A DESIGN APPROACH FOR A MODEL-SCALE VTOL POWERED BY TWO PIVOTING KEROSENE TURBINES

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Abstract

At the Institute of Air Transportation Systems, an innovative vertical take-off and landing (VTOL) model is being developed as a test vehicle to stimulate future research on combined highly automated flying and ground systems. The aircraft, primarily powered by two pivoting kerosene turbines, will serve as a multi-role transport aircraft for different mission scenarios, resulting in different payloads. Intended missions include surveillance in disaster scenario, ground and airborne vehicle jettison during landing or in-flight, and flight algorithm testing. The research question is how the design can be achieved and what design methodologies are appropriate. This paper describes the design methodology for the aircraft design process according to the given requirements and presents two of the main aircraft concepts under consideration. It also details the key steps in the process, such as iterating and alternating designs. The aim of the paper is to provide a design methodology that motivates disruptive variation for more efficient design evolution.

Keywords: VTOL, UAV design, design methodology, aircraft design, design philosophy

1. Introduction

Research on VTOL unmanned aerial vehicles (UAVs) is of great importance to universities because of its potential for academic exploration and practical applications. The study of these aircraft provides a broad platform for multidisciplinary studies involving engineering, aerodynamics and software development. It provides students and researchers with hands-on experience in designing, building and optimising advanced aerial systems. In addition, VTOL UAV research can lead to collaborations with industry and other academic institutions, providing avenues for innovation, funding opportunities and real-world problem solving, thereby enhancing the University's academic reputation and contributing to technological advancement. Therefore, the Institute of Air Transportation Systems is working on UAV design concepts and application examples to provide a platform for future research topics and student projects.

The aircraft to be designed should be able to take off and land vertically to avoid the need for a runway. The size should be in the range of models, resulting in an assumed wingspan between 2 and 4 m. The maximum take-off mass (MTOM/ m_{tom}) should not exceed 25 kg for ease of certification and operation. Contrary to the current trend for electric motors with batteries, the customer (≙the Institute) decided to integrate combustion engines to investigate also new control algorithm for this type of power drive. This increases the complexity of the system due to subsystems such as tanks, fuel pumps, etc., and their associated characteristics such as a changing and/or moving mass during flight, to mention just one example. As a result, a key feature is the use of two kerosene engines for main propulsion, mounted preferably on the wingtips. The engine types can be selected from standard model components. The VTOL functionality results in the need for a swivel mechanism to allow the engines to change the angle of the thrust vector during the transition from hover to horizontal flight and back.

The field of application covers very interesting research topics, depending on the type of payload. Initially, the design of flight control laws of this aircraft forms the basis for further research. The optimisation and implementation of advanced flight algorithms opens up the possibility of semi-automatic path planning, collision avoidance and even take-off and landing assistance. A second application is the use of the aircraft as a reconnaissance tool for mainly optical payloads. Together with other research topics at the Institute, the aircraft is used to detect fire and smoke in forested areas to assist rescue services in hot and dry weather. Alternatively, thermal imaging may be used to search for missing persons. The aircraft can be used as a transporter for ground-based and airborne vehicles. To start with the former, in a disaster scenario, the carrier aircraft could fly into the affected area, land, offload a ground-based vehicle and fly back to the starting position. This ground vehicle could then be used for other tasks, probably ensuring much longer operational times. The alternative option of an airborne vehicle could be used in conjunction with the above-mentioned fire detection or missing person search missions. Smaller UAVs, either fixed-wing or multi-rotor, are dropped in flight. The following mission profiles can be divided into two main ones. In the first mission, the dropped UAVs can fly and scan areas independently, resulting in multiple small covered areas. In the second mission profile, the carrier flies together with the dropped UAV in a pattern-based formation. This allows areas to be scanned simultaneously, maximising the probability of finding a moving object.
Finally, the aircraft provides a basis for trade-off studies. For example, the engines could be compared with other types within the fixed design. In addition, an upscaling of the aircraft can be considered for various larger payload options or even for a manned aircraft system.

2. Requirements

Requirements serve as the blueprint for success in any project or endeavour. They outline the objectives, functionality and constraints, ensuring clarity and alignment between the customer and the project deliverer. They act as a guiding force, shaping the path to achieving the desired outcomes.
In addition, requirements often evolve and expand throughout a project's lifecycle. As a project unfolds, stakeholders gain a better understanding of the final product and therefore need to adapt to changing circumstances. As a result, the initial set of requirements may be modified or added to reflect new needs and insights. This is normal in iterative processes such as aircraft design.

For the sake of clarity, the basic requirements are recapitulated. The aircraft must not exceed a MTOM of 25 kg. Payloads of different sizes must be considered for missions such as reconnaissance and/or ground and air vehicle drop with a maximum payload mass equal to or greater than 3 kg. The aircraft must also be capable of vertical take-off and landing. Propulsion is mainly provided by two kerosene engines preferably mounted on the wing tips. In addition, a flight time of 30 minutes should be aimed for.

These requirements are usually filled into a requirements list which contains several focus groups such as mass, loads & stresses and so on [1]. Basically any necessary group that is part of the entire system. In case of an UAV there are necessary requirements for operations and handling. An extract of this list is given in the Table 1. Each requirement is given a unique number to ensure accurate allocation.

Other requirements can be added to ensure safe operations and good handling qualities. Regarding the first, to give some insight, safe operations includes general safety in the handling of the UAV including fuel, fail-safe mechanisms in different flight profiles and redundant avionics architecture in case of failures. In terms of handling characteristics, this can be further subdivided into the control behaviour of the UAV in flight, for example flight-bound, and handling on the ground, so that the aircraft can be disassembled into smaller main modules for easier transport to and from the airfield. As a result of this refinement, the requirements also drive the direction of the actual design and its features but also the costs.

No.	Requirement	Description / Value	Type
	Mass		
R1	MTOM	max. 25 kg	fix
R2	payload mass	$\geq$ 3 kg	fix
	Loads & Stresses		
R3	max. loadfactor flight	+4, -2	fix
R4	max. loadfactor landing	8	fix
	Flight Performance		
R5	VTOL ability	-	fix
R6	missiontime	$\geq$ 30 min	wish
R7	payloads for carrier mission	-	wish
	Components		
R8	propulsion	model turbines	fix
	Assembly/Transport		
R9	interfaces	max. module length 1.6m	fix
...	...	...	
...	...		

Table 1 – Extract from the list of requirements after [1]

3. Design Methodology

A methodical approach to aircraft design is important because it focuses on systematic detailed analysis and estimation calculations for defined aircraft disciplines. It involves a complete process of analysing aerodynamics, structural integrity and performance characteristics using an appropriate method. These calculations drive critical decisions that ensure the stability, efficiency and safety of the aircraft. Incorporating iterative cycles allow the design to be refined and improved by making adjustments based on extensive data and testing. The following is an explanation of the methodology that is used to create a suitable aircraft solution to meet the needs of the customer.

3.1 Main Approach

The basis of the methodology is an aircraft design process according to [2], which is presented in Figure 1 and adapted. From there, the process is divided into two main branches, the initial and the iterative. The process starts with the upper branch, the initial, and proceeds in one direction without any loop until it meets the lower branch. The lower branch proceeds to the iterative steps of the methodology, which is proceeded in loops.

3.1.1 Initial branch

To start the design process, the **Requirements** must first be defined to meet and fulfil the customer's needs. This includes extending the requirements by using different focus areas, as explained earlier, to simplify and guide the design towards its solution.
The next step is to make assumptions (compare **First Assumptions** in Figure 1) based on the raw data available on requirements, for example how much thrust is needed for the required MTOM in the most critical flight state[1]. Furthermore, a brief engine selection can be analysed based on existing products to gain a better understanding for the intended dimension of the model. The latter, an

[1] According to [3], a thrust to weight ratio of 1.3 can be assumed

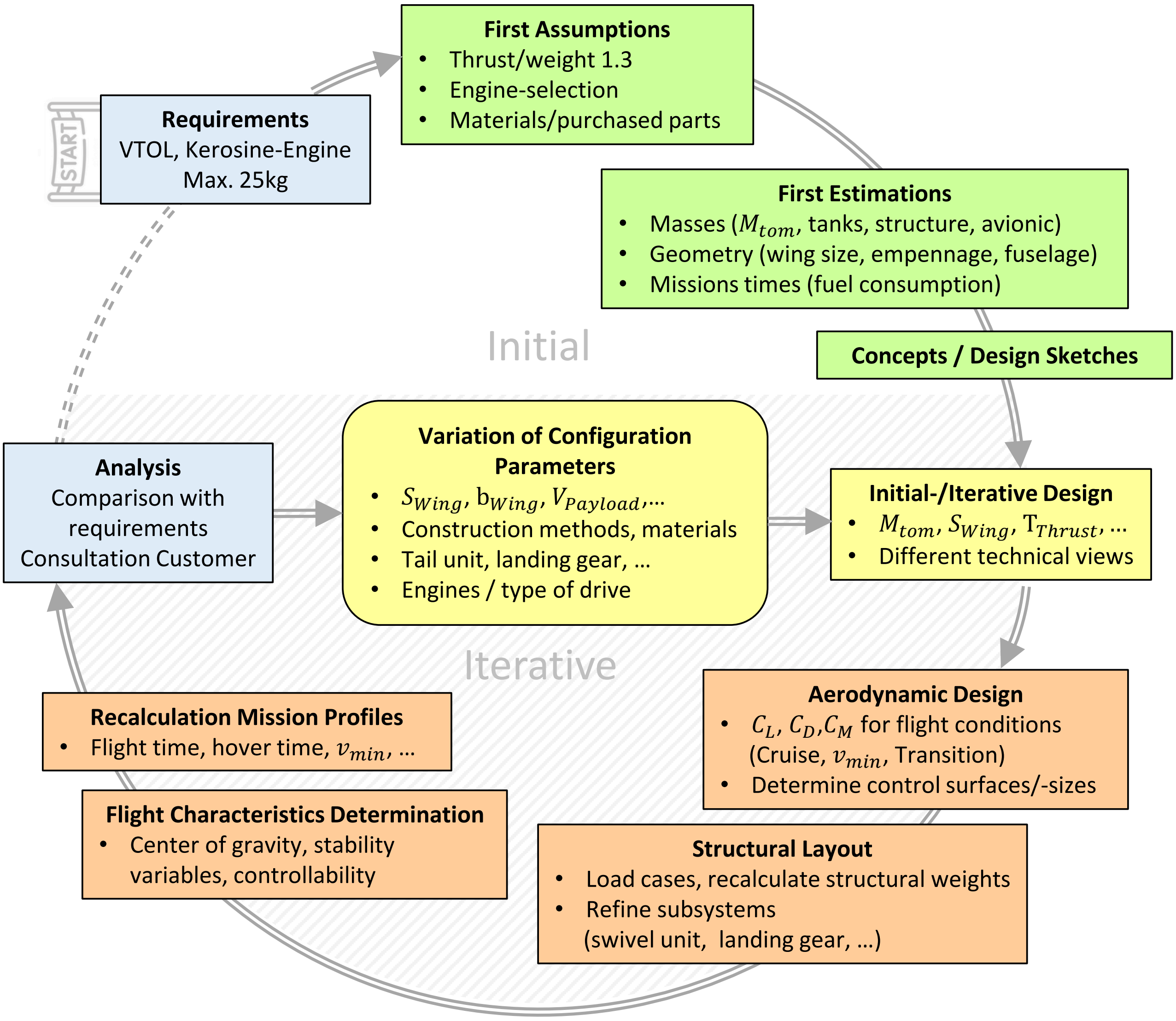


Figure 1 – Adapted design methodology following [2]

understanding and feel for the initial layout, also includes a consideration of the materials and other parts required for the aircraft.

This is followed by **First Estimations** for masses and geometry sizing. Masses can be broken down into basic components such as tanks, airframe structure, avionics and so on. For geometry, both wing and tail size could be estimated using either tabulated reference values and/or pre-estimation calculations. This is used to derive flight performance data such as mission times or cruise speeds. The overall aim of all this preliminary work is to get a better feel and impression of the dimensions of the aircraft and therefore the resulting shapes. This finializes in **Concepts** and **Design Sketches**, where complete concepts can be developed, even if they are at a early stage, usually drawn on paper. Simplified CAD models can also be considered at this stage, but are not necessarily required. A number of different concepts should emerge from this stage, with the aim that each concept works in its overall design. Depending on capacity and/or other constraints, a pre-selection may be made here to provide selected concepts for the initial phase.

3.1.2 Iterative branch

Coming from the initial branch to the lower part of Figure 1 (shown hatched in grey) with at least one concept, the **Initial-/Iterative Design** can be seen as the starting point for the iterative approach. It should provide basic values for MTOM, wing area, required thrust and many others. For the initial loop only a few values are acceptable at this stage. However, as the number of loop runs increases, the detail of the design should increase along with the number of key figures. Optionally, technical drawings would aid the design process and communication with the customer by making it easier to identify certain dimensional relationships. This bunch of data serves as input to the lower modules of the iterative branch (highlighted in orange in Figure 1). Further unknown values must be estimated or similarly determined for the first iteration. After several loop runs they should converge to a certain value.

Typical aerodynamic coefficients such as the lift coefficient c_L for the whole aircraft, but also for the individual wings and their respective tail sections or canards, are calculated within the **Aerodynamic Design** block. The drag coefficient c_D and its equivalents for the individual shell components are calculated as well as the coefficient of moment c_M. The nature of these parameters is such that they must be defined for different flight conditions to ensure that the aircraft remains stable or at least trimmable with appropriate control surfaces. The size of the control surface must also be calculated including margins such as the volume coefficient for longitudinal stability. If in some cases there are limits to some of the side values, for example maximum wing area, this leads directly to the iterative nature of the aircraft design process. If this is the case, other values must be adjusted to obtain a functional system. This may also involve changing the values of other modules such as mass.

	wing mass	
+	fuselage mass	
+	horizontal stabilizer mass	
+	vertical stabilizer mass	
+	nose landing gear mass	
+	main landing gear mass	
+	engine nacelle mass	
=	**structural mass**	
+	engine mass	
+	system mass	
=	**manufacturer mass empty**	(MME)
+	max. payload	
=	**max. zero fuel mass**	(MZFM)
+	max. fuel with max. payload	
=	**max. take-off mass**	(MTOM)
+	rolling fuel	
=	**max ramp mass**	(MRM)

Table 2 – Mass breakdown according to DIN9020 and [2]

The **Structural Layout** is essential to the mass composition of the aircraft and it often carries the risk, if not carefully and accurately followed, that the final aircraft will be heavier than expected, with a direct impact on performance. It is therefore rational to use a guide for the mass distribution. In this case the mass grouping of DIN 9020 has been used, as shown in Table 2.[2] Each component has its

[2]A mass breakdown for a manned aircraft includes an additional mass group, the Operating Mass Empty (OME), be-

own mass allocation and can be further subdivided into split sub-groups, for example if multiple main wings are used, or to show separate masses for control surfaces, hinges and/or servos.
Mass estimates can be made using reference parts, surface projections, simplified CAD models and/or, more accurately, strength-related designs together with selected load cases. Examples of load cases can be derived by analysing the mission profile, in this case for take-off, cruise with manoeuvring loads and landing. Some areas of the aircraft should be able to withstand pressure points from human handling during transport. With each iteration loop, critical systems can be refined to give a more accurate estimate of actual mass. Alternatively, subsystems could be built as a physical part or mock-up. It is also common practice to add weight margins, but this should be used carefully as it wastes potential aircraft performance.
Together with the masses and aerodynamics within the **Flight Characteristics Determination** module, the actual flight behaviour is analysed. To start with, the centre of gravity (CoG) is determined by knowing the individual masses and their respective positions on/at the aircraft. For more complex parts, such as the fuselage, the area centre of gravity of the projected surfaces is used. Once the location of the CoG is known, stability variables can be calculated. To define how much margins are left for for example an elevator deflection and under what conditions the aircraft can still be controlled. The result will probably affect the position of the wing along the longitudinal axis, the size of the stabilisers and their control surfaces (elevator, rudder or elevons etc.).

The last calculation module of the iterative branch considers the **Recalculation Mission Profiles** with the updated values from the previous modules. This includes the total flight time of the mission, the actual pure hover time and other mission related metrics. Flight performance factors such as v_{min}, v_{cruise}, v_{flaps} and so on are calculated at this stage to provide the necessary data for analysis.

As the **Analysis** and **Variation of Configuration Parameters** modules have a major impact on finding the most suitable aircraft design, they will be explained in more detail in the subsequent sections.

3.2 Loop of Requirements

The second-last module within the iterative branch handles the **Analysis** of the emerging design of the respective iteration loop. This step is important as it compares the required requirements with those actually fulfilled. It is useful to consult the customer after some iteration loops, so that any outstanding issues or disliked designs can be discussed before productive time is wasted.
Another part of the analysis is to check whether the requirements already stated are still up to date or need to be adjusted, in some cases more requirements may be needed. For example, the desire to carry a ground vehicle could lead to a requirement for a minimum payload bay volume or a minimum height for loading and unloading certain vehicles. As a result, the requirements are iterated, as is the entire design.

In addition to the above, it is worth following a few design philosophies to simplify and improve the actual aircraft design. The following are taken from [6] and were first applied at company Space X [7].

- Make the requirements less dumb

The intent of this statement is to challenge a requirement that requires a complex solution. A complex solution results in a special mechanical and/or structural mass gain and therefore reduces the performance of the aircraft.

- Delete the part or process

The purpose of this statement is to find redundant or unnecessary parts of the design, leading to the questioning of parts or even entire modules. For example, is a landing gear with tyres necessary for a VTOL capable aircraft?

tween the MME and MZFM, which includes the masses of the pilots and service crew including their luggage.

- Simplify or optimise the design

Although this statement is simple and usually well taught in any institution, the key lies in the combination of the first two statements. Is it necessary to simplify or optimise a part or component if it should not exist in the first place?

In conclusion, the analysis module is interestingly the key module in achieving a good design. It also provides the input for the following module and the design variations within it. However, at some point it has to be decided whether a particular design meets the requirements, either in part or in full. This is done to proceed with the detailed design, construction and flight testing.

3.3 Expanded Variation of Configuration Parameters

The **Variation of Configuration Parameters** module, hereafter VCP, from the iterative branch of Figure 1 can be extended to include further subtasks. The complete VCP module, including all subtasks, is shown in Figure 2, which will be explained in more detail below.

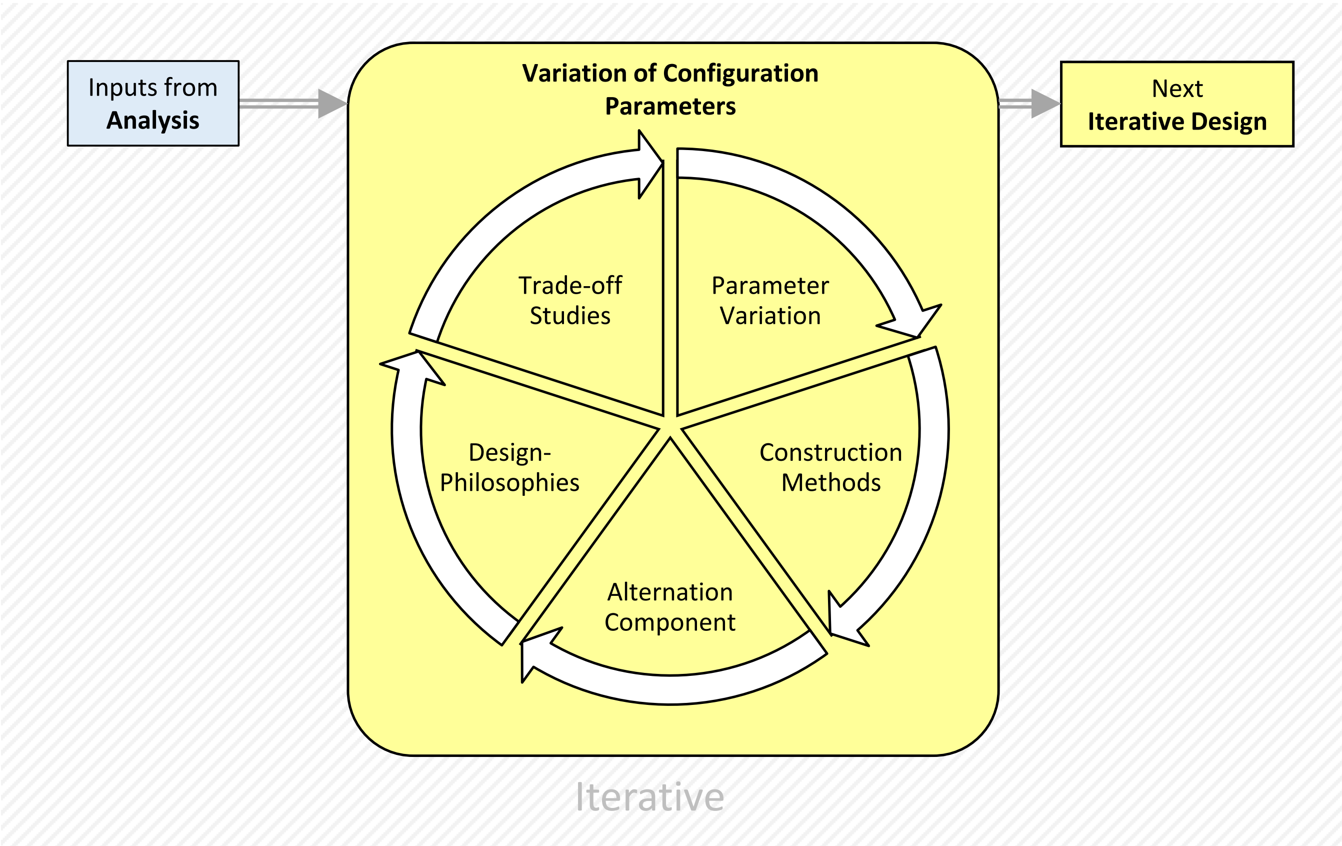


Figure 2 – Subtasks of the VCP module

Firstly, in **Parameter Variation** certain parameters or key values are changed in a defined range and the effect on the overall design is analysed. Examples are the wing area S_{Wing}, the wingspan b_{Wing}, the payload bay volume and many others. The results provide a broad discussion base for the customer to argue for a particular design size and/or decision.
Another point of attack is **Construction Methods**, which are mostly dependent on the available project budget and the existing machinery infrastructure. The latter focuses on the available manufacturing methods, for example the production of composite materials. Changing the construction method is likely to result in a different structural layout and material selection. Both will result in a change in mass and stiffness of the airframe, which affects the overall design.
Alternation Component means that parts or modules of the aircraft are changed, such as the type of tail. To be more specific, the tail unit could be changed from a classic T-empennage to a V-empennage. This could also be applied to other parts of the aircraft such as landing gear, engines, etc..

As discussed in the previous chapter, different **Design Philosophies** should be used and applied consistently. Particularly complex parts or mechanisms must be questioned as to whether the benefits justify their existence. Otherwise, the design should be kept as minimal as possible to meet the requirements.
Trade-off Studies can be used to show alternative options and their impact on the performance of the design[3]. For example, drastically scaling up or down the model. Or changing the entire propulsion system from combustion to electric. The purpose of this is more likely to be to find a possible better solution or to open up further application scenarios.

4. Concepts

From the set of design concepts, two main ones were selected to be presented in this article. In the following, the key features of each concept are explained, together with their respective advantages and disadvantages, as well as the reasons why the subcomponents were selected. These concepts are the input for the iterative design branch.

4.1 Concept: Folding Wing

This concept, shown in Figure 3, has its origins in the design of Bell-Boeing's V-22 Osprey, which is also a VTOL. The V-22 uses two large propeller rotors driven by turboprop engines and mounted on the wingtips. Each rotor is individually controllable, which means that the angle of attack of the blades can be changed in the same way as in helicopters. This control principle is essentially reversed for the Folding Wing concept. Each turbine is equipped with a thrust vectoring mechanism to allow the direction of the outlet flow to be changed. The thrust vectoring is only applied around the transverse axis (=spanwise direction), thus allowing the application of variable pitching moments. In addition, both turbines can be swivelled by a total of 120° to allow the transition from hover flight (position 90° upwards) to horizontal flight (position 0° forwards). This pivoting, together with the thrust vectoring, requires the CoG to be very close to the axis of the pivoting mechanism.

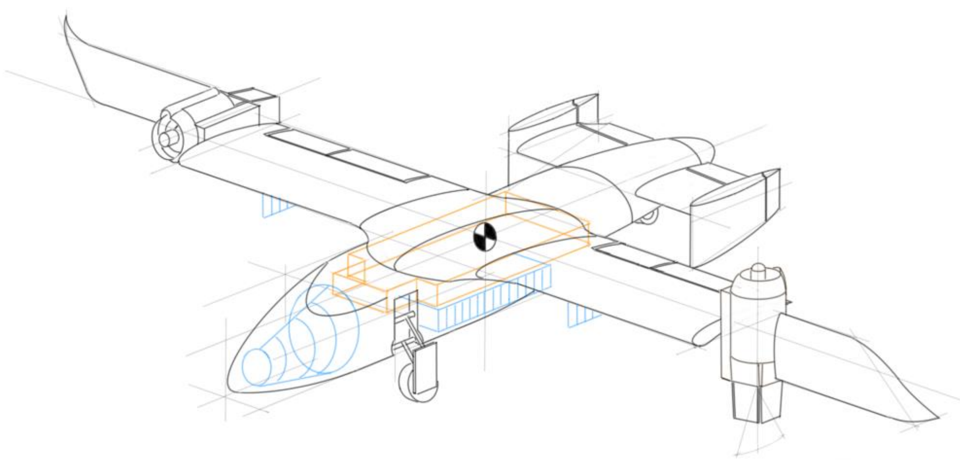


Figure 3 – Concept: Folding Wing

Another feature of the concept is the ability to fold in the wing, similar to the V-22, but here it could be considered to fold while airborne in hover mode due to the thrust vectoring.
As a result of the alignment of the wing and fuselage, the geometric volume is reduced to a minimum, allowing take-off and landing from small sites. This unique key feature could be used in disaster relief

[3]This is not to be confused with Parameter Variation, where major changes are not considered

operations or in small corridors where the landing area is too small for conventional UAVs.

The tailplane was designed as an H-empennage and is positioned lower than the wing due to the aforementioned folding capability. The two fins are also necessary to stabilise the aircraft in the event of an engine failure during horizontal flight.
The wing extensions are there to improve the aspect ratio of the whole wing and therefore its aerodynamic efficiency[4]. They reduce the structural load on the main wing box during hover and the resulting bending moment because the engines are closer located to the center. The extensions themselves will rotate with the turbines, so they will turn at the same rate as the turbines. This can be used for an aileron-like control surface, but has the disadvantage that the pitching moment c_M varies during the transition from hover to cruise flight.
The landing gear was chosen to be a main undercarriage with tailwheel arrangement, as this provides tilt-over stability during landing.
For transport and to allow testing of other components, the aircraft is divided into four modules for disassembly. Two interfaces on each side of the wing root and another interface between the fuselage and the tail (the three interfaces are shown in the Figure 3).

Regarding the fuel tanks, there are two tanks in the fuselage close to the CoG, highlighted in orange in the Figure 3. This position was chosen because the CoG must remain close to the hinge axis. Both tanks will have surge ribs to reduce moving masses during flight manoeuvres. In addition, if necessary, e.g. during a payload offset, fuel can be used for trimming by pumping into the respective tank.

For a given potential payload there are three positions available on the concept. All positions are highlighted in blue in the Figure 3. The main payload bay is located at the bottom of the fuselage. This box-like area will be about 40x40 cm long and wide and 5-6 cm high. A second allocation could be within the nose section, which is suitable for an optical sensor payload to provide a widely unrestricted field of view. Optionally, another nose section could then be considered. The final locations would be on pylon positions on the wing. If these are in use, the folding capability can not be used for this arrangement, but provide a fairly flexible space for payloads.

To summarise the folding wing concept, Table 3 lists the likely advantages and disadvantages.

Advantages	**Disadvantages**
+ aerodynamic efficiency	**-** c_M change during transition
+ modular / interchangeability	**-** ΔCoG small
+ cruise flight border stable	

Table 3 – Advantages and disadvantages of the Folding Wing concept

[4] the original idea was seen in the concept of Bell's 247 UAV

4.2 Concept: Orca

This concept is powered by three engines and looks similar to a classic tricopter configuration. The difference is that all three turbines can be swivelled[5], the two main turbines on the wingtips with a swivel angle of 120° and a smaller turbine that can only swivel 90°. The actual design concept of the Orca is shown in Figure 4.

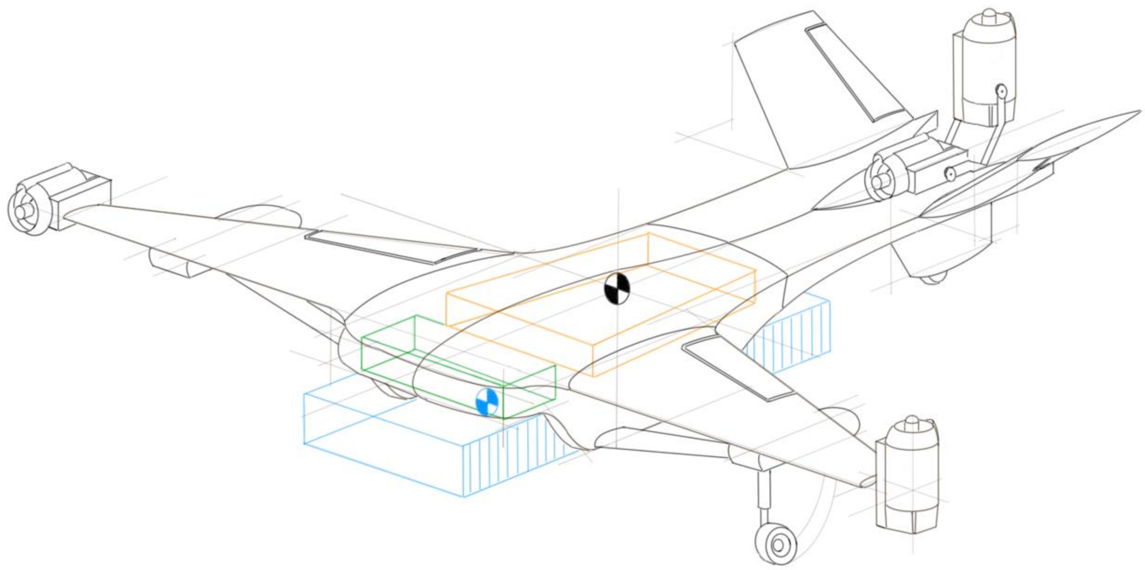


Figure 4 – Concept: Orca

The three-engine configuration allows large deviations from the CoG, as they can be easily compensated by the thrust setting of the rear turbine. This makes the concept easier to operate and could forgive an operator error such as incorrect payload positioning. The compensation is then handled by a robust flight controller setting. Another feature of this concept is the larger payload bay. It provides a space of approximately 40 x 80 cm in width and length and 10 cm in height. Optionally, even longer payloads can be integrated due to the open continuous bay concept.
Consequently, this payload arrangement provides suitable conditions for ground and airborne vehicle transport. In the case of the latter, either multi-copter drones or fixed-wing drones with deployable wings could be used.

The braced wing, integrated to reduce the wingbox bending moment, has a high aspect ratio with fairings for the main landing gear. The strut ends in the fuselage with the open payload bay behind it. This means that either the payload bay itself must have an additional horizontal strut connecting the two sides, or a C-shaped outrigger must be integrated into the payload bay.
The upper part of the fuselage is wing-shaped to produce more lift than a normal cigar-shaped fuselage. At the rear, the shape continues into the turbine inlet.
The tail section is divided into a V-tail with control surfaces and an additional fin which incorporates a tail wheel for landing.
The three-engine configuration provides greater safety in the event of an engine failure during cruise and allows as a result to fulfil its mission. If one of the wing-mounted engines fails, the other engine could also be shut down and a high-speed landing could be made using only the rear engine. On the other hand, if the rear engine fails, both main engines will provide the necessary thrust to land conventionally. Perhaps at an even slower speed, the main engines could be used in an angled position to provide the necessary lift.

[5] This engine configuration was originally taken from the Hunter Killer drone seen in the science fiction film Terminator 3

Even if this concept seems to have more advantages, the CoG position will definitely be behind the aerodynamic centre of the aircraft and therefore have a statically unstable flight behaviour that needs to be compensated by the flight controller. In addition, the third engine adds more system mass to the aircraft and requires its own amount of fuel. The resulting flight time will be less than with a two engine configuration. All advantages and disadvantages of the Orca concept are summarised in the Table 4.

Advantages	Disadvantages
+ ΔCoG big	- 3rd engine system mass
+ size of payload bay	- mass main landing gear
+ one engine-out handling	- cruise flight static unstable

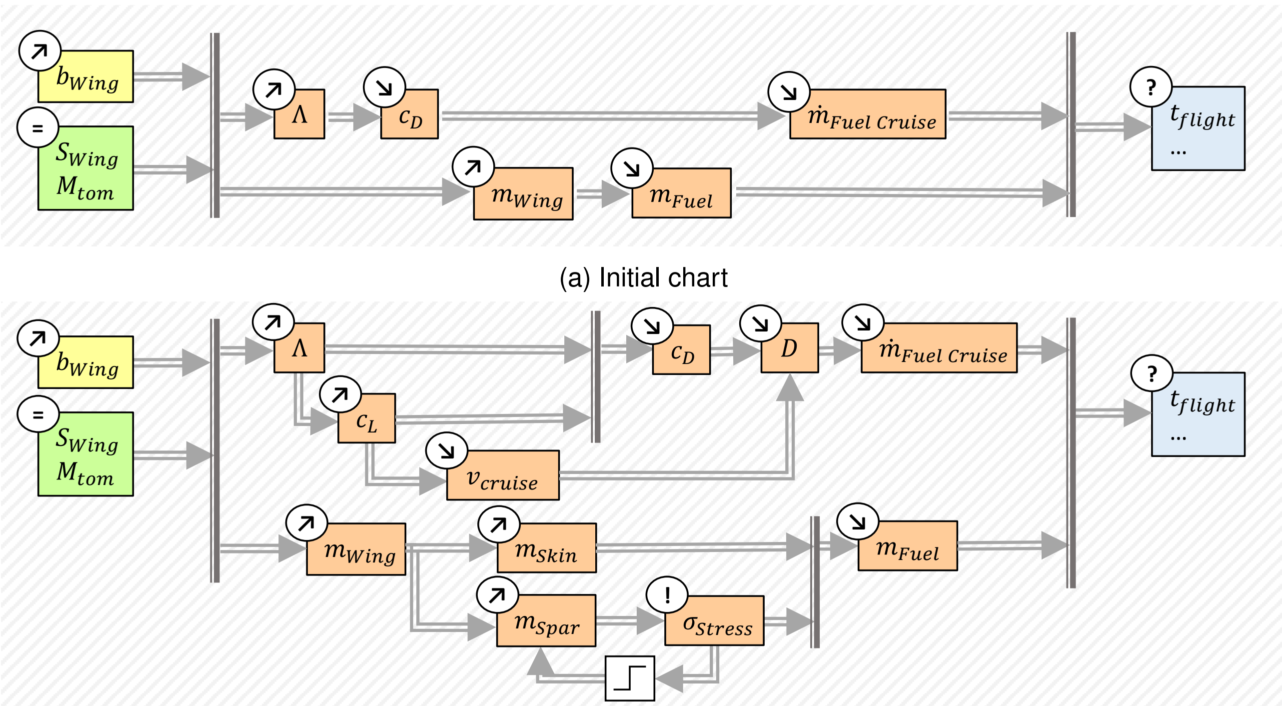
Table 4 – Advantages and disadvantages of the Orca concept

5. Insights from VCP Iterations

Selected VCP iterations and their effect on performance are described below. For better comparison, only the relative changes in performance are shown, without changing anything else in an iteration.
The following assumptions have been made:
The thrust ratio of the engines (1.3) was kept the same. Mass changes were compensated for by either adding or subtracting fuel to maintain the same MTOM.

5.1 Parameter Variation

For parameter variation, the wing span b is analysed in more detail. In order to visualise the actual flow within the iterated branch, a signal flow diagram, known from control theory, can be used in a similar way. Therefore Figure 5 shows two signal flow charts used in this analysis. As can be seen, the first flow chart (Figure 5a) contained only a few parameters. In particular, the wing mass was considered with a linear progression with increasing wing span.

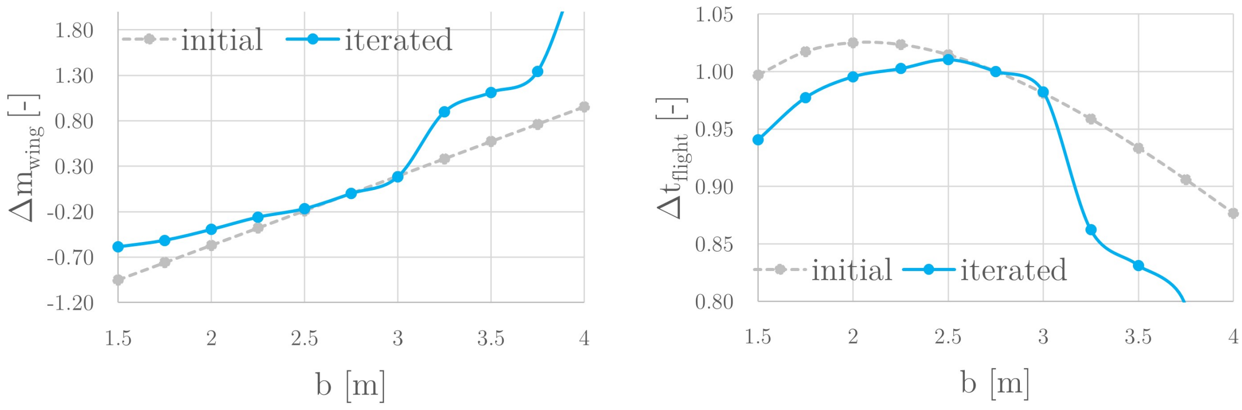


(a) Initial chart

(b) Iterated chart

Figure 5 – Signal flow charts for visualization of trade off parameters

Figure 6a shows the corresponding graph of the difference in wing mass. With further iterations, the mass prediction for the wing became more detailed, resulting in the consideration of the individual components of the wing. As a result, in Figure 5b, the mass is split within the lower branch of m_{Wing}. There, m_{Spar} also considers a stress analysis, in this case for bending moments, together with a discontinuous size change. The discontinuity is due to fixed sizes for the spar as it is a purchased part and only available in definite sizes. This creates steps in the mass prediction of the wing (see Figure 6a).



(a) Δ in wing mass

(b) Δ in flight time

Figure 6 – Trade off in wingspan sizing

The resulting delta in flight time is shown in Figure 6b. Depending on the iteration state, either a span of 2m for the initial state or 2.5m for the iterated state should be selected to achieve optimal flight times compared to the initial design state ($b_{initial}$=2.75m [6]).
Consequently, when a major design change is made to a concept, all parameter variations should be re-run to ensure optimum flight performance. In addition, changes from each iteration should be noted and compared. This can be used to avoid mistakes, gain data of development states and build experience in dealing with design effects.

(Base data for the analysis shown is the Folding Wing concept with the following parameters: NACA6412, c_l=1.2, b=2.75m, t_{chord}=0.3m, S_{Wing}=0.825m^2, $\dot{m}_{fuel}$=234.6ml/min, m_{Wing}=761g/m, m_{fuel}=9l, $m_{fuel,cruise}$=6.57l)

5.2 Alternate Components

5.2.1 Landing Gear vs. Wingalike Skids

A fixed landing gear is typical for VTOL capable UAVs, as they normally never need a runway. The shape of this fixed gear is similar to a wing to reduce drag. To maintain the same ground clearance, the length of the skids is the same as for the landing gear. Table 5 lists the relevant data, which results in the Folding Wing concept, skids being preferred. The Orca concept should stay with the undercarriage if using same position for the landing gear as in the initial concept stated. However, if the skid is positioned at the fuselage, a minor benefit is achieved[7]. Even if these changes are small, they can add up to a larger improvement when combined with other changes.
Further analysis of the Orca with skids at the fuselage need to consider whether the ground clearance of the engines together with the engine behaviour (=>deadtimes) will ensure safe operation in case of a gust. Alternatively, if repositioning is not possible, simple retractable swing arms could be considered instead of wheels to further reduce mass.
(Base data for the analysis shown are following parameters: skid airfoil NACA0010 [8], c_{D0}=0.016, $c_{skid,chord}$=100mm, v_{cruise}=70km/h)

[6] The actual span of the wing is shown here, together with the engines and nacelles, the nominal span is 3m.
[7] This includes a 50g surcharge to reinforce fuselage structure

Feature	Unit	Folding Wing	Orca	
$pos_{LandingGear}$		fuselage	wing pylons	fuselage
$\Delta\ m_{LandingGear}$	g	-58	43	-51
$\Delta\ m_{Fuel}$	ml	69	-51	61
$\Delta\ \dot{m}_{Fuel}$	ml/min	0.25	0.97	0.97
$\Delta\ t_{flight}$	%	+0.94	-1.03	+0.52

Table 5 – Key figures comparison of landing gear vs. skids trade

5.2.2 Switch Systemconcepts

An optional approach is to cluster the systems of a concept, thus obtaining a bundle of system solutions that can be switched between concepts.
For this analysis, the thrust vectoring mechanism (TVM) of the Folding Wing concept was replaced by an additional engine at the rear of the aircraft. This rear engine was considered to be driven by an electric ducted fan (EDF) of various sizes. The internal layout is similar to a no tail rotor (NOTAR) system known from helicopters [9].

Feature	Unit	Cases		
EDF type		Ø50	Ø50	Ø70
$x_{leveram}$	m	0.6	0.8	0.6
mission related				
$\Delta\ m_{TVM/NOTAR}$	g	-95	-45	85
$\Delta\ m_{Fuel}$	ml	113	53.6	-101
$\Delta\ t_{flight}$	%	+1.72	+0.82	-1.54
operational related				
max ΔCoG	mm	18	24	42
$\Delta\%l_{MAC}$	%	6	8	14
max $\Delta x_{payload}$ for m_{tom}	mm	102	136	238
max $\Delta x_{payload}$ for m_{fuel}=0	mm	60	80	140
ΔCoG	%	-49	-32	+19

Table 6 – Key figures comparison of NOTAR trade

The results in Table 6 need to be analysed in more detail. In terms of flight times, both cases from the left with a 50mm EDF give an increase in flight time. For the second case, a higher leveram was considered, which extends the tail of the fuselage, but still results in an improvement. On the other hand, the possible Δ in CoG compared to TVM was reduced by almost half. Therefore, a third analysis with a 70mm EDF increases the possible Δ in the CoG but also reduces the flight time.
In any case, whether TVM or EDF is used, the spread with respect to the mean aerodynamic chord $\Delta\%l_{MAC}$ is only between 5 and 14%[8]. According to data from [10] this value for manned aircraft is in the range of 20%.
However, the driver for this value is determined by the mission scenario. If, for example, a ground vehicle has to load, unload and reload itself automatically, there will definitely be a shift in position for each load. Hence, the maximum allowable payload position shift (see max $\Delta x_{payload}$ in Table 6)

[8]Note that this is not the relative position to l_{MAC}. It is the range from max forward to max backward CoG relative to the size of l_{MAC} in %

has been analysed. Depending on the fuel state, the position can vary up to 60mm at the end of a mission for the first case. This is considered acceptable.
(Base data for the analysis shown are following parameters: EDF data taken from [11], thrust margin EDF=20%, l_{MAC}=300mm, TVM max thrust angle=10°, TVM leveram to vertical CoG=100mm)

5.2.3 Merged Concept

The aim of the concept Merged is to combine the advantageous system solutions of each concept to achieve a more efficient design compared to the first two concepts. To achieve this, five major changes are considered. Starting point is the Folding Wing concept. In the first, a braced wing is chosen, together with a change in the engine position at the joint of the brace. Secondly, the TVM is replaced by the NOTAR system described earlier (see Table 6). Next, the landing gear is replaced by skids and the V-tail is taken from the Orca concept. Finally, the height of the payload bay is increased to meet new customer requirements which will be discussed at the end of this paper.

Feature	**Unit**	**Iterations**				
change		braced wing	NOTAR	skids	V-tail	Bayheight
relative to previous iteration						
$\Delta\, m_{Fuel}$	ml	77.5	53.6	69	~0	-396
$\Delta\, \dot{m}_{Fuel}$	ml/min	0.02	0	0.25	~0	~0
$\Delta\, t_{flight}$	%	+1.17	+0.81	+0.4	+0.0003	-5.85
relative to initial						
$\Delta\, t_{flight}$	%	+1.17	+1.99	+2.4	+2.4	-3.59

Table 7 – Key figures comparison of merged concept

The resulting metrics in Table 7 show a continuous improvement. However, the last change reduces the overall efficiency. Compared to the initial state, this results in a decrease in flight time of -3.59%, which translates into 29 minutes of flight time. The concept Merged is shown in Figure 7 and highlights the possible payload bay in lightblue[9]. Depending on the shape of the bay, the total drag of the aircraft changes resulting in different flight times.

From here, further iterations, such as parameter sizing, can be considered to improve the design. If the requirements are still not met, disruptive changes should be investigated further.

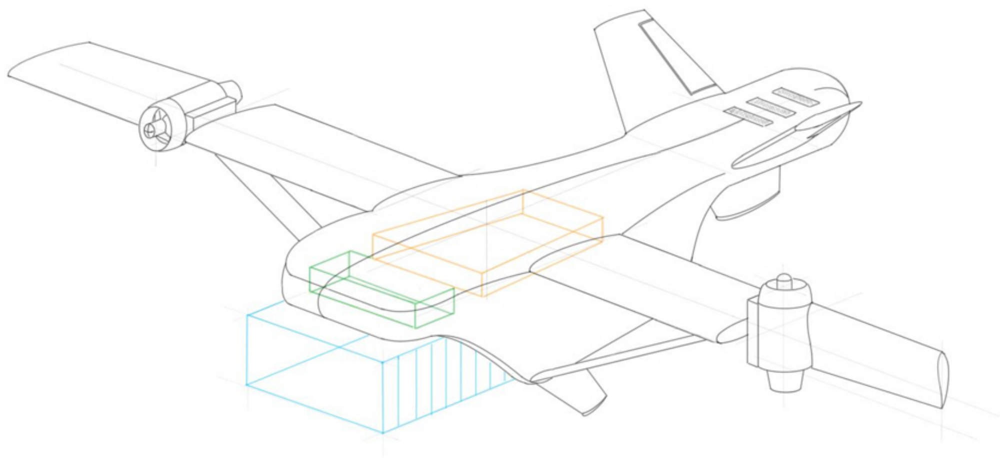


Figure 7 – Concept: Merged

[9] Aestic may not be as elegant as previous concepts, but it shows that form follows function

6. Conclusion

The paper concludes with a brief summary of the methodology presented. The aircraft design process is iterative in every detail. This means that in addition to the design concepts and their respective figures, the calculation methods are likewise changed iteratively. This leads to a consistent improvement of the design details.
After the initial sizing and formation of the first concepts, various iteration loops are performed on these concepts. There are two key points to consider. Firstly, the analysis should prioritise customer consultation and requirements fulfilment. Secondly, the VCP cycle provides several guidelines to obtain variations of the concepts and consequently improve their design.
Finally, the concepts analysed in this paper and their initial and iterated design figures are presented in the following.

Feature	Unit	Folding Wing		Orca		Merged*
state		initial	iterated	initial	iterated	iterated
m_{tom}	kg	20	20	22.5	22.5	20
$m_{structure}$	kg	4.27	4.117	4.74	4.73	4.11
V_{fuel}	l	9.1	9.48	10.1	10.2	9.3
t_{flight}	min	30	31.1	26	26.4	30.72
$t_{onlyhovering}$	min	12.5	12.9	11.5	11.53	12.7
v_{min}	km/h	55	57	60	61	54
v_{cruise}	km/h	70	72.6	70	70.8	67
$b_{wingspan}$	m	3	2.5	3	2.75	2.8
$l_{fuselage}$	m	1.5	1.5	1.3	1.3	1.3

Table 8 – Key figure comparison of the individual concepts

As can be seen from Table 8, the Folding Wing concept achieves the target flight time of 30 minutes for a regular mission and seems to be the more efficient choice at any design stage.
However, after consultation with the customer, the Orca concept was preferred due to the large payload bay, which allows larger ground vehicles to be transported. As a result, the payload bay requirements are adapted to accommodate a larger volume, twice the height of the initial.
The concept Merged* in Table 8 is specified in its iteration before the payload bay adaptation and is thus marked with *. Yet, as stated in the previous chapter, the integration of a larger payload bay will significantly reduce the flight time. Consequently, all concepts will have to be adapted to meet the new requirements.

6.1 Outlook

As part of the ongoing design process, a next step will be to build testparts for smaller structural sections of the aircraft. This has two objectives. The first is to gain more accurate weight estimates within the design process, and the second is to establish the infrastructure for the actual build and gain experience with the considered materials.
In parallel, the engines are being tested and thrust vs. throttle maps are being produced to provide data for simulating engine behaviour in preparation for flight control.
Finally, the aim is to build an Ironbird test bed to begin testing key functions during take-off, hover and landing, and to develop a robust flight control system for initial hover flight.
During and after each of these key steps which will provide more detailed data of a system component, the design is iteratively improved as outlined in the Design Methodology section. Once the concept data converge, the detailed design of the VTOL can begin.

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7. Copyright Statement

References

[1] Anforderungsliste/Lastenheft, netzkonstrukteur.de, Accessed on 22.08.2023, https://netzkonstrukteur.de/konstruktionsmethodik/anforderungsliste/

[2] Strohmeyer A. *Flugzeugentwurf I*. Rev 1.03, University of Stuttgart, 2020, in German

[3] Hafer X., Sachs G. *Senkrechtstarttechnik*. 1st edition, Springer, 1982, in German

[4] Gundlach J. *Designing Unmanned Aircraft Systems*. 2nd edition, American Institute of Aeronautics and Astronautics, 2014

[5] Raymer D. *Aircraft Design: A Conceptual Approach*. 5th edition, American Institute of Aeronautics and Astronautics, 2012

[6] Musk's 5 Step Design Process, modelthinkers.com, accessed on 07.12.2023, https://modelthinkers.com/mental-model/musks-5-step-design-process

[7] SpaceX, accessed on 20.05.2024, https://www.spacex.com/

[8] NACA 0010 (naca0010-il), airfoiltools.com, accessed on 23.05.2024, http://airfoiltools.com/airfoil/details?airfoil=naca0010-il

[9] Pegado, Helio & Heer, Diego. (2019). NOTAR TECHNOLOGY: A SIMPLIFIED MATHEMATICAL MODEL. 10.29327/2cab2019.224850.

[10] Strohmeyer A. *Flugzeugentwurf II*. Rev 1.01, University of Stuttgart, 2020, in German

[11] D50 -90mm Impeller, pichler.de, accessed on 22.05.2024, https://pichler.de/O-50-90mm-Impeller