YAMATO HOLDINGS

CycloTech

CycloRotors
for Advanced Aerial Logistics

White Paper 2022

Cargo drone concept for logistics operations within urban areas.

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Abbreviations

CCY-01 .... CycloRotor-applied aircraft, CycloTech-Yamato designed

ConOps.............. Concept of Operations

eVTOL .... Electrical Vertical Take-off and Landing

MTOW .... Maximum Take-off Weight

PUPA .... Pod Unit for Parcel Air-transportation

RPM .... Revolutions Per Minute

TLAR.............. Top Level Aircraft Requirements

UAM.............. Urban Air Mobility

UAV .... Unmanned Air Vehicle

VTOL .... Vertical Take-off and Landing

1. Introduction

Imagine if a parcel you are to receive could fly and perch into your neighborhood like a bird. Or what if you could fly multiple freighter aircraft connecting multiple points WITHIN a city? The result should be a revolutionary speed-up in logistics, not only in terms of higher maximum velocity but also shorter overall lead time and higher frequency of available service, resulting in higher productivity and a more convenient life within the area benefitted by the system. The popularization of the Internet and smart devices and ongoing innovation in aviation automation and electrification will realize this dream in the form of advanced aerial logistics.

In order to make this happen, one of the dominant factors is the size of the aircraft. The smaller size will enable a broader option of points for landing and take-off. However, small aircraft can only contain small and light cargo, which sometimes is not enough to match the customer's need. Moreover, as we want the aircraft to have a robustness that can fly over the populated area to worth serve it, we have to make the aircraft have a high level of redundancy. Hence, making the aircraft lean with fine design will be extremely important for its utility.

The aircraft design and manufacturing environment should also be different from the current industry standard when applying them for daily use. Shorter development, simpler design process, easy manufacturing, and smaller unit price will be required for a low fixed cost, as well as its high energy efficiency that will contribute to reducing its variable expense. Otherwise, it cannot solve the very reason why its conventional ancestors could not have served intra-urban logistics wants.

Throughout a collaborative study between Yamato Holdings and CycloTech, we have found that the application of CycloRotors, a classical but neglected idea of an alternative lift/propulsion system, is a design-worthy solution to this new challenge. Through this document, we discuss the use of CycloRotors and propose a configuration of an advanced logistics air vehicle with CycloRotors based on Yamato requirements and the concept of operations.

2. State of Requirements

2.1. Concept of Operations (ConOps)

The centric ConOps of the aircraft to be designed (we name this model CCY-01: CycloRotor-applied aircraft, CycloTech-Yamato designed) serves as a last-mile logistics aircraft urban environment. Compared to passenger air mobility that provides a broad experience to passengers (that is not limited to just a shorter time for travel, but also includes: less agony to be crammed into a limited space of the vehicle, viewing the landscape from above the sky, and possibly showing off their social status), the different customer experience gained by flying their parcel is just limited to shorter lead time and on-demand ability. Because of this relatively limited amount of customer experience, a priceworthy cargo air mobility exists only at overall high speed but with a limited unit service price. The density of service, as well as market size, will be an essential factor to meet the price requirement, as constant demand and less waiting time for each aircraft will be crucial. Thus, a large and busy metropolis will be an ideal core location for such service, while neighboring suburban or rural areas could also benefit from the service.

Aircraft to enable this future service should have some unique features. Although the details of the target performance will be stated later, it can be generally said that this type of aircraft should have a specific size (more significant than a few-kilogram-payload drone), high reliability, and harsh weather tolerance to meet the conceived demand. If any of these were to lack, it would not be easy to exceed the break-even point and form a profitable network.

Existing rooftop helipads will be ideal initial infrastructures to provide this urban service. As the aircraft is to have a specific size, the landing zone will be restricted, at least when compared to delivery vans. Many of the existing rooftop helipads should satisfy the use of an aircraft with less weight and footprint and better maneuverability than existing helicopters. In addition, skyscrapers with helipads tend to house busy businesses and livings that want urgent and on-demand delivery. Aircrafts hopping over the urban skyline will be the most iconic image illustrating the ConOps.

Nevertheless, the rooftop of skyscrapers won't be the only ground on which these aircraft are to land. Extensive facilities, such as factories, warehouses, fresh-food markets, fruit farms, fishing wharves, train terminals, hotels, shopping malls, or convention centers could be other points where the aircraft can connect and provide extra logistics value while connecting the network with long-haul ground/air transportation via transfer hub, freight station, or airport will expand the capability of this revolutionary service from intra-urban to inter-city range. The more locations the aircraft can land and serve, the higher the gross service value the network can provide; this ConOps has a typical positive network externality.

2.2. Serviceability and Safety

Regarding such extension within the ConOps, the critical success factor will be to make the aircraft independent from ground requirements as much as possible to enable a smooth and economical introduction to the site newly added to the logistics network. High operability on the ground, compact airframe, and the use of PUPA (as discussed in the next section) will be critical to this point.

The range will be another critical factor as well. Although the longer, the better for range, the minimum coverage required for intra-urban missions is relatively small for conventional aircraft. If CCY-01 has at least 40 km of range without recharging, it can connect any two points within a 20-km-diameter circle without recharging, and that limit can be expanded to the 40-km circle when the aircraft can be restored at both ends. As shown in Figure 1, this seems to be an acceptable value even considering the world’s largest and busiest metropolises. Nevertheless, a range under 40 km should essentially limit service coverage in an extent city. Thus the value is a minimum requirement.

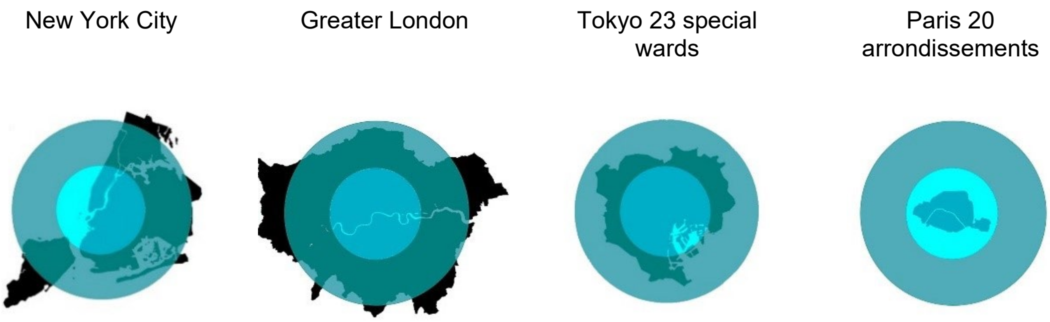

Figure 1: Example of metropolis sizes.

The inner/outer circles present those with diameters respectively of 20 km and 40 km.

Safety will be the most fundamental element to enable such an urban mission. In 1977, the landing gear of a passenger helicopter had a fatigue fracture on the rooftop heliport of the Pan Am Building in New York City, causing the deaths and severe injuries of 5 passengers waiting to get on board at the heliport, and 2 pedestrians on the street corner nearby, as the aircraft rolled over and disintegrated its moving main rotor blade into deadly showering fragments (Bailey et al., 1977). Such disaster should never retake place, and the aircraft has to be equipped with an especially high degree of safety to avoid any possible danger.

Reliability and redundancy will be the key to this primary requirement. In addition, operation around the urban skyline also requires the aircraft to handle eddies of wind uniquely caused by skyscrapers.

Finally, when considering the ConOps, a high degree of autonomy both on the level of aircraft navigation and on a fleet management level will be necessary, as well as information and communication infrastructures that make them possible. However, as this study is mainly on the innovative propulsion system, these issues are out of the scope of this paper.

2.3. PUPA®

PUPA® (Pod Unit for Parcel Air-transportation) is a family of aerodynamic compatible cargo pods to be carried by eVTOL aircrafts or other advanced air mobility, developed by Yamato. Its concept is to enable multiple types of pods to be swapped easily to broaden missions and use scenes, as well as to separate loading/unloading sequence from the aircraft's process cycle to secure the ground crew's safety and maximize the utility of the aircraft.

Although multiple types of PUPA have been planned so far, PUPA701, capable of carrying about 30 kg of payload, is chosen as the centric model to be taken by CCY-01 regarding its ConOps. PUPA701 has its integral elevator system to lift and lower itself onto the suspension rail attached to its lift-craft while extending and retracting its gears for ground mobility. In other words, the pod is a transformative flying pushcart that can be used for last-mile delivery (Figure 2). This concept would enable a safe and efficient loading/unloading as the practice would be separated from where the aircraft has landed to in front of the customer: swapping pre-loaded PUPAs will make the downtime of the aircraft minimal and prevent vulnerable parcels from being wet, overheated, affected by sand, or blown by wind outdoors. Given the ability to lift and lower itself to/from the aircraft without any additional ground support equipment, this should ease the constraints of the landing site and help expand the network for service.

As the development of the PUPA701 on materials and structure to make the pod light and economical is still ongoing at the moment of this study, the final dry mass of the pod has not yet been decided. However, the MTOW of the pod (dry mass + payload) could be assumed to be around 45 kg, both from the latest examination, and several kgs of offset between the payload and the pod should be tolerated in actual operations. Thus, the payload of the CCY-01 will be defined as 45 kg, including the dry mass of the detachable pod.

Figure 2: 1/1 sized ground demonstrator of the PUPA701

Of course, the ground handling structure of the PUPA701 will be a dead weight in the air. Therefore, an additional option called PUPA702 is also designed (Figure 3). This concept omits gears and an onboard elevator system from the pod and transplants them onto a special crate that won't leave the ground. The change from PUPA701 to 702 will accept more payload, while the independence from the outdoor condition and ground support (if to swap the pods) will no longer exist in this case. PUPA702 will only be efficient in delivering to a point where service frequency is not high, carrying a non-vulnerable payload. However, as both models share the same attaching mechanism and rails on the airframe, conversion between 701 and 702 is as easy and rapid as swapping 701s on site. Therefore, either use of the two models can be selected simply based on mission and the subject of transportation. Nevertheless, in order to use PUPA702, the aircraft design has to allow easy access for the ground crew to the cargo bay, if not require the crates to be placed in advance at every single location the pod might serve.

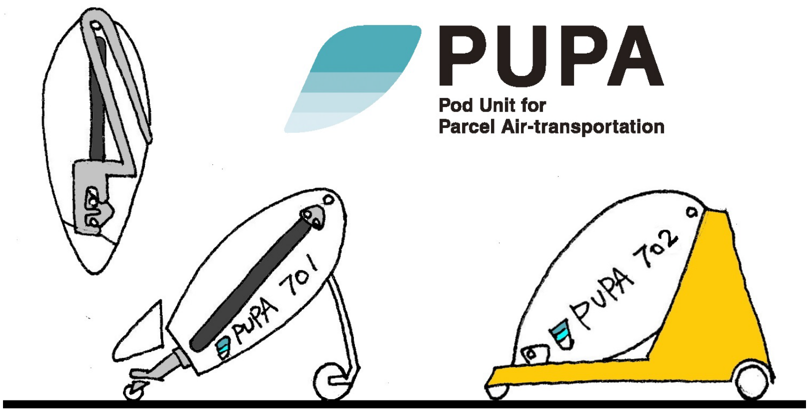

Figure 3: Concept drawing of PUPA701 and 702

2.4. Target Performance

Regarding the statements above, the quantitative target performance values of the CCY-01 are set in Table 1. The necessity level indicates whether each criterion is mandatory to be satisfied or just a desirable parameter for the study. This study has taken an exploratory attitude and left as many criteria as possible desirable so that we could broaden the design space for CCY-01.

Content	Necessity		Value	Unit
Payload definition	Mandatory	Type	PUPA701 and 702	
	Mandatory	Weight	45	kg
Range (with maximum payload)	Mandatory		40	km
Maximum cruise speed	Desirable		130	kph
Crosswind capability at landing	Desirable	Average	10	m/sec
	Mandatory	Gust	13	m/sec
Altitude ceiling (above sea level)	Desirable		1,500	m
Lowest operable temperature	Mandatory		-5	°C
Highest operable temperature	Mandatory		40	°C
Average energy consumption rate	Desirable		50	MJ/tkm
Footprint φ	Desirable		3,500	mm
Minimum operable landing zone φ	Desirable		5,000	mm
MTOW of the aircraft	Desirable		Under 150	kg

Table 1: Quantitative target performance list for CCY-01

3. About CycloRotors

Through more than 10 years of intense research at CycloTech, a new aviation propulsion system was developed based on the cyclogyro principle. These CycloRotors are 360° thrust vector systems based on the same physical principle as the Voith-Schneider-Propeller, successfully applied for decades for highly agile and stable ships in the maritime industry.

CycloTech is taking this technology into the air to offer a competitive alternative to the existing propulsion systems. The company has so far successfully developed five generations of CycloRotors. The latest version was showcased in 2021 when CycloTech presented a flying demonstrator solely propelled by CycloRotors. A key feature of CycloRotors is the ability to instantaneously direct the thrust vector in a full circle of 360 degrees. In contrast, all other propulsion systems pull or push basically into one direction. Thus, CycloRotors offer unique new capabilities to the worldwide emerging unmanned air vehicle (UAV) and urban air mobility (UAM) markets of the 21st century. It gives vehicle manufacturers unprecedented freedom in designing and operating VTOL aircraft and drones.

3.1. Cyclogyro Principle

A cyclogyro rotor is a propulsion unit that can change the magnitude and direction of thrust without tilting any aircraft structures. It contains several parallel blades rotating around a central rotation axis. A combined airflow generates the thrust through the rotor originating from each blade, and its periodic pitch angle change during one rotation. A specific pitch mechanism controls the individual pitch angle of the blades. Usually, each blade is mechanically connected to a central hub with a conrod.

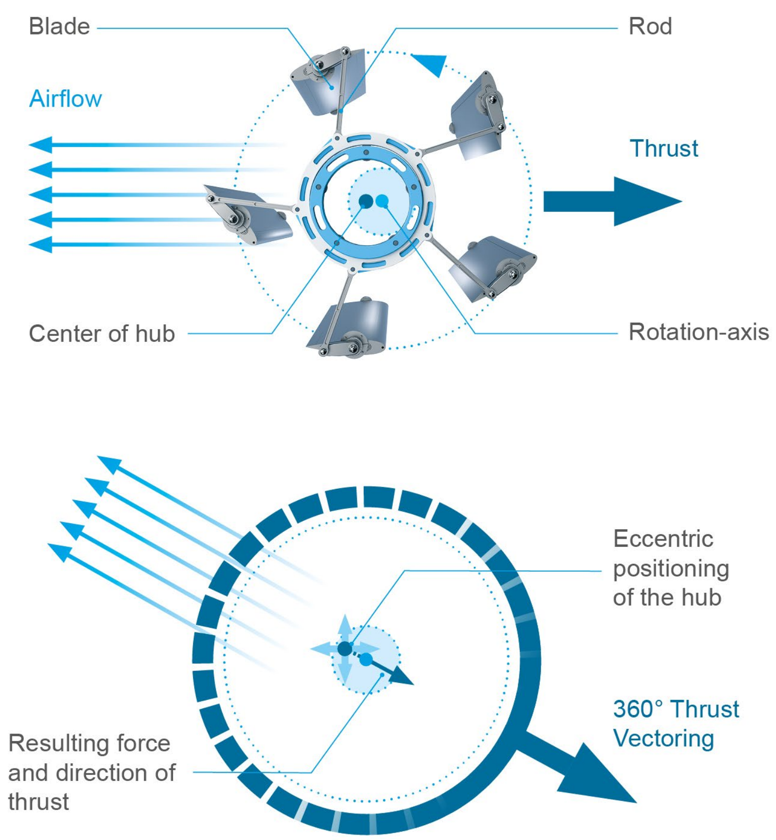

Figure 4: Cyclogyro principal

The cyclogyro rotor magnitude of thrust and its direction can be directly controlled by the eccentric positioning of this hub. This enables an easy and fast way of thrust-vector control of the propulsion unit.

3.2. Unique Characteristics

Compared to traditional aircraft propulsion systems, CycloRotors provide a unique feature-set that offers benefits, especially to VTOL operations.

The basis is the 360° thrust vectoring capability. The ability to instantaneously steer the magnitude and direction of thrust around the rotation axis translates into three key features:

1. Easy Transition - While the transition from hover to forward flight and back is a highly critical phase for VTOL aircraft, the natural and precise thrust vector control of the CycloRotor allows a smooth transition phase without any complex tilting of aircraft structures or nose-down or nose-up operations of the aircraft.

2. Superior Maneuverability – The preciseness and high reactivity of the system is ideal for crosswind and gust control as well as precision landing.

3. Decoupling of flight path and vehicle attitude – As the thrust vector can be controlled 360° around its rotation axis, it is possible to keep the aircraft fuselage at any angle, independent from the flight direction. In the case of passenger transport, the passenger cell could be kept horizontal in all flight phases or adjusted as needed and thus provide superior riding comfort and visibility.

In addition, CycloRotors offer a compact design as they provide lift and thrust in one system. Compared to fixed-wing, tilt-wing, or tilt-rotor systems, aircraft with CycloRotors as the primary propulsion system offer a significant reduction of the aircraft footprint.

Combining these elements makes CycloRotors an ideal propulsion system for operation in confined areas, crowded airspace, and harsher, unpredictable weather conditions.

As the performance of CycloRotors increases and energy consumption decreases with rising speed, CycloRotors are best suited for short- and mid-range flight missions.

4. Solution

For the first time, the unique characteristics of CycloRotors were used to design a mission optimized unmanned cargo eVTOL aircraft, compact in size, stable in windy weather with precision landing capability, based on Yamato's mission requirements and logistics concept, including the PUPA701.

The main design perspectives for this new breed of aircraft, solely propelled by CycloRotors, are mission capability, safety in flight and on the ground, efficient and ergonomic logistics operation, compactness, and maneuverability in urban areas. This study does not include the more generic aspects of autonomous navigation or vehicle-related factors like cost or certification.

The design is based on extensive calculations, wind tunnel testing, and flights of a technology demonstrator.

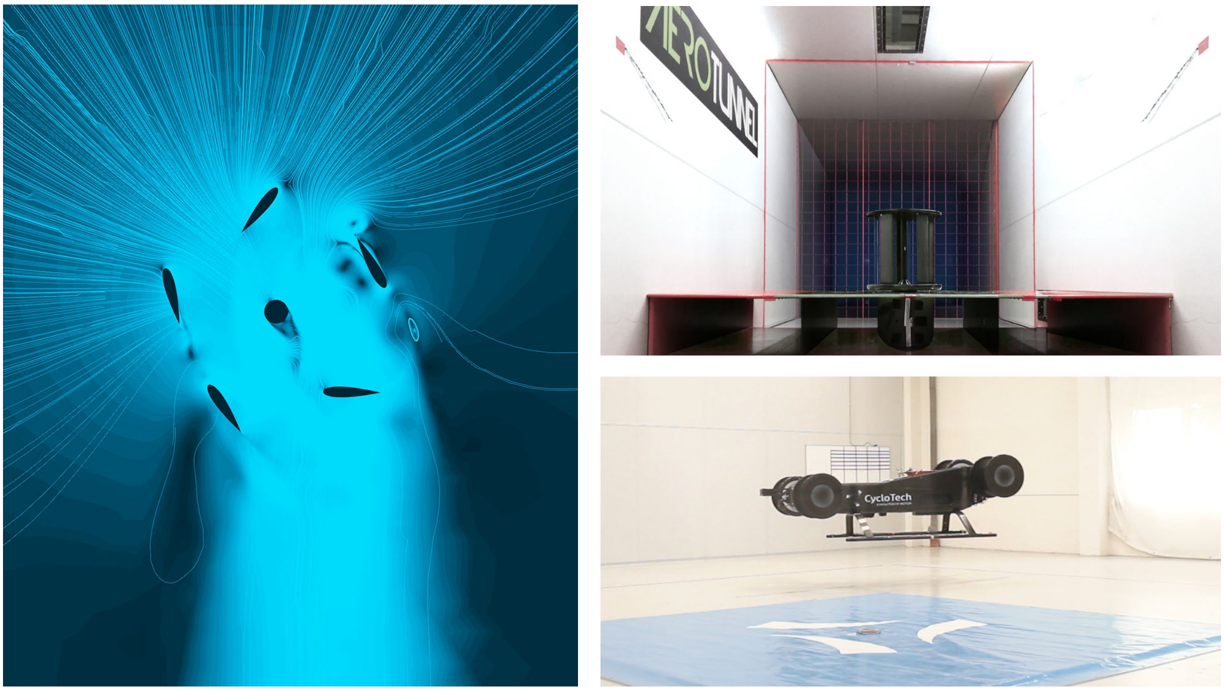

Figure 5: CFDs simulation, wind tunnel testing and demonstrator flights

4.1. Vehicle Design Concept

The design process was performed in several phases: ideation, conception, detailing and finalizing. During the vehicle design, three key elements were worked on simultaneously - rotor configuration, eVTOL aircraft architecture, and structural design - as these elements strongly influence each other.

As the primary purpose of the cargo drone is logistics operation, efficient, ergonomic, and safe handling of the payload on the ground is essential. The payload, be it the PUPA itself or just parcels in the PUPA, can be accessed easily in an unobstructed operator bay from the back of the aircraft. The accessibility to the pod is enabled by the direct and unobstructed entry to the payload to load and unload or exchange the PUPA (Figure 7). Furthermore, it is possible to directly access single parcels transported within the pod. Parcels can be taken out of the PUPA by opening the compartment's lid while the pod is still loaded within the vehicle (Figure 8). This human-centered design results in safer ground handling and shorter travel time of the parcel.

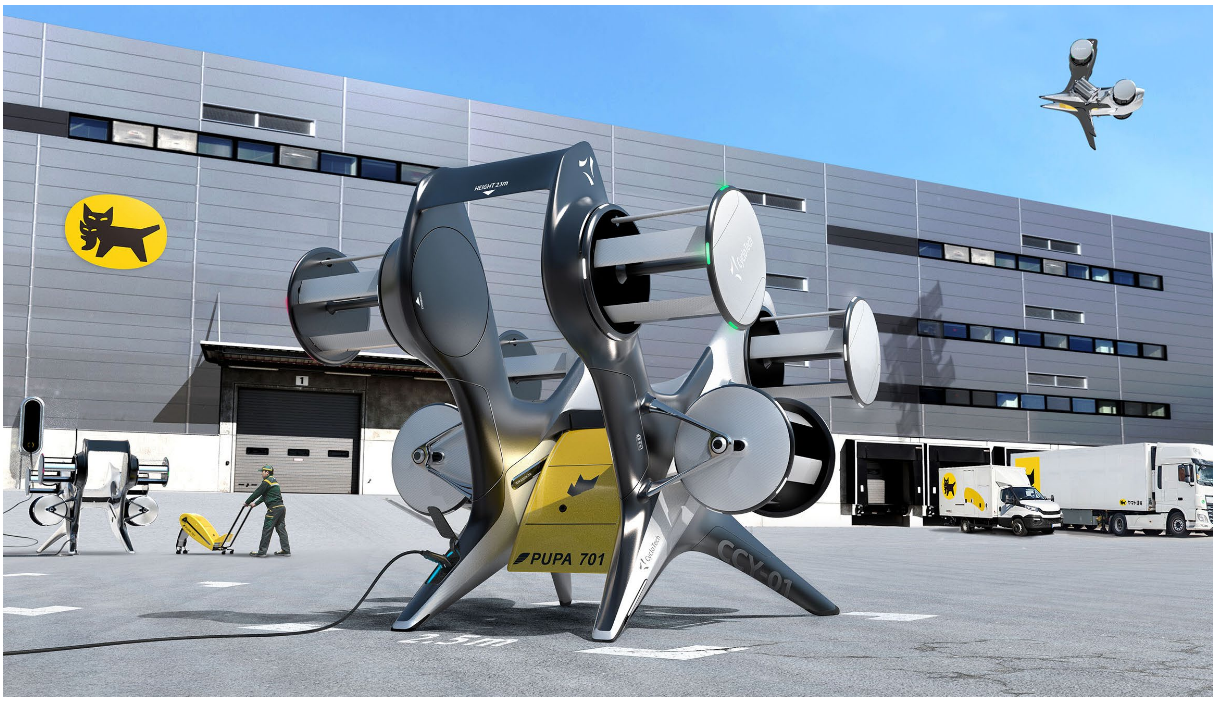

Figure 6: CCY-01 logistic center

During the exchange of the PUPAs, the cargo drone can be connected to a power supply to recharge the batteries. In addition, it is possible to exchange battery packs to speed up the charging procedure. All operations can be handled from one side, an important feature when the operation takes place at elevated landing pads or confined areas. All this ensures flexible, fast, safe, and ergonomic operation minimizing hazards to the operator or the vehicle. With this, shorter turnaround times for a highly efficient aerial last-mile delivery can be performed.

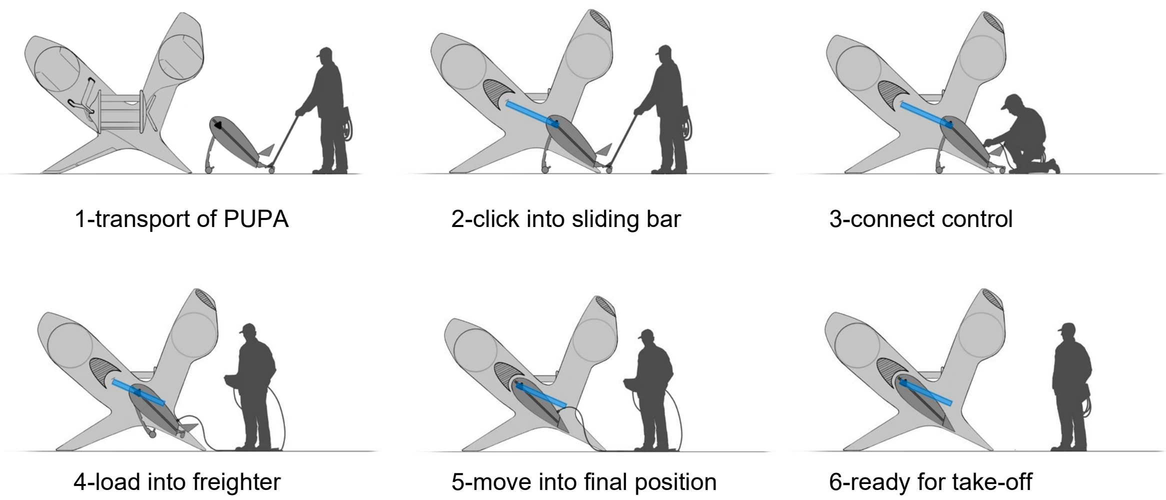

Figure 7: Loading and unloading of PUPA pod

PUPA loaded condition

access single parcels

Figure 8: Loading and unloading of single parcels

The images in this section highlight the final concept and visualization of the cargo freighter concept designed together by CycloTech and Yamato, resulting from an intensive and collaborative development process.

With the operational aspects on-ground well addressed, the vehicle is in parallel optimized to the airborne operation in an urban environment. One of the critical features of the freighter drone is the very small footprint of 2.7 x 2.5 m, which gives the possibility to land in very small and obstructed areas, in prepared as well as unprepared landing sites. The drone can land on any surface, which provides a landing area of 3.5 x 3.5 m, be it on rooftops, parking lots, helipads, or other places.

Figure 9: CCY-01 urban delivery

In order to have a minimum footprint, the aircraft operates in two orientations - a landing and a flight orientation. This allows for the optimization of each operational phase to the highest efficiency. On the ground, the vehicle is optimized to access logistics operations (e.g., to the PUPA) and for easy inspection and maintenance of the aircraft. Additionally, in landing orientation, the vehicle can utilize

100% performance from all rotors for the hover/ascent/descent mode, the most demanding flight phase, e.g., in case of a one-rotor-failure. After take-off, the aircraft leans smoothly forward by 45° into the flight mode, easily done with the thrust vector system. In forwarding flight mode, the vehicle uses optimized rotor settings and utilizes the PUPA as an airfoil reducing drag.

The 6-rotor configuration for this aircraft permits a safe and stable landing even if one CycloRotor fails. This CycloRotor redundancy coupled with the omnidirectional thrust system ensures a safe flight mission with high maneuverability, even in harsh weather conditions. The chosen relative positioning of rotors allows for compensating crosswind from any direction and enables precision landing.

In order to utilize sustainable energy resource, the electric motors driving the CycloRotors are battery-powered.

4.2. Vehicle Design Approach

Every aircraft design is targeted to a specific operational task. Thus, the driving force behind any vehicle's design is its primary objective and the defined boundary conditions. For the joint study, the primary objective has been defined as:

Safe transportation of Yamato's PUPA701 (45 kg payload) over a distance of 45 km with operational capability to withstand a gust of 25 knots during the VTOL phase.

The vehicle design concept contains the configuration process with the hard and soft requirements from Yamato, performance calculations, and the first brainstorming on possible aircraft configurations. Additionally, a configuration down selection was performed, followed by setting up the ideal configuration for utilizing the thrust capabilities of the CycloRotors. In the last phase of the vehicle design concept, the artistic design concept for the freighter drone was created, which was structured into ideation, 2D development, and finally, a 3D development with high-quality renderings.

The final design concept has resulted from close collaboration between the project teams of CycloTech and Yamato with several calculation and reconciliation loops to find the ideal aircraft configuration and derive the specific vehicle design.

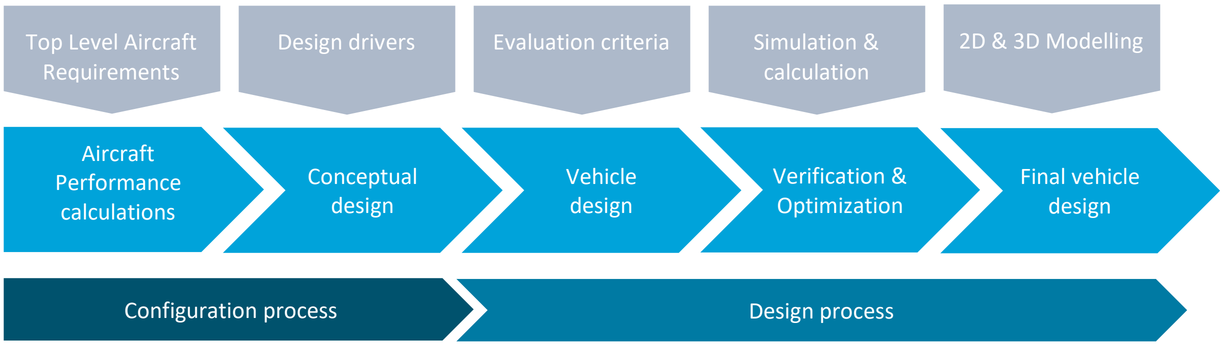

Figure 10:Vehicle design approach schematics

4.3. Aircraft Configuration & Design Process

The configuration process describes the steps from the initial aircraft configuration idea to the latest version of the aircraft as it is further used for calculations and simulations in the design phase. The configuration itself describes the layout and basic structure of the freighter vehicle.

4.3.1. Top Level Aircraft Requirements (TLAR)

As a necessary input for the first aircraft performance calculations, CycloTech defined the Top-Level Aircraft requirements (TLARs) for the Vehicle concept identified from Yamato's CCY-01 requirements:

Parameter	Unit	Value	Comment
Payload	kg	45	Mandatory Yamato Requirements CCY-01
Total Mission Distance	km	40	Mandatory Yamato Requirements CCY-01
MTOW	kg	Minimum	Output of Flight Performance Tool
Energy Consumption Rate Gross	MJ/tkm	Minimum	Output of Flight Performance Tool
Cruise Speed	km/h	Efficient	Output of Flight Performance Tool

Table 2: Flight Characteristics - Yamato Design Concept

4.3.2. Flight Performance Tool

The initial performance calculations and all other optimization loops have been conducted with a simulation tool developed in-house by CycloTech to analyze vehicle concepts with different configurations of CycloRotors while operating under diverse environmental conditions.

Figure 11: Flight Performance Tool schematics

The Flight Performance Tool is an essential element of CycloTechs ability to customize CycloRotors to specific mission requirements. The rotor dimensions and operational parameters need to be tailor-made to the use case to exploit the full potential of the thrust vector control system. The tool is highly automated, contains a highly flexible visualization of performance characteristics, and enables fast parameter and sensitivity studies. The calculations of the Flight Performance Tool are based on:

- Top Level Aircraft Requirements (TLARs)
  Flight range, payload
- Rotor and Vehicle Aerodynamics
  CycloTech's Performance Map with aerodynamic data from wind-tunnel tests of CycloRotors
  Aerodynamic characteristics of the vehicle – lift, drag, side force
- Weight Estimation Module
  Intelligent scaling of CycloRotors based on the total number of CycloRotors in the vehicle design concept and desired safety thrust margins for CycloRotors
  Experience from Cyclogyro rotor design in terms of structural stability
  Empirical scaling of vehicle component weights based on vehicle lift and thrust requirements
  Maximizing battery energy storage for the highest flight mission range

- Aircraft Configuration

  Simulate airframe design with multi-rotor configuration [primary + side CycloRotors]

  Vehicle footprint and size

- Flight Mission Profile

  Simulation of user-defined flight phases; take-off, hover, climb, cruise, descent, landing with flight path angle

- Energy source

  Battery Module design based on user-defined battery database

  Battery cooling and housing requirements to maximize the operational life of the battery in the vehicle

  Adaptation of battery energy density based on battery discharge load requirements of the Vehicle

- Sensitivity study

  Feasibility checks of the vehicle concepts based on multiple safety parameters and safe landing with one-rotor-failure

  Multiple internally linked modules to understand the confluence of limiting conditions of a vehicle concept and design: Battery/Hybrid, Rotor/Aircraft configuration, Mission, Cruise speed, and other

The Flight Performance tool thus allowed for simulation of vehicle concepts using CycloRotors and their instant adaptation based on individual customer requirements.

4.3.3. Aircraft Concept Selection

The results from the Flight Performance Tool have been the basis for the conceptual design phase for the freighter drone. Together with the requirements for the whole vehicle, the dimension of the CycloRotors formed the boundaries for the concept.

Besides the TLAR described in section 4.3.1, the following main design drivers (among many others) have been taken into consideration within the concept workshops to identify, evaluate and down select possible aircraft configurations.

- Propulsion system

  Utilization of the unique feature set of the 360° thrust vector system

- Safety

  Safety to the operator and vehicle

  Ability to land safely in emergency conditions in case of one rotor failure

- Optimized logistics process
  Easy and safe ground handling process (ground worthiness)
  Unobstructed access to PUPA701
  Repeated and fast logistics operations
  Good accessibility of the vehicle for inspection, recharging, and ease of maintenance
- Minimum vehicle footprint
  Ability to start and land in confined, obstructed, prepared, and unprepared urban places
- Aircraft stability
  Gust compensation in harsh weather conditions
  The structural integrity of the vehicle
- Aerodynamics
  Utilizing aerodynamics of vehicle surfaces to generate lift, reduce drag, and dynamic orientation of vehicle for efficient operation of the vehicle
  Minimizing influence and interaction between vehicle and rotor aerodynamics

With the criteria mentioned above, a total number of 18 configuration concepts have been systematically evaluated, ranked, and down-selected to the final concept for a detailed vehicle design phase.

4.3.4. Optimization and Verification Phase

The final design direction and sizing of the structural elements have been used as input parameters for the Flight Performance Tool described in section 4.3.2 to verify the performance figures of the initial configuration calculations.

In parallel to the ongoing design process, the derived parameters have been constantly reviewed and used for optimization and verification calculations.

- Safety – ensuring the safe landing of the vehicle with a multi-rotor configuration for a rotor failure by applying appropriate safety margins of the CycloRotors and battery system for a go-around mission
- Flight mission optimization – optimization of speed and acceleration rates as well as an optimal vehicle orientation through flight path angle across different flight mission phases of a standard cargo mission
- Gust control – verifying the TLAR of gust compensation during the VTOL phase to handle challenging wind conditions.

A key objective of the Yamato Cargo Drone CCY-01 is the ability to land with precision in confirmed areas and the ability to handle challenging wind conditions. The design features 6 omni-directional thrust generating CycloRotors with dedicated rotors on the left and right sides to ensure maximum maneuverability and gust control in harsh weather conditions. The required limit of 20 kts constant wind at landing could be significantly exceeded, and a maximum offset of only 0.4 m at a 25 kts gust wind at landing was calculated.

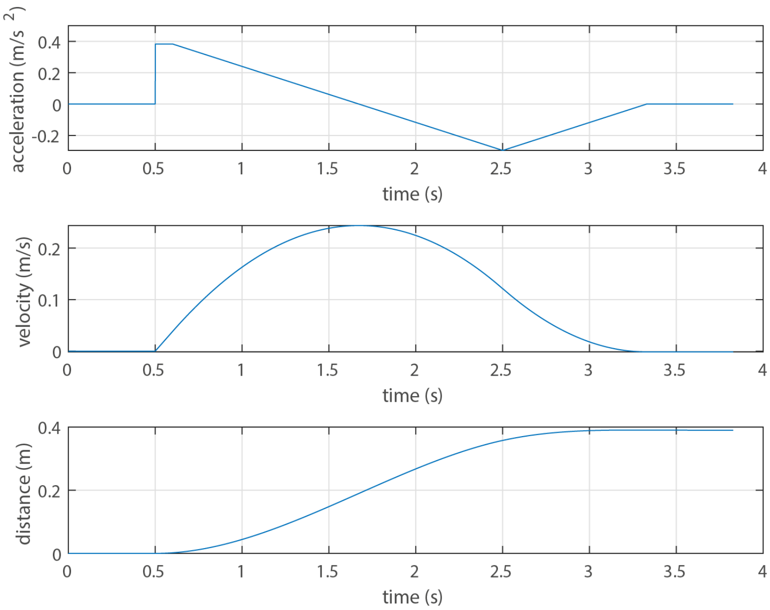

Figure 12: Gust control

The maximum limit of 36.5 kts for constant crosswind was calculated, assuming that the gusting wind can be compensated if the propulsion system can produce enough force to counter the drag force originating from the gusting wind. The primary boundary condition is to be still able to hover at a minimum of controllability. Therefore, only a static state is calculated based on the equilibrium of the force of gravity, the drag force of a constant gust wind, and the force of the propulsion system. It is assumed that the crosswind in hover will be acting from the side, and only one side rotor is acting against the gust. This is considered the most critical case. A minimum of 15% overall surplus of lift is estimated to maintain general controllability. The calculation assumes rotor performance and vehicle characteristics based on CycloTech`s Flight Performance Tool.

The maximum offset of 0.4 m at 25 kts gusts wind at landing was calculated based on an on-moment inertia calculation. Further results of the forces, accelerations, velocity and distance can be seen in Figure 12.

4.4. eVTOL Configuration

The specification of the final design is summarized below.

4.4.1. Dimensions

Vehicle in landing orientation, length: 2.70 m, width: 2.50 m, height: 2.40 m

Vehicle in-flight orientation, length: 3.08 m, width: 2.50 m, height: 3.25 m

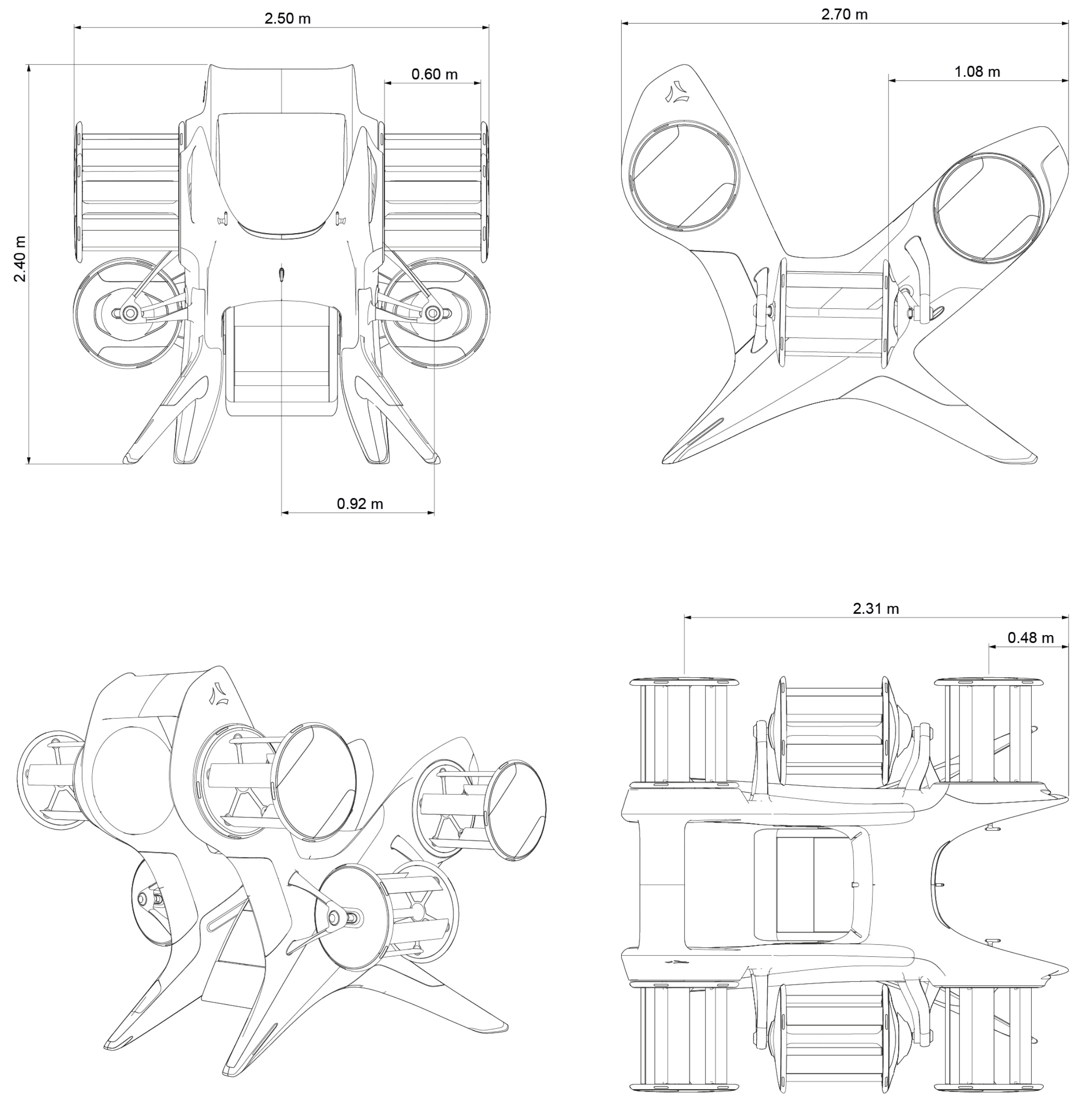

Figure 13: Vehicle design and dimensions in landing orientation

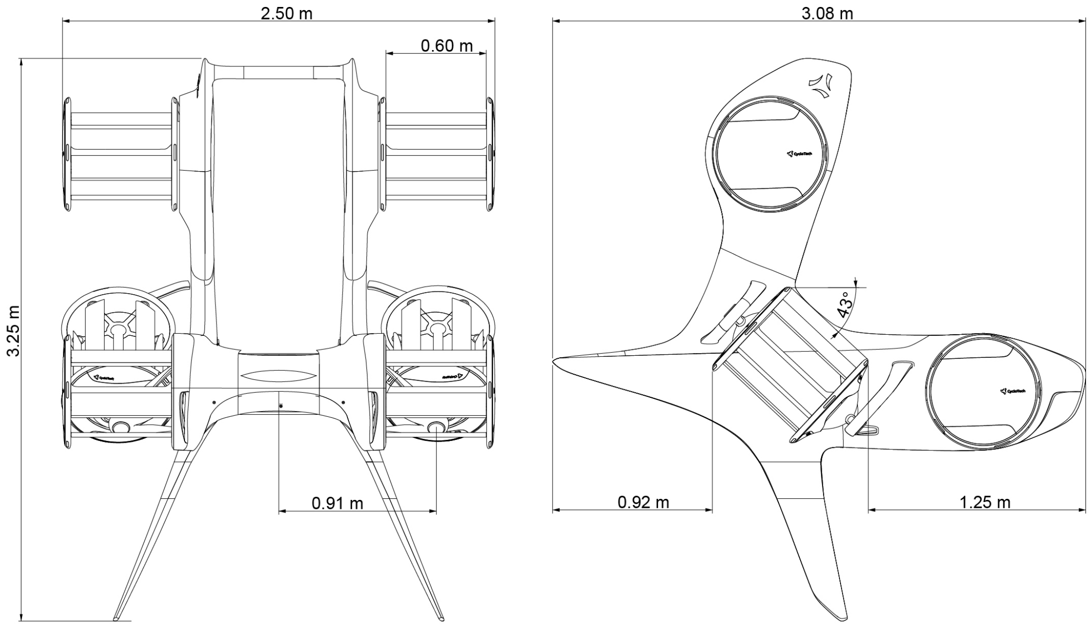

Figure 14:Vehicle design and dimensions in-flight orientation

4.4.2. Weight and Structural Breakdown

The weight breakdown is derived from the Flight Performance Tool, state-of-the-art technology, and empirical relations for the Yamato Vehicle Design Concept, as shown in the table below.

Mass Breakdown	Unit (kg)	Percent	Comments
Propulsion System	48.2	17.2 %	Rotor weight calculation from Rotor Performance Scaling and Rotor Weight Distribution
Airframe Structure	45.3	16.2 %	Scaled values based on Technology Demonstrator and statistical values
Motors / Controllers / Power Wiring	48.1	17.2 %	From State-of-the-Art Technology. Calculated using Power and Energy densities.
Energy Storage	79.4	28.3 %	From State-of-the-Art Technology. Calculated using Power and Energy densities. Battery Energy Density referenced from eVTOL Configuration
Avionics / Electronics / Servos	11.2	4.0 %	From Scaled values based on Technology Demonstrator
Misc	2.8	1.0 %	Miscellaneous

Payload	45.0	16.1 %	From Target Yamato Requirements CCY-01 Section 2.4
Total			
MTOW	280	100 %	Designed Yamato Concept Output from Flight Performance Tool

Table 3: Mass Breakdown - Yamato Design Concept

4.4.3. Energy System

The energy storage characteristics of the Yamato design concept, designed by the Flight Performance Tool based on the mass of the energy storage module calculated in Section 4.4.2, are summarized below.

Battery Pack	Value	Unit	Comment
Cell - Energy Density	0.320	kWh/kg	High Battery Energy Density Cells, typical value from Lilium GmbH
Module - Energy Density	0.248	kWh/kg	Effective Battery Energy Density, including cooling and housing requirements for Battery Module
Module – Weight	79.36	kg	Calculated from Energy Storage in Weight Breakdown
Module – Design Energy Capacity	19.89	kWh	Output from Battery Design Calculations
Module – Operating Voltage	240	V	Maximum Operating voltage based on Safety Requirements for the MTOW
Module – Effective Useable Capacity	90	%	Based on Discharge rate of the battery, and wear over time, overall reduction in useable battery capacity
Battery Discharge Load (Hover)	5.92	C	Calculated from Flight Performance Tool output of Flight Mission Profile.

Table 4: Energy Storage Characteristics - Yamato Design Concept

For the given flight mission profile, the hover discharge load is observed at 5.92 C. This low discharge load allows for compact and higher battery energy density cells of 0.32 kWh/kg (Nathen, 2021).

The battery module is designed with maximum safe operating voltage for this vehicle's MTOW - 240V [State of the Art Technology] and with the housing and cooling requirements of the battery module. Thus, the effective energy density of the battery module is determined as 0.248 kWh/kg.

4.4.4. Propulsion System

The aircraft is solely propelled by CycloRotors with their omni-directional thrust capabilities providing lift and forward thrust. For safety, maneuverability, and compactness reasons, a 6 rotors configuration is chosen. Four CycloRotors in the primary flight direction (main rotors), offset in height to prevent airflow interaction, and 2 CycloRotors in 45° angle hereto (side rotors). This permits all 6 rotors to be 100% oriented in take-off and landing direction, the phase where the maximum thrust is needed. The thrust requirements are lower in forwarding flight and can be served by the 4 rotors and the side 2 rotors.

The side rotors also ensure lateral side force generation for gust/crosswind control and precision landing.

By choosing 6 CycloRotors, the safety of the vehicle is ensured by redundancy in case of a one-rotor failure. Safety margins in all CycloRotors ensure instant compensation of lift and thrust requirements in case of one engine failure to enable safe landing in all conditions.

In order to provide the best prerequisites for the optimization of production cost and ease of maintenance, all 6 rotors are of the same design. More details of the individual CycloRotors design are given in chapter 4.7.

4.4.5. Flight Characteristics

The flight characteristics of the final vehicle concept are summarized in the table below.

Parameter	Value	Unit	Comment
MTOW	280	kg	Output of Flight Performance Tool
Payload	45	kg	Mandatory Yamato Requirements CCY-01
Total Mission Distance	40	km	Mandatory Yamato Requirements CCY-01
Average Energy Consumption Rate	37.35	MJ/tkm	Output of Flight Performance Tool
Cruise Speed	120	km/h	Output of Flight Performance Tool
Service Ceiling	1,500	m	Desirable Yamato Requirements CCY-01

Table 5: Flight Characteristics - Yamato Design Concept

4.4.6. Drivetrain Specifications

The drivetrain characteristics, based on CycloRotors driven by electric motors without gearboxes needed (type: Direct Drive based on state-of-the-art technology), are summarized in the table below.

Drivetrain Specs	Value	Unit	Comment
Power Density – Electric Motor and Controller	5.9	kW/kg	State of the Art (Siemens, 2019)
Power Efficiency – Friction losses	94 %	Percent	From Technology Demonstrator
Power Efficiency – Electric Motor	96 %	Percent	From Technology Demonstrator
Power Efficiency – Motor Controller	99 %	Percent	From Technology Demonstrator
Total Power Efficiency	89 %	Percent	From Technology Demonstrator

Table 6: Drivetrain Specifications - Yamato Design Concept

4.5. Drag Calculation

The drag estimation of the eVTOL configuration in cruise conditions uses a semi-empirical approach based on historical data (Raymer, 2004). The airframe was decomposed into substructures that could be approximated by wing-like components and fuselage-like components (Figure 14). It is important to note that it is considered that the drone's body generates no appreciable lift and that PUPA and its leading-edge cover/housing act as a single wing-shaped structure. This leads to a drag coefficient of 1,110 drag counts. It is important to note that all non-dimensional coefficients related to the airframe adopt the frontal projected area of the airframe as reference.

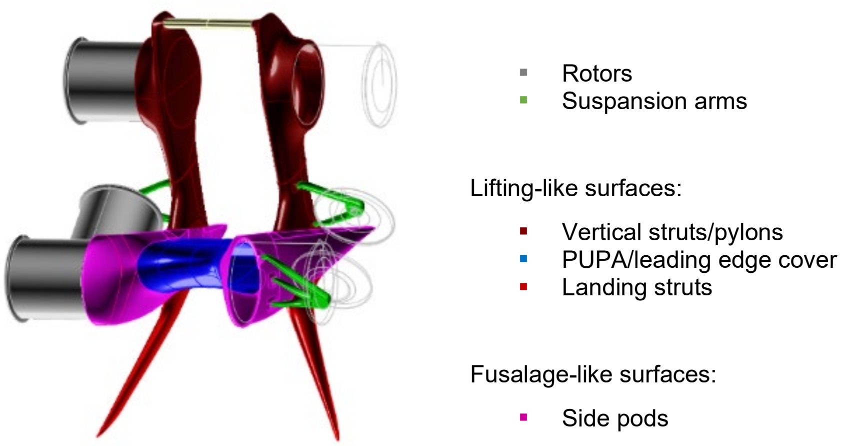

Figure 15: Airframe decomposition for cruise drag calculation

For take-off, landing, climbing, and descending phases, the vehicle faces vertical aerodynamic resistance. In a similar fashion to the cruise drag, a semi-empirical approach was used, resulting in a vertical force coefficient of 8,180 drag counts, with an additional induced-like drag in the longitudinal axis equal to 4,307 counts.

Similarly, the side force coefficient due to gusts was calculated as 7,890 counts, with an associated longitudinal drag-like force coefficient of 765 counts.

4.6. Rotor Configuration

The design of CycloRotors is the core competence of CycloTech and is here not further elaborated. It is noted that this is a highly complex process mastered by CycloTech as a worldwide leading technology company in this field. Theoretical knowledge, prototype bench, wind tunnel testing, computer simulations, and experience from flight demonstrations form the basis of CycloTech's unique know-how on CycloRotors. The critical parameters of the CycloRotors of the final vehicle concept are summarized in the table below.

Rotor Characteristics	Value	Unit	Comment
Number of Rotors	6.00	Nr.	From Yamato Design Concept
Rotor Radius	0.25	m	Output of CycloRotor Performance Scaling Formulation
Rotor Wingspan	0.60	m	Output of CycloRotor Performance Scaling Formulation
Rotor RPM	2,600	RPM	Output of CycloRotor Performance Scaling Formulation
Max Overall Thrust	4,395	N	Output of CycloRotor Performance Scaling Formulation
Max Overall Drive Power	210	kW	Output of CycloRotor Performance Scaling Formulation
Overall Hover Thrust	2,750	N	Based on Rotor Safety Design Margins
Overall Hover Drive Power	118	kW	Based on Rotor Safety Design Margins

Table 7: CycloRotor characteristics – Yamato Design Concept

4.7. Mission

The transport mission is segmented into different real-world flight phases and calculated with the Flight Performance Tool applying the Yamato requirements, such as transport of 45 kg of payload over a 40 km range. Here it is noteworthy that there is no need for a dedicated transition phase –

necessary for the other eVTOL aircraft – as CycloRotors offer the natural thrust vectoring with smooth change of direction and magnitude of thrust.

4.7.1. Flight Mission Profile

The following flight mission profile has been adopted for Yamato's Cargo Drone, keeping in mind the CCY-01 requirements of highest range, lowest flight time, and safe cruising altitudes to fly safely over urban areas (x-axis as Flight Mission Time vs. Density Altitude at ISA).

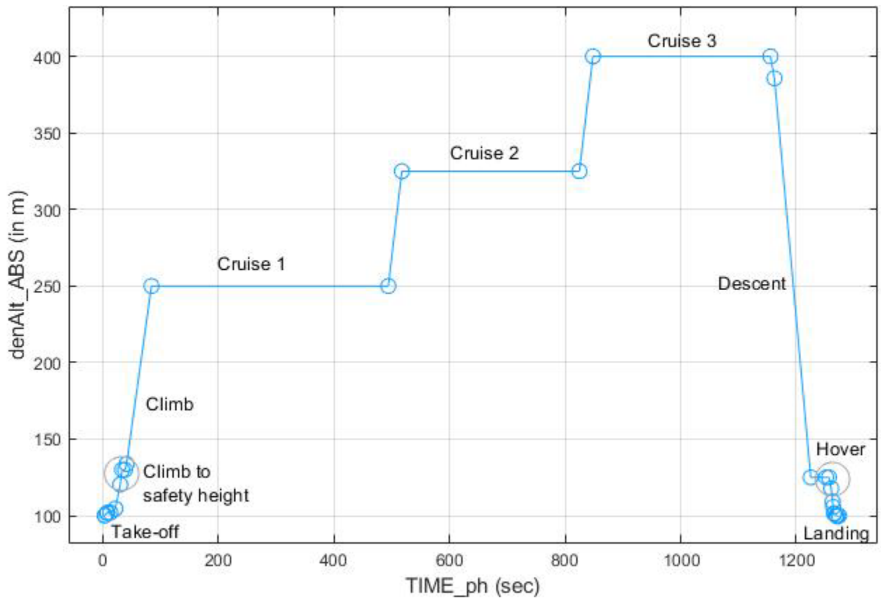

Figure 16: Flight Performance Tool – Simulated Flight Mission Profile

4.7.2. Energy Consumption Rate during Flight Phases

The energy consumption of the different flight phases is directly proportional to the time spent in different flight phases. The breakdown is shown in the graph below.

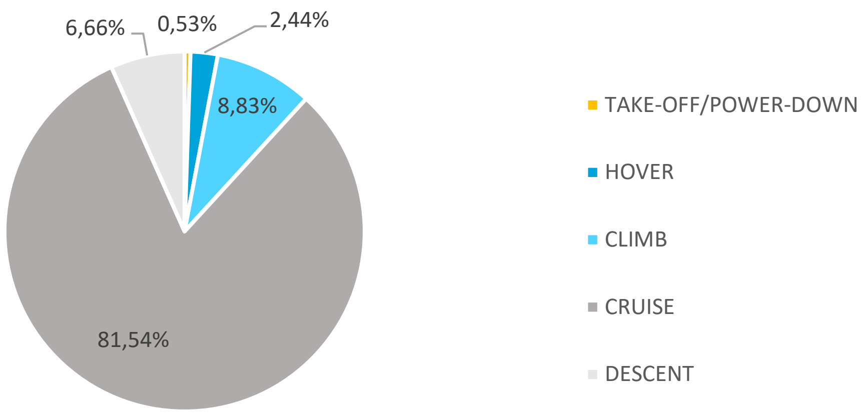

Figure 17: Rate of Energy Consumption per phase type - Yamato Design Concept

The performance settings of the CycloRotors have been optimized to deliver the highest efficiency in the rate of energy consumption during cruise phases.

It is seen that for this aircraft concept, the energy consumption during the cruise phase is 3 times less than the one during a hover phase.

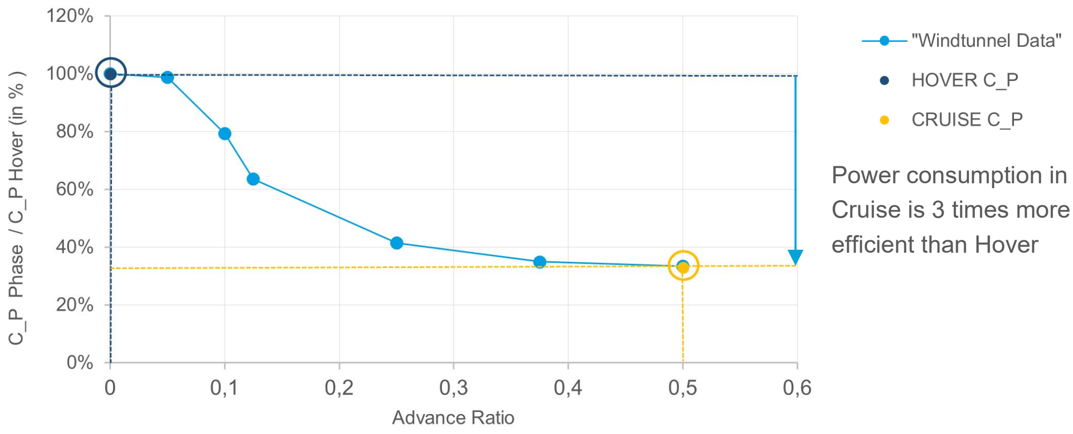

Figure 18: CycloRotor rate of energy consumption – Cruise vs Hover

4.8. Conclusion

The feasibility of applying the new thrust vectoring propulsion technology, named CycloRotors, to create a mid-class, battery powered cargo eVTOL (electric vertical take-off and landing) aircraft capable of carrying 45 kg of payload over a range of 40 km and handling challenging wind conditions, such as up to 36.5 kts constant crosswind, has been shown.

The unique features of CycloRotors led to a compact design, with the vehicle fitting into a box of 2.7 x 2.5 x 2.4 m, making it ideal for operation in confined areas, particularly in urban environments. Superior maneuverability based on the 360° thrust vectoring allows for precision landing at a crosswind of 25 kts into landing sites of just 3.5 x 3.5 m.

The freedom provided by the omnidirectional thrust rotors allowed to design of an aircraft perfectly fitted to the intended logistical operation creating an aircraft shape embracing human interaction with the vehicle, easy loading and unloading of freight, fast turn-around times, and safe and ergonomic ground operation.

5. Discussion

5.1. Extended application of thrust vectoring

The significance of the rapid and omni-directional thrust vectoring of CycloRotors for the application in urban logistics vehicles has been argued in the context of its precise landing and wind tolerance capability so far. However, other meanings could also be considered. This section highlights the extended application of the thrust vectoring capability of the CCY-01 design to increase safety and operability.

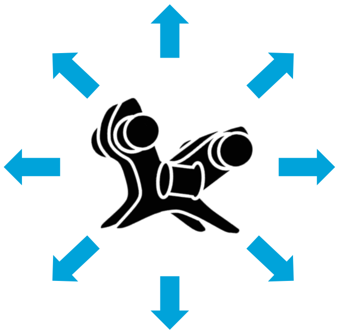

Figure 19: Thrust vectoring performance

First, as the rotors can instantly produce negative (or downward) lift, this force could be used to press the airframe to the landing pad just after landing in gusty conditions to prevent it from being blown away. This should increase safety, especially when operating on rooftop landing pads on skyscrapers.

An equivalent extended application could be considered on moving or uneven surfaces. It is known that helicopters have an upper limit for slope landing of about 5° due to the limited angle the main rotor can orient its lift (Federal Aviation Administration, 2019). Regarding CycloRotors, this limitation does not apply, and the aircraft can land on a much wider range of inclined terrains.

The tolerance to the inclination of the landing surface is not limited to a static surface: it can also respond to a moving or unsolid surface. Landing onto ships or difficult terrains that requires high pilot skill for helicopters could be more easily automated when applying CycloRotors.

5.2. ConOps expanded from urban mission

5.2.1. Disaster relief

An essential role outside regular urban missions will be disaster relief. Japan, Yamato's primary market, is hit by typhoons every year and threatened by a possible major earthquake. According to the report by the Greater Tokyo Area Earthquakes Countermeasures Working Group, Central Disaster Measures Council (2013), a magnitude 7.0 class earthquake having its seismic center inside the Tokyo Metropolitan area is predicted to take place with a 70% probability within the coming next 30 years. The report assumes that 3 million people will be forced to evacuate from their homes or workplaces, while up to 60,000 buildings will collapse or be burnt down. Supplying food, water, clothing, medicines, and critical spare parts with this scale, over an area whose ground infrastructure is completely destroyed (and perhaps flooded by Tsunami) will be one of the most significant air bridge operations in history that will require all VTOL capable aircrafts available. As discussed in the previous section, CCY-01 capability of landing on uneven surfaces could be a precious tool to deliver vital supplies to sites not yet cleared of debris and flattened for helicopter operation. Even if not to directly carry the wounded, taking the role of urgent air delivery could also make room for helicopters to be used for human transportation.

5.2.2. Maritime operations

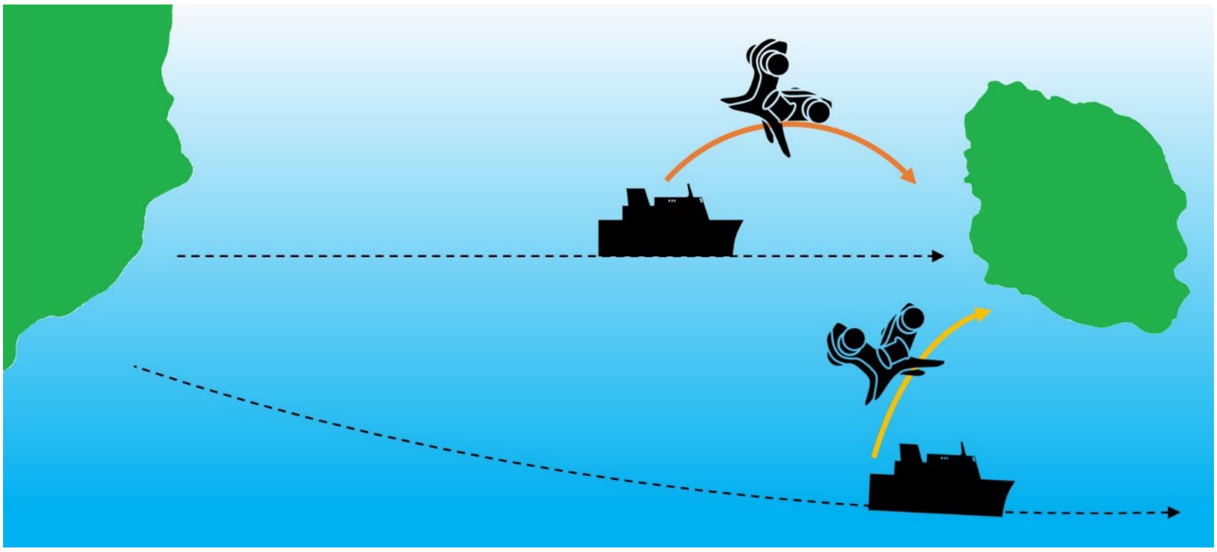

Figure 20: Maritime operation scenario

As discussed previously, the CCY-01 type of aircraft might easily acquire its capability to land on a moving ship. The application of this feature could be to serve remote island operations. The main logistics problem on remote islands is that the time window for delivery and sending is extremely small due to the limited service of ships. A short distance flight could solve this problem without spending much extra cost, only if the aircraft could land on a ship.

One solution will be to use ships passing by near but not stopping at the island. In this case, the aircraft will travel between the ship and the island while the ship is passing by. This will have the meaning to increase ship service to the island virtually. Especially in Japan which has an elongated homeland surrounded by sea, many ferry routes are set to connect major cities, bypassing remote islands. The fact not only enlarges the feasibility but also provides multi-directional services whose destination will not be limited to just one city.

Another will be to launch aircraft from the ship traveling towards the island. When the ship is in the range of the aircraft, the aircraft starts toward the island. The aircraft will depart the island for the return journey after the ship sails away. In this operation, the aircraft will provide people on the island an enlarged time window for logistics, making it the same as if the ship anchored longer at the island but still maintained the original timetable. This operation is similar to the Heinkel HE-12 seaplanes that Deutsche Luft Hansa operated from S.S. *Bremen* and *Europa* on their trans-Atlantic routes around the 1930s.

5.3. Outlook

The vehicle presented and discussed in this document is one of the first of a new breed of aircraft that will emerge with the arrival of CyclorRotor technology in the aviation world. CycloRotors can be used as primary propulsion systems (as in this case) or auxiliary systems. CycloRotors can be configured and combined in many ways, with themselves in different sizes, orientations, and quantities or with other typical aircraft components, such as lifting surfaces or other propulsion systems.

The unique characteristics of CycloRotors give vehicle manufacturers unprecedented freedom in inventing and designing new aircraft for the new air mobility requirements of this century.

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About Yamato Holdings

Yamato Holdings is a holding company of Yamato Group which contains Yamato Transport, the largest and leading parcel delivery provider in Japan. Since its founding in 1919, the company has achieved multiple radical innovations, including the introduction of route transportation and the introduction of the nationwide popular TA-Q-BIN. The company continues to create new values by integrating functions of the group companies into the TA-Q-BIN network.

https://yamato-hd.co.jp/english/

About CycloTech

CycloTech GmbH is the world leading company for aviation propulsion systems based on the Voith-Schneider-Principle. The Austrian company develops the unique 360° thrust vectoring CycloRotor, a new, sustainable, highly maneuverable propulsion system for the new air mobility demands of the 21st century. The compact design and instant control of magnitude and orientation of the omnidirectional thrust of CycloRotors enable an easy transition from hover to forward flight regimes, gust control, and precision landing, ideal for safe operation in crowed airspace and confined areas. CycloTech aims at making individual air mobility as normal as driving a car - opening the sky for everyone.

https://www.cyclotech.at/