	-	1200	-	32.659	28.7	0.096
9	Takeoff HOGE	1	-	1200	-	25.698	28.5	0.475
10	Climb	0.51	0.5	1350	56.01	27.421	24.1	0.204
11	Cruise	14.7	49	1350	200	20.871	18.3	4.484
12	Descent	0.5	0.5	1200	56.92	21.410	18.8	0.157
13	Land HOGE	1	-	1200	-	25.698	28.5	0.475
14	Reserve	20	-	1350	74.08	13.159	11.5	3.840

The overall performance metrics for the local delivery mission are as follows:

- Block time: 27.6 mins (total time to the end of segment 8)
- Total time: 65.3 mins (including 20 min reserve)
- Total fuel consumed: 19.3 litres (including 3.8 litres reserve)
- Maximum speed: 220 km/hr

Thus, the RFP requirement of block time under 28 minutes is met.

Logistics Mission Performance

#	Segment	Time (min)	Range (km)	Altitude (m)	Airspeed (km/h)	Power (kW)	Fuel Rate (l/hr)	Fuel Consumption (litres)
1	Load package	5	-	1200	-	-	-	-
2	Warmup	5	-	1200	-	9.396	8.26	0.688
3	Takeoff HIGE	2	-	1200	-	31.345	27.6	0.919
4	Climb	0.51	0.5	1350	56.01	38.391	33.7	0.285
5	Cruise	59.7	199	1350	200	29.220	25.7	25.572
6	Descent	0.5	0.5	1200	56.92	30.432	26.7	0.223
7	Land HOGE	1	-	1200	-	32.466	28.5	0.475
8	Unload package	1	-	1200	-	32.659	28.7	0.478
9	Reserve	20	-	1350	74.08	13.159	11.5	3.840

The overall performance metrics for the logistics mission were:

- Block time: 74.7 mins (total time to the end of segment 8)
- Total time: 94.7 mins (including 20 min reserve)
- Total fuel consumed: 32.5 litres (including 3.8 litres reserve)
- Maximum speed: 200 km/hr

Thus, the RFP requirement of block time under 75 minutes is met.

These claims are substantiated by the individual component performance figures, in which the power consumed by each component of the drive system was estimated. The individual component performance for the logistics mission is presented in the table below.

Logistics Mission Component Performance (kW)

#	Segment	Belt Drive	Main Bevel Gears	Plan. Gears	Tail Bevel Gears	Main Rotor	Tail Rotor	Avio's	Total
1	Load package	-	-	-	-	-	-	-	-
2	Warmup	0.047	0.093	0.278	0.093	8.077	0.642	0.166	9.396
3	Takeoff HIGE	0.162	0.323	0.959	0.320	29.156	1.380	0.166	32.466
4	Climb	0.192	0.382	1.135	0.378	33.516	2.623	0.166	38.391
5	Cruise	0.146	0.291	0.863	0.288	22.383	5.083	0.166	29.220
6	Descent	0.152	0.303	0.899	0.300	26.533	2.079	0.166	30.432
7	Land HOGE	0.162	0.323	0.959	0.320	29.156	1.380	0.166	32.466
8	Unload package	0.163	0.325	0.965	0.322	29.190	1.380	0.315	32.659
9	Reserve	0.066	0.131	0.389	0.130	11.379	0.899	0.166	13.159

The vehicle productivity was evaluated for each mission, though no target value was specified by the RFP. The productivity for each mission is presented here.

Mission Productivity

Mission	**Payload** (kg)	**Block Speed** (m/s)	**Gross Weight** (kg)	**Productivity** (m/s)
Local Delivery	50	47.4	211.7	11.2
Logistics	50	51.5	221.2	11.6

All evaluations were carried out for the appropriate operating environment, including the effects of lower air density. The craft's on-board systems provide the capability for day and night VFR.

The maximum required power for any of the mission segments is 80% of the installed power, the RFP allowed for 95%. Hence, the engine's service life will increase, as it is being put under less stress. It also allows for extra drag force to be countered (increase forward speed) or carry extra weight if desired.

Design Limitations

The block time requirements are both met by under 30 seconds. This concept design placed major emphasis on system safety as stipulated in the RFP but compromised potential speed in the process.

Proposed Solutions

As mentioned, only 80% of the installed power is used at any time, so there is scope to increase the vehicle's speed in both missions, particularly during cruise. An alternative is to design a vehicle with a smaller engine that can still meet the block time requirements, though engine service life and power safety margins will decrease.

4. Ground Operations and Payload Handling

Design Objectives

The vehicle ground operations including on-board safety features and on-ground infrastructure that provides protection are to be considered. Emergency landings in which the vehicle may land on an unprepared surface is to be discussed, including the safety of people and animals on the ground. The delivery site is specified as 15.25 x 15.25 m of flat, clear space. The vehicle is to be designed such that the risk to any ground personnel in the craft's vicinity is minimised. Sensors that enable obstacle detection near the landing site are to be included in the design.

The size and weight of the payload are specified as either of 70 x 70 x 70 cm or 140 x 50 x 50 cm dimension weighing 50 kg, containing medical supplies, with appropriate mounting points for carriage. Either internal or external carriage is permitted if range and block time requirements are met. Payload handling is of primary concern, with an emphasis on convenience and speed of loading and unloading. Unloading is mandated to be autonomous.

Design Achievements

Safety systems and procedures for ground operations were suggested. Logistics centres are to place high-visibility markers, such as cones, to demarcate the landing site. This clarifies to personnel where the craft will land. The on-board cameras identify the markers, and the vehicle will proceed to land in the centre of the marked area. Fencing or similar solutions are deemed too costly to justify the increased safety. At end-user customer sites no on-ground infrastructure is expected, hence the on-board safety systems are relied upon to provide adequate safety for personnel, animals, and the craft itself. As a result, redundancy of all on-board safety systems is necessary. The vehicle is capable of hovering for limited periods (governed by fuel) until the delivery site is clear. The rotor tips are painted white for increased visibility.

Five qualitative MCAs were dedicated to determining the directions and methods of loading and unloading. Simplicity, low-weight, and cost-effectiveness were the common theme among all five selections for progression to design. A summary of those selections is presented here.

Loading and Unloading Systems Summary

Mid-Air or On-Land Unloading	**On-Land**	Mid-Air Controlled	Mid-Air Uncontrolled	-
Unloading Directional Mode	Aft	Lateral	**Vertical**	-
Unloading Release System	Rolling Shutter	Sliding Door	**Hinged Doors**	Open
Loading Directional Mode	Aft	**Lateral**	Vertical	-
Loading Access System	Rollable Cover	Sliding Door	**Hinged Doors**	Detachable Panels

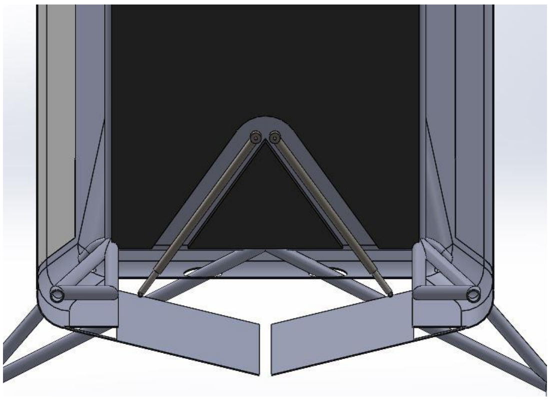
The payloads are carried internally, providing environmental protection and increased system safety. Loading is achieved laterally, on either side of the craft for operational convenience. Below is a depiction of the loading sequence, note the side doors are not represented with the foam pads that will be present.

Loading Sequence

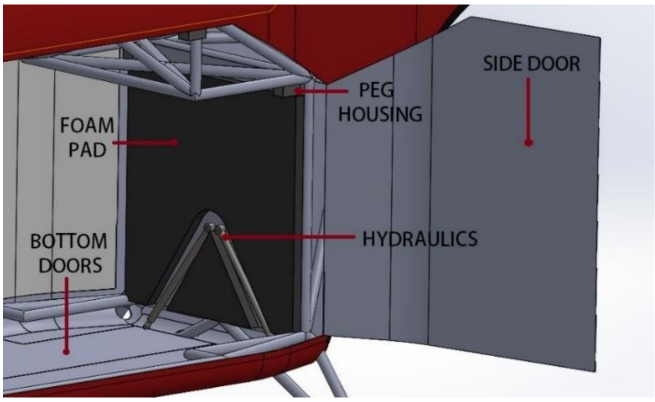
Mounting points at each of the four top corners of the payload are required, to be secured via the on-board motorised pegs. The small grey boxes at the top of the cargo bay in the following figures represent those peg housings. Below is a figure of the payload secured in the cargo bay.

Payload Secure (Doors Open)

Unloading occurs vertically and is done so via the following sequence: As the craft descends for landing, the bottom access doors unlatch and are opened with hydraulics, depicted in the below figures.

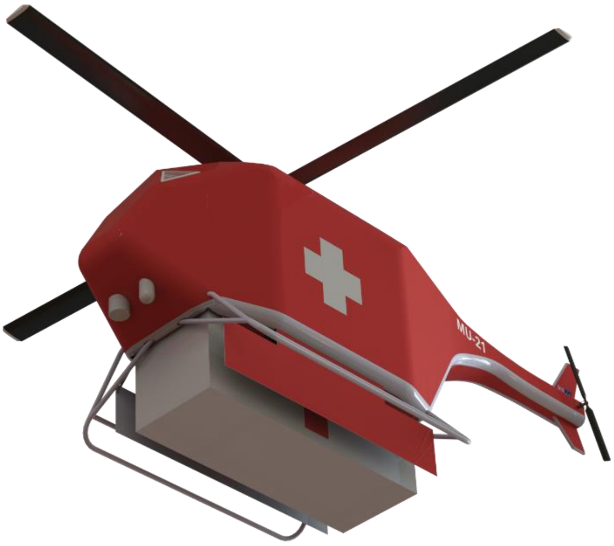


Unloading Hinged Doors and Hydraulics



Payload Slow Release

Upon landing (or hovering just above ground level if desired), the pegs retract and the payload descends slowly and safely, due to the rigid foam that lines all four sides of the payload bay. The unloading sequence is depicted in the below figure. The craft then takes off, the bottom doors shut via the hydraulics, and are locked via the electronic latches.



Unloading Sequence

The peg and foam unloading systems provide safe and secure carriage inflight, and an innovative, simple, and cost-effective method for autonomous unloading. Service life of the foam requires consideration as part of the maintenance schedule.

Design Limitations

The main rotor height above the ground is 1.55 m, less than the median population height and is inconvenient for loading. The tail rotor is also at a dangerous height for personnel and has no protection such as a Fenestron tail rotor. The craft has a blind spot looking rearwards, as the LiDAR and EO/IR camera are blocked by the fuselage, increasing the vulnerability and danger of the tail rotor.

The peg and foam unloading system requires the payload to be exactly of the dimension and weight specified to operate correctly. A smaller payload could be transported, but not with the redundancy provided by the pegs. A lighter payload may be held up between the foam during unloading. To unload autonomously the craft must takeoff, as the vehicle ground clearance is less than the payload height.

Proposed Solutions

Increase of skid height need be considered, as this increases the rotor height above the median population height, increasing personnel safety and loading convenience, and allowing for autonomous unloading without requiring takeoff. It also increases the height of the CG which reduces on-ground stability and introduces additional aerodynamic penalties. A sensor placed at the rear of the tail addresses the blind spot, increasing safety for both landing and takeoff procedures.

To carry payloads not in accordance with the RFP, a separate mounting frame need be built, such that it mounts to the pegs on the craft, and any smaller payloads attach to the frame. For the frame to not be lost with every payload delivered, the frame is required to be a powered system.

5. Safety and Certification

Design Objectives

In accordance with the RFP, safety of the system is to be prioritised throughout the design process. Concepts that feature enhanced safety aspects are to be "valued more highly", with evidence shown that the safety assessment process influenced the design process.

The vehicle is to be capable of continued safe flight and landing after any single failure or combination of failures not classified as catastrophic. The threshold is 15 minutes of safe operation at best range speed with full payload to a contingency landing site, followed by a controlled landing resulting in no damage beyond acceptable maintenance limits. The craft is to be capable of determining if the landing site is clear and safe. The objective is to return to the launch site with full payload for the Local Delivery mission, and return to launch site or destination with full payload for the Logistics mission.

A "Means-to-Certification" is to be shown for cargo commercial operations over rural and suburban environments. This is to include analysis of primary aircraft functions, critical systems, and system interconnection. Specifically, understanding the FAA's fail-safe design concept is to be shown, development of a critical parts program, and a safety assessment to the level of a Preliminary System Safety Assessment (PSSA) as described in SAE ARP4761.

Design Achievements

As detailed in Design Method, system safety was considered in all design trade-offs and evaluations. Enhanced safety aspects of the craft include redundancy in critical flight and mission systems, in particular payload carriage, vehicle management computer, and sensing systems. Battery capacity is such that if the generator malfunctions, the avionics receive the required power longer than either mission profile. Dual fuel tanks provide redundancy upon leakage or malfunction. The single, large rotor provides excellent autorotation performance in emergency scenarios.

Emergency procedures following varying degrees of failure were detailed, with the craft capable of the RFP objective to return to the launch or delivery sites depending on the type of failure. For severe failure, the craft is designed to meet the threshold of 15 minutes of safe flight and subsequent landing with full payload.

A "Means-to-Certification" was demonstrated, consisting of a certification basis, a safety assessment and analysis for safe operation. The certification basis is a modified version of the EASA SC-S100c, as the MU21-Juggernaut is similar in size and operation to the Schiebel S-100 Camcopter. The appropriate modifications were made to account for the differences between the two vehicles, including engine and landing gear type. Preliminary System Safety Assessment was conducted for the craft, including Functional Hazard Analyses (FHA) at system and component levels. The Risk Hazard Index from the FAA was applied for the FHAs and is summarised in the below tables. An estimation of each hazard's severity and likelihood result in either an orange or green score. Orange-classified hazards are too high-risk and must be mitigated.

Hazard Severity

Description	Category
Catastrophic	I
Critical	II
Marginal	III
Negligible	IV

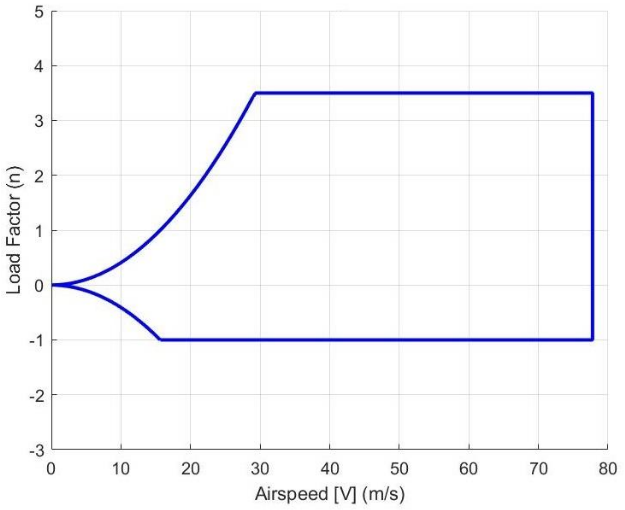
Hazard Likelihood

Description	Level
Frequent	A
Probable	B
Occasional	C
Remote	D
Extremely Remote	E

Risk Hazard Index

	I	II	III	IV
A	1	3	7	13
B	2	5	9	16
C	4	6	11	18
D	8	10	14	19
E	12	15	17	20

The component FHA was developed into a Critical Parts Program, where service life and fail-safe design principles were considered. A Fault Tree Analysis (FTA) was built for both controlled and uncontrolled emergency scenarios. The safe operating envelope (depicted in the below figure) and emergency procedures were determined to form the safe operation analysis.



V-n Diagram

Design Limitations

Though emergency procedures were generated, and safety assessments conducted, the effectiveness and accuracy of these are limited as the design is only conceptual. It was not possible to determine the duration of safe operation after non-catastrophic failure, as a detailed analysis would be required for each type of possible failure.

It was specified that a new subpart of the certification basis addressing the autonomous control systems of the craft is required. This subpart was not addressed due to time limitations.

Proposed Solutions

To determine the performance of the craft following non-catastrophic failure, the detailed analysis and testing need be conducted in the preliminary design process. The additional subpart of the certification basis for autonomous control systems needs to be addressed.

The poster created for the University of Melbourne Endeavour Exhibition held in May 2021 is presented below. (Original poster size is A0).

MU-21 JUGGERNAUT

Team: Benjamin Fleming (Captain), Hariharan Rajasekaran, Reuben D'Souza, Vatsal Desai
Supervisors: Lt Col (Dr) Arvind Sinha, Gp Capt Anthony J. Veliath, Dr Simon Illingworth

A NEW WORLD

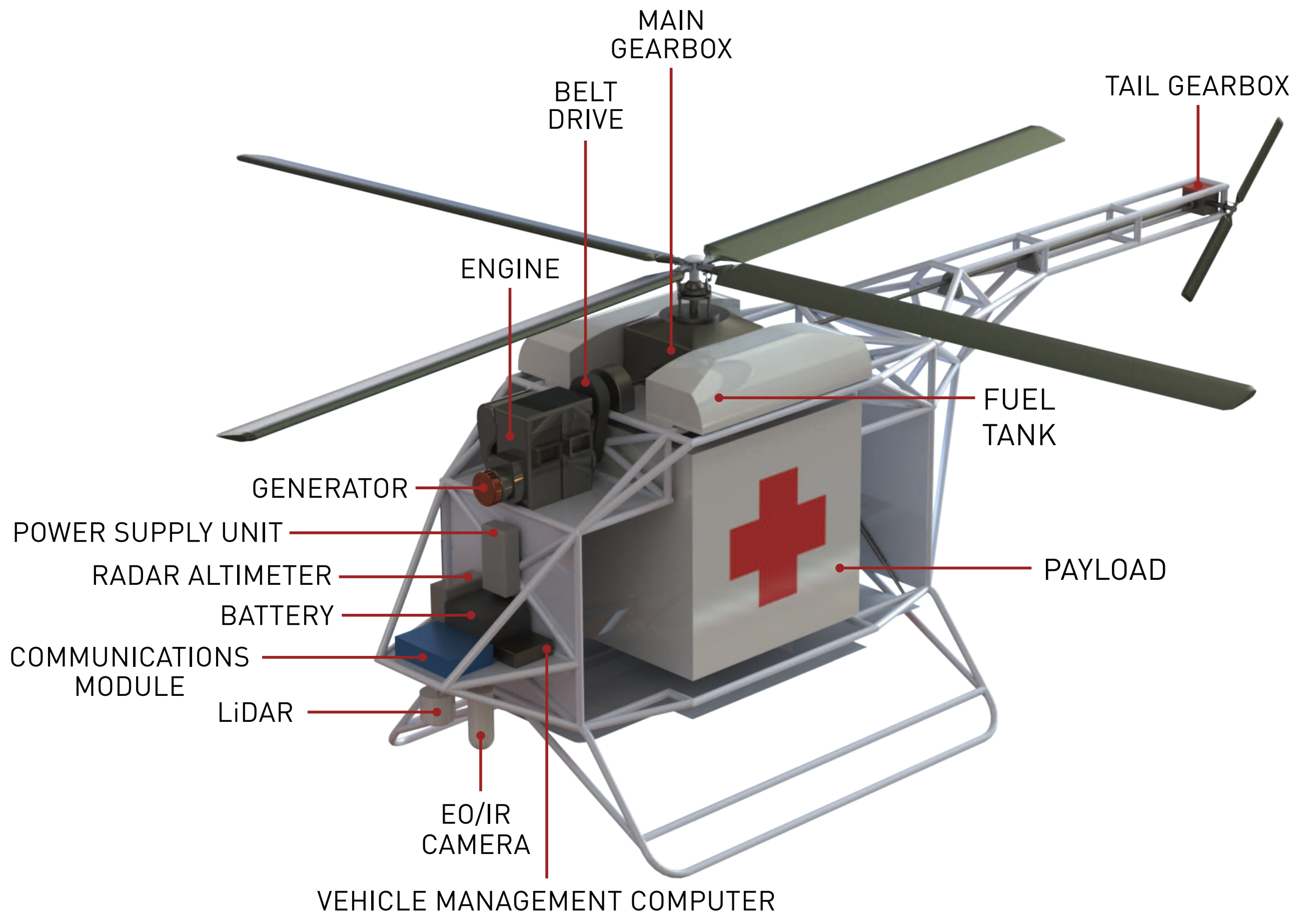
The COVID-19 pandemic has amplified the need for fast autonomous delivery to precise locations. Among many impacts to daily life, the pandemic has forced a re-examination of how medical and basic supplies are distributed within large communities or between different communities, especially if a lockdown is in place. Vertical lift technology can aid the worldwide community through safe distribution of medical supplies and other commodities through runway independent 'contactless' delivery.

INDUSTRY BRIEF

The Boeing Company has sponsored an international design competition to design an unmanned VTOL concept to deliver 50kg of medical supplies at high speed.

The design is to feature:

- Autonomous flight, with an emergency operator at a ground control station
- Two mission profiles: 200 km one-way and 100 km return trip (50 km each way)
- Capability to transport payloads of two differing sizes
- Only current-year technologies, for 2025 initial entry into service
- Maximum size: 6.1m x 6.1m, Target size: 4.6m x 4.6m
- Day and night operation
- Safety of the design is paramount



DESIGN METHOD

1. **Operation Analysis**
   Extract the operational and design requirements from the Request-for-Proposal (RFP)
2. **Systems Analysis**
   Apply the operational and design requirements as comparative analysis parameters.
   Determine what flight and mission systems are required against those parameters.
3. **Technology Readiness Level (TRL) Analysis**
   Identify technologies currently available in the market.
   Select technologies for each flight and mission system and determine their TRL.
4. **Configuration Analysis**
   Determine rotor, tail, and fuselage configurations for the craft against the operational and design parameters.
5. **Design Development**
   Evaluate the weight, power, and sizing of the conceptual design.
   Select system and component materials where appropriate.
   Develop 3D model of the craft.

DESIGN RESULT

Gross Weight:	227 kg
Power Required:	32.7 kW
Fuselage:	3.6 x 0.84 x 1.3 m
Main Rotor Diameter:	3.67 m

SAFETY FOCUS

- System safety was considered throughout entirety of design process
- Large percentage of all design tradeoff parameters were safety-based
- "Means-to-certification" completed for cargo commercial operations
  - Modified EASA SC-S100c as certification basis for this craft
- Completed safety assessment to required level, including:
  - Preliminary and System Safety Assessments (PSSA & SSA)
  - Functional Hazard Analyses (FHA) at system and component levels
  - System Fault Tree Analysis (FTA)
  - Adheres to FAA 'fail safe design concept'
  - Development of Critical Parts Program (CPP)
- Established safe operation flight envelope and emergency landing procedures