Enabling Technologies for
Personal Aerial Transportation Systems

Deliverable D6.5
Final list of desirable features/ options for the PAV and supporting systems

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Dissemination level[1]		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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Revision Table

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1.0 (D6.1)	21.12.2011	all	Gursky, Nieuwenhuizen, Perfect	
2.0 (D6.5)	09.01.2015	all sections revised and amended	Schuchardt	Initial list of features serves as baseline for the final list.

Executive Summary

This deliverable gives an overview on the features and options a future PAV should exhibit and gives some insight into what a functional personal aerial transportation system could look like. Beginning with a short explanation of the intended use scenarios and the capabilities of the target users, requirements regarding the level of automation of the vehicle are derived. The need for “easy” handling characteristics is addressed in the following section and available response types for the vehicle dynamics to fulfil these needs are presented. The following two sections deal with the interaction of a PAV user with the vehicle itself. Conventional flight controls and new control concepts imaginable for PAVs are compared and human-machine interfaces like haptic feedback, displays, or brain-computer interfaces are discussed. The next section briefly discussed the issues a PAV navigation system has to cope with before the final list is concluded. Where appropriate the reader is referred to the deliverables and publications completed throughout the myCopter project for further reading.

Abbreviations

AAcCVH	Attitude/Acceleration Command Velocity Hold
ACAH	Attitude Command Attitude Hold
AcCVH	Acceleration Command Velocity Hold
ACHH	Attitude Command Hover Hold
ACT/FHS	Active Control Technology / Flying Helicopter Simulator
ARCAL	Attitude/Rate Command Attitude Levelling
BCI	Brain-Computer Interface
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DoF	Degree of Freedom
EEG	Electro-Encephalography
EPFL	École Polytechnique Fédérale de Lausanne
ETHZ	Eidgenösische Technische Hochschule Zürich
GTC	Ground Turn Coordination
HH	Height Hold
HITS	Highway-in-the-Sky
HMI	Human-Machine Interface
HQR	Handling Qualities Rating
IMC	Instrument Flight Conditions
KIT	Karlsruher Institut für Technologie
MAV	Micro Aerial Vehicle
MPI	Max-Planck-Institut für biologische Kybernetik
MTE	Mission Task Element
PAV	Personal Aerial Vehicle
PATS	Personal Aerial Transportation System
PH	Position Hold
PPL-H	Private Pilot Licence for Helicopters
RCAH	Rate Command Attitude Hold
RCDH	Rate Command Direction Hold
RCHH	Rate Command Height Hold
RCVH	Rate Command Velocity Hold
TC	Turn Coordination
TRC	Translational Rate Command
UAV	Unmanned Aerial Vehicle
UoL	University of Liverpool
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VTOL	Vertical Take-Off and Landing
WP	Work Package

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1 Objective

The objective of this deliverable is to revise the initial list of features that has been presented in deliverable D6.1 "List of desirable features/options for the PAV and supporting systems" [55]. The final list contains design features and options for a Personal Aerial Vehicle (PAV) itself and to a certain extent for the Personal Aerial Transportation System (PATS) in general. Among the topics that are addressed are handling characteristics, response types, flight controls, human-machine interfaces and proposals for navigation systems.

2 Progress and Finalisation

The content of the initial list of features was based on agreements and decisions that had been made on consortium meetings and discussions throughout the first twelve months of the project's runtime. The results from investigations and developments as well as insights and experience gained during the rest of the project are used to complete the final list. Where appropriate the reader is referred to the more detailed deliverables and publications that have been completed throughout the myCopter project.

3 Intended Use of PAVs

The PAV the myCopter project envisions is a commuter vehicle that allows the user to travel from home to work and back again without using conventional ground based modes of travel and especially without time consuming changes between different modes of travel. For example a commuting system that would require the pilot to drive to an airport in his car, take a PAV from there to the next airport and then wait for the bus to take him to his office building is regarded as not desirable as the advantages over existing transportation systems would be minimal. Therefore the envisioned PAV system is foreseen to provide a point-to-point connection between any working place and any living area.

Both starting and landing point can be situated in a sparsely or densely populated area. The living area and the starting point for the commuter could be a rural area with plenty of free space around every building or an urban district in the city centre with skyscrapers and limited space for landing or parking. The same differentiation is true for the destination as the office building may be situated in an office park in the sparsely populated outskirts or in the central business district of a major city. In total there are four different combinations of starting and landing points: from a sparsely populated area to a similarly sparsely populated location, from sparse to dense, dense to sparse, or dense to dense.

This initial view on the intended use of PAVs has been kept throughout the project. It is further elaborated in D7.1 "Screening report of socio-technological environment" [60]. The following deliverable D7.2 "Design criteria report" [61] looks deeper into the dependencies between the existing infrastructure in cities and the possible impact of a PATS. It is assumed that substituting 10% of the recent car traffic would result in a measurable impact on the traffic congestion situation. In a typical city with 300.000 daily commuters this would result in 2.500 to 10.000 PAV approaches per hour at 40 to 160 independent landing sites. These thoughts will be brought to conclusion in D7.4 "Final report on scenarios for implementing a PATS" due by the end of the project.

4 PAV Users

The concept of a personal aerial transportation system implies that the system will be open to be used by the general public. Not only well trained pilots but an “averagely skilled” person with only a minimum knowledge of aviation shall have the opportunity to use a PAV for his personal transportation.

Opening the regimes of vertical flight to the general public leads to new requirements regarding the training and qualification of pilots. Users with only a minimal training shall be able to fly their PAVs safely from point to point. Looking at today’s licensing requirements for private helicopter pilots (PPL-H) in comparison to obtaining a licence for the main commuter vehicle, the car, reveals huge differences in the training curricula. For example only 9 hours of obligatory practical training (12 units of 45 minutes) are required for obtaining a German driving licence (class B) [1]. The compulsory training includes driving on all types of streets or highways and driving by night. The average training time novice drivers take to attain proficiency his higher, e.g. in the United Kingdom this is 45 hours. The applicant must then go through a theoretical and practical examination before obtaining the driving license.

In contrast to that, a private helicopter pilot needs to go through a significantly longer training. The minimal flight experience for obtaining the PPL-H is 45 hours according to JAR-FCL 2 [2] but the average training time is around 60 hours for a R22 helicopter with annual requirements for keeping the license. Additional type rating is mandatory for all variations of helicopters the pilot intends to fly. Type rating for a single engine, single pilot helicopter requires a minimum of 70 flight hours and a proficiency check is mandatory after two years of not flying a certain type to renew the rating. The basic licence allows the pilot to fly under visual flight rules (VFR) but for flights by night additional licensing is necessary. The applicant for a night qualification shall have at least 100 hours of flight experience after obtaining his basic licence. If a private pilot wants to fly under instrument flight rules (IFR), he must apply for an instrument rating. Holding a night rating and a minimum experience of 50 hours cross-country flying is mandatory for a PPL-H holder for obtaining the instrument rating.

Table 4.1 summarises the training requirements for helicopters and cars in the UK. In order to shorten the required training time for flying a PAV, the handling of the commuter vehicle must be clearly less complicated and more intuitive than the control of today’s aircraft. Several technologies, such as autopilot functionalities, improved handling through advanced control laws, navigation aids and novel human-machine interfaces have been investigated in the project with the goal to reduce the required training time and make flying easier. Further detail into the training syllabus of future PAV users is given in the deliverable D2.4 “Guidelines for improved training effectiveness through use of new control and information systems”.

Table 4.1: Comparison between helicopter and automobile training in the UK [4]

	Helicopter	Car
Translational Axes	Surge, Sway, Heave	Surge
Rotational Axes	Pitch, Roll, Yaw	Yaw
Controls	4 (Lateral Cyclic, Longitudinal Cyclic, Collective, Pedals)	3 (Accelerator, Brake, Wheel)
Experience and Testing (legal requirement) in UK	40 hour flight time, seven written exams, minimum 10 hours solo flight, two hour practical exam (Ref.6)	One practical hour exam, One written exam
Approx. hours to obtain license in UK	60-90 hours (mixture of tuition and practice)	20-50 hours (mixture of tuition and practice)
Approx. cost in UK	20,000-30,000 GBP	500-1500 GBP

Another aspect to consider is the level of autonomy a PAV should incorporate. Above considerations only apply if the PAV is to be flown in manual mode. A second mode of operation has been discussed in the past years: the fully autonomous PAV. This is further discussed in section 6.

5 Initial Design Features

The reference PAV that had been agreed on in the first stage of the project was widely used as common basis for discussions and developments throughout the later project phases. Although the overall goal of the myCopter project was not the design or construction of a certain vehicle some basic design criteria were necessary. The idea was to focus on one practical and coherent concept for a commuter air vehicle to facilitate communication and discussion between the project partners along a common guideline. The chosen concept served as a reference basis for the development of further technical requirements within the different work packages (WP).

Current statistics about European traffic and transport trends show that average occupancy rates for cars are low (for example 1.6 occupants per vehicle in the UK, 1.5 in other Western European countries and slightly higher numbers for Eastern European countries [3, 5]). For commuting and business trips the average occupancy rate even goes down to 1.1 to 1.2 passengers per vehicle [6, 7]. To cope with this demand for individual transportation, the reference PAV concept for the project was chosen to be a 1+1 seater. The pilot on the first seat has the option to use a second seat for an accompanying passenger or for extra luggage. The maximum take-off weight of the vehicle should lie below 450 kg in order to remain within the limits of JAR-1 for microlight aircraft with up to two seats [8].

Initially, the consortium found an average cruising speed of 150 to 200 km/h suitable for a PAV in order to be clearly superior to other earth bound commuting vehicles. After further discussion it was proposed that a wider range of 100 to 200 km/h is preferable in order not to limit the conceptual process too early. A lower cruising speed facilitates for example the initial integration of navigation systems whose sensoring capabilities depend on the flight velocity. Taking into account the advantage of point-to-point connections and the fact that a PAV user does not need to stop at traffic lights or gets stuck in traffic jams, travelling in a PAV would still be faster than current urban commuting.

The maximum range of the reference PAV was designated to be around 100 km to cover typical commuting distances. As the PAV is not supposed to interfere with the controlled air traffic as it exists today, cruising flight would typically take place in heights of 500 m above ground.

In order to cope with the requirements coming from the necessity of landing in densely populated areas, it was agreed that vertical take-off and landing (VTOL) capabilities are essential for the successful implementation of a PATS. With the ability of vertical movement the need for manoeuvrability on ground is limited. Certainly short distances, e.g. a few meters into a garage, have to be covered on ground but the vehicle shall not be a “roadable aircraft” and its primary environment for transportation remains the airway.

The PATS shall become a reliable transportation system and not a recreational activity that would be practised only in VMC (Visual Meteorological Conditions). Therefore the consortium believes that the vehicle should be available for the daily commute at least for 90 % of all days per year. This leads to the necessity of flying in darkness or in weather conditions with very low visibility. A weather analysis that has been conducted for a typical region in Germany shows that this is an ambitious goal, see deliverable D7.1 [60].

The amount of desirable automation depends on the intended mission, the pilot, his background, but as well on safety issues. As PAVs are expected to be piloted by untrained persons or to require only minimal training, the option for fully automated flight seems necessary. Full automation would especially include automatic take-off and landing and automatic collision avoidance. These thoughts are further elaborated in the following section. The initial PAV requirements are stated in Table 5.1 and further elaborated in D7.1 [60] and D7.2 [61].

Table 5.1: Initial PAV requirements

Number of seats	1 + 1
Maximum take of weight	450 kg
Cruising speed	100 – 200 km/h
Average cruising height	500 m above ground level
Range	100 km
Manoeuvrability	VTOL
Usability	90 % per year
Automation	Including “full” automation

Although the myCopter project was not aiming at designing a PAV in detail, a short preliminary design study was conducted in order to estimate the energy consumption a reference vehicle would have [9]. For completeness, these calculations are also added to the Appendix. Assuming a commuting scenario over 30 km distance at 175 km/h (= 48.61 m/s) and vertical climb and descent at 5 m/s up to an average cruising height of 500 m above sea level lead to an energy consumption of 12.81 kWh for the PAV. The parameters for reference vehicle and reference flight and the resulting power requirements are summarised in the following tables.

Table 5.2: Reference design parameter

Maximum take of weight	450 kg
Number of main rotors	4
Rotor radius	0.86 m
Rotor disk area	9.29 m^2
Number of blades	3
Blade chord	0.11 m
Rotor tip velocity	200 m/s
Solidity	0.12
Profile drag coefficient	0.009
Equivalent drag area	0.42 m^2
Wake contraction due to ducting	0.95

Table 5.3: Reference Flight

Distance	30 km
Cruising altitude	500 m
Cruising velocity	48.61 m/s
Climb rate	5 m/s
Descent rate	-5 m/s

Table 5.4: Power Requirements and Energy Consumption

Hovering power	57.12 kW
Cruising power	55.60 kW
Climb power	66.54 kW
Descent power	51.35 kW
Energy consumption	12.81 kWh

Through research and industry electric propulsion systems achieve continuous improvement. Modern electric engines have high specific powers of 3.5 kW/kg. The best energy supply is currently the lithium ion battery. Specific energies of about 150 Wh/kg are achieved. Figure 5.1 shows the energy densities of existing batteries. Thus, the required battery for the reference PAV would have a minimum weight of 85 kg without any safety margin for the delivery of the necessary 12.81 kWh. Its small energy density is the limiting factor. Nevertheless, electric powered flying for short distance and time is possible today. Further system improvements are expected from research and industry that will make practical flying become more realistic.

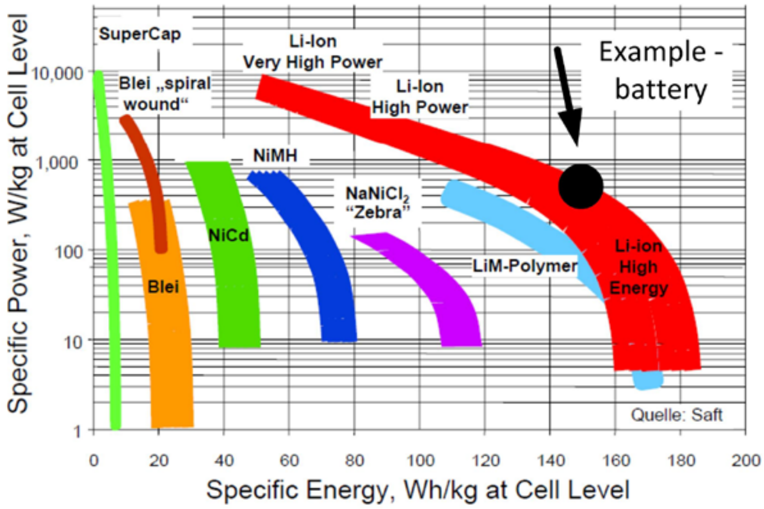

Figure 5.1: Energy densities of existing batteries with example battery selected for PAV usage [10]

Another aspect to consider in developing a PATS is the emitted noise. Existing VTOL aircraft like helicopters or tilt-rotor aircraft exhibit a level of noise pollution that does not allow them to start from housing areas in high frequency as the noise impact would be inacceptable for the residents. Restricting take-off and landing zones to less densely populated areas like remote airfields decreases the noise impact to inhabited areas but contradicts the idea of offering point-to-point travel. To make a PATS to be accepted by the public it is essential to reduce the emitted noise of each PAV to a minimum.

The question remains open how large numbers of parking PAVs are dealt with in densely populated inner cities. One could think of parking systems especially designed for PAVs with stow-away possibilities on roof tops. The problem could be dealt with more easily when assuming fully automated PAVs. The vehicle could then drop off its passenger at any desired landing spot and then manoeuvre itself to a parking site in a less densely populated area. The passenger could later call its PAV by some wireless device and let it pick him up at any other place fully automatically. A first step towards the self-flying PATS could be a taxi-like system with trained pilots flying the PAVs and bringing one passenger at a time from point to point. These and other ideas have been lively discussed in group interviews and are summarised in D7.3 [62].

6 Automation and Autonomy

The assigned level of automation is of paramount importance for the further development of PAV concepts. The question is whether the user of a PAV is understood to be a pilot or a passenger in a fully automated or even autonomously acting vehicle. If the user is actually piloting the vehicle, the handling characteristics must be appropriate for a minimally-trained pilot. The vehicle would need to provide a certain level of pilot assistance to support the pilot during his mission and the human-machine interfaces and the flight controls would need to be tailored towards the capabilities of the user.

On the other hand, the concept changes when full automation is assumed. The user would then use a PAV like lifts are used nowadays. You enter the cabin of a lift, press a button, the doors close and don't open again before you have reached the floor of destination. Travelling in a PAV would not differ much from a lift scenario. The user would enter his PAV, choose a destination and could then relax while the vehicle fully autonomously finds its way through the airspace. In this case pilot controls would not be necessary at all and cockpit displays would have an informational character but would not be needed for navigation. The main responsibility would then lie in designing fail-safe navigation systems and to provide automatic collision avoidance. This option might not be realistic for today's aviation environment due to safety issues but it might become possible in the future as efforts are already undertaken to integrate Unmanned Aerial Vehicles (UAV) into civil air traffic.

For the myCopter project none of the scenarios above were excluded but both were seen as possible directions a future PAV concept could go. During the first progress meeting a two-phase scenario proposal was elaborated. The first phase would address the early adopters and would provide limited automation and technology that is available in the near future. For example existing commercial UAVs already provide attitude stabilization, altitude control / vertical speed control, lateral speed / turnrate control (including position hold), and GPS-based navigation (up to a precision of ± 5m) although it is not yet fail-safe. During the first phase the changes in infrastructure would be minimal what makes landing on unprepared sites such as car parking lots necessary. In a partially automated PAV the user would fly the vehicle manually but receive assistance in certain flight scenarios, such as landing place selection or collision avoidance. The focus of the first phase is to provide appropriate handling characteristics, pilot assistance functions and HMIs to further support the pilot.

The second phase is a long-term scenario aiming at fully autonomous PAVs with supporting infrastructure especially designed towards the needs of a personal aerial transportation system. One could imagine parking sites for PAVs on roof tops or a PAV sharing scheme where electrically driven vehicles could automatically get recharged and redistributed to other locations. Technologies that need to be developed for the fully automated flight include automatic landing and take-off, mid-air collision avoidance in dense traffic, flocking or formation flying, and failure handling of the complete automated system.

In the group interviews conducted for WP7 the autonomous flight was identified as good option for routine flying such as the daily commute under high traffic density. Nevertheless, the manual option was still favourable in regard of leisure activities or sports in areas with lower traffic density as reported in deliverable D7.3 “User perspectives and expectations” [62].

7 Investigation of Handling Characteristics

It is anticipated that a PAV should exhibit at least good Level 1 handling qualities in order for its minimally-trained operator to be able to achieve a satisfactory level of performance during manual flight phases. During a piloted simulation [11], a range of vehicle configurations with handling characteristics in the Level 1 region were assessed. The trial showed that conferring a vehicle with handling qualities well within existing Level 1 boundaries allowed a reduction in the piloting effort associated with completing tasks. This is shown in Figure 7.1, where cyclic activity during a hover task for a ‘good Level 1’ PAV model is compared with that for a Bell 412 equipped with an Attitude Command, Attitude Hold (ACAH) controller (see Section 8). It is possible to quantify the control activity, and hence the pilot's compensation – the additional inputs over and above those minimally required to complete the manoeuvre – through the use of metrics such as those described in [12, 13]. These methods allow direct measurements of the reduction in compensation to be made, and thereby facilitate quantification of the level of compensation that will be required for a PAV. The control data for the two models has been normalised to the range [-1:1].

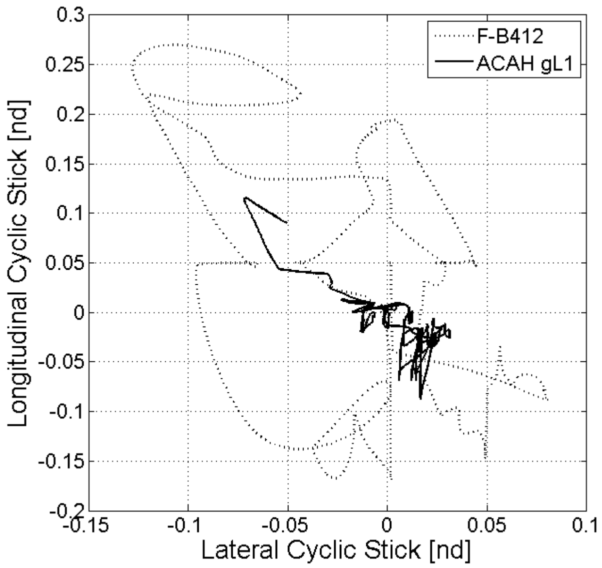

Figure 7.1: Lateral and longitudinal cyclic activity during a hover task

Figure 7.1 raises a number of issues for PAV handling qualities. Firstly, while the amplitude of control activity in the hover task has been reduced relative to the Bell 412, the frequency at which inputs were made has increased. Secondly, the control inputs follow a multi-axis path for the majority of the task – both lateral and longitudinal inputs being made simultaneously. These features of the pilot's control activity both indicate that, even with good Level 1 handling qualities, a conventional combination of response type and handling qualities is unsuitable for a PAV. This hypothesis has been proved in later experiments with participants with various backgrounds and resulted in a series of publications [14, 15, 16]. The investigated command types that were used for evaluation are described in the following sections.

In addition to the hover task discussed above, a range of tasks (Mission Task Elements, or MTEs) can be defined that are representative of a PAV 'mission', and that can be used to assess the handling qualities of the vehicle during manual flight phases. The tasks may not all be relevant to every scenario, depending on the nature of the mission and the allowed/required level of PAV automation. For the most complex scenarios, where complete operation of the PAV is manual, the task list may include the following:

7.1 Standard Mission Task Elements

These MTEs are those that can be drawn from existing handling qualities evaluation processes, such as that prescribed by Aeronautical Design Standard ADS-33E-PRF for military rotorcraft [17]. The ADS-33 MTEs that can be adapted to the PAV role include:

- Hover (ADS-33 3.11.1)
- Landing (ADS-33 3.11.2)
- Hovering Turn (ADS-33 3.11.4)
- Vertical Manoeuvre (ADS-33 3.11.6)
- Depart/Abort (ADS-33 3.11.7)

- Lateral Reposition (ADS-33 3.11.8)
- Approach Procedures (ADS-33 3.11.20-3.11.22)
- Speed Control (ADS-33 3.11.23)

As the PAV is operating in a civilian role, it may be necessary to reduce the level of task aggression associated with some of these MTEs in order to maintain appropriateness with the mission. An example could be the lateral reposition task, where, for the military rotorcraft, the aircraft must be translated a distance of 400ft in a time of 18 seconds (including stabilisation at the new hover point).

7.2 New Mission Task Elements

In addition to the MTEs listed above, additional MTEs are required to fully assess a PAV's mission. These additional tasks may be subdivided into categories depending on their nature.

Navigating Through the Urban Environment

- Lateral manoeuvring during low-altitude forward flight (Roll Step)
- Vertical manoeuvring during low-altitude forward flight (Heave Hop)

En-Route

- Altitude Change (climbing & descending)
- Heading Change

Swarms

- Join formation of PAVs
- Maintain formation (straight & level, altitude change, heading change, speed change)
- Depart formation

Emergency Scenarios

A PAV must be safe to operate in the face of emergencies. These could include, but not be limited to:

- Resumption of manual control following the failure of an automated system (in any flight phase)
- Mid-air collision avoidance
- Failure of the manual flight stability augmentation systems

8 Response Types

The Aeronautical Design Standard ADS-33E-PRF [17] defines handling qualities requirements and necessary response types for military rotorcraft. The selection of adequate response types is connected to the visual cues that are available to the pilot. In general, advanced modes with higher stabilization are required when the visual environment degrades. Examples for a degraded visual environment are foggy weather, snow, or flight over limited visual cueing landscapes like water or snow fields.

The selection of appropriate response types for a PAV pilot must not be based only on the environmental conditions alone but mainly on the capabilities of the pilot. A minimally-trained pilot probably needs more advanced stabilization modes but can do without highly agile commands as the requirements for aggressive manoeuvres in a civil PAV scenario are lower than for military purposes. The following paragraphs present some of the command types that are specified by ADS-33E-PRF and that were studied in recent projects on the development of modern control laws.

8.1 Rate Command

A rate command (RC) is the most basic response type according to ADS-33E-PRF [17]. Constant inceptor deflections, e.g. in roll, pitch, or yaw axis, create constant angular rates in the corresponding axis. Rate command is as well available for the heave axis where a constant deflection of the collective results in a constant climb rate. The basic rate command can be augmented by holding functions, e.g. attitude hold (RCAH) in roll or pitch axis, direction hold (RCDH) for the yaw axis, or height hold (RCHH) for collective command. When a holding function is activated, the corresponding attitude, heading, or altitude is kept constant on stick release.

Conventional helicopters without modern control laws usually provide a basic rate command. Examples for RCAH are the development of the Digital Automatic Flight Control System (DAFCS) for the CH-47F tandem helicopter and the Modern Control Laws (MCLAWS) of AH-64D [18, 19]. Both incorporate RCAH for roll axis control in forward flight. RCDH is a typical command type for yaw axis behaviour in hover and low speed and is used throughout many projects. For the heave axis height hold functions are typically used but for the project “Active Control Technology for Improved Mission Effectiveness” (ACT-IME) flown on DLR’s ACT/FHS research helicopter, a vertical speed command with speed hold function (RCRH) was studied as well but not flight tested [20].

8.2 Attitude Command

A more stabilizing response type is attitude command (AC). In this case the aircraft attitude is proportional to the deflection of the control inputs in pitch or roll axis. Additional attitude hold (ACAH) keeps the attitude constant on stick release, like incorporated for low speeds in CH-47F DAFCS and AH-64D MCLAWS. For the UH-60M Upgrade a special response type of attitude command with hover hold (ACHH) was developed. In pitch and roll axis the attitude changes proportionally to the displacement of the cyclic inceptor. When the cyclic is returned to the centre, the aircraft decelerates to zero velocity and attains a stable hover position [21].

8.3 Translational Rate Command

The translational rate command (TRC) is a response type for precise ground referenced movement used in the low speed regime. Constant pitch and roll controller forces provide a proportional translational rate in longitudinal or lateral direction. On stick release hover is attained automatically. TRC is available among the control laws for UH-60M Upgrade, CH-47F DAFCS, and AH-64D MCLAWS, and was as well tested during the project ACT-IME.

Position hold is an additional pilot selectable mode that was used for UH-60M Upgrade, CH-47F DAFCS, and AH-64D. A ground speed feedback loop is used to hold the helicopter at a stable position relative to earth coordinates.

8.4 Acceleration Command

An acceleration command (AcC) allows controlling the aircraft’s acceleration proportional to the stick deflection in longitudinal or lateral direction. This mode is more aggressive than the previous modes and best suited for fast forward flight. One advantage over other modes is that trimming is managed automatically in forward flight. When the pilot has reached the desired speed after holding a constant acceleration, he can return the stick back to the centre position and does not need to hold any stick forces during cruising flight with constant velocity.

The AcC response type was used for CH-47F DAFCS and during the ACT-IME project. In ACT-IME additional velocity hold (AcCVH) was provided based on the ground speed around hover and based on airspeed for higher velocities. For the UH-60M Upgrade AcC was part of a hybrid mode in pitch axis specially design for forward flight.

8.5 Turn Coordination

Turn coordination (TC) allows the pilot to fly coordinated turns. The side slip angle remains zero during banked turns with feet off and lateral acceleration is kept at zero. Displacement of the pedals from the centre position results in a change in side-slip proportional to the amount of pedal displacement. In higher control laws turn coordination is available in forward flight above certain velocities but for ACT-IME additional ground turn coordination (GTC) was included. This mode can compensate wind effects and keeps the fuselage aligned with the flight direction.

8.6 Command Type Blending

Command type blending is necessary for automatic transition between different modes. For example groundspeed or airspeed can be used as switching variable to activate the transition between precision modes around hover and more agile modes for higher speeds. For example the ACT-IME control laws switch from TRC to AcCVH in pitch axis when a certain ground speed is reached. In roll axis the same project provides a hybrid mode ARCAL that blends from attitude command to rate command beyond a given bank angle. On stick release roll attitude levelling is automatically recovered.

For the upgraded control laws of UH-60M a hybrid mode between attitude and acceleration command with velocity hold (AAcCVH) is available. Initial displacement of the cyclic stick in pitch or roll axis results in a proportional attitude change and returning the stick to the centre position acquires a new velocity. When the pilot continuously keeps the stick deflected, the mode is slowly blended over to an acceleration command. This blending allows the pilot to quickly switch between modes for more aggressive manoeuvres.

Table 8.1: Response types in hover and low speed

	AcCVH	AAcCVH	ACAH	ACHH	RCAH	TRC	TRC PH	Yaw RCDH	GTC	HH	Height RCHH
ACT-IME	P					R P		Y	Y	H	
UH-60M Upgrade		R P		R P			R P	Y			H
CH-47F DAFCS			R P				R P	Y		H	
AH-64D MCLAWS			R P				R P	Y		H	

R: roll controller, P: pitch controller, Y: yaw controller, H: heave controller

Table 8.2: Response types in forward flight

	AcCVH	AAcCVH	ACAH	RCAH	RCVH	ARCAL	TC	HH	Height RCHH	Flight path hold
ACT-IME	P					R	Y	H		H
UH-60M Upgrade		P	R				Y		H	H
CH-47F DAFCS	P			R			Y	H		
AH-64D MCLAWS				R	P		Y	H		H

R: roll controller, P: pitch controller, Y: yaw controller, H: heave controller

Figure 8.1: ACT-IME on ACT/FHS (DLR)

Figure 8.2: UH-60M (www.sikorsky.com)

Figure 8.3: CH-47F (www. boeing.com)

Figure 8.4: AH-64D (www.boeing.com)

8.7 Advanced Response Types for PAV Usage

The data presented in section 7 indicate that a conventional ACAH-style response type is unsuitable for use in a PAV, as the level of compensation associated with these response types for PAV tasks is higher than that expected from a minimally-trained PAV operator. The higher-order response types discussed above, such as TRC for the hover, have the potential to reduce pilot workload to the level where Handling Qualities Ratings (HQRs) of 1 (the best handling characteristics) are achievable.

The research conducted in WP2 led to the development of a flight dynamics model with variable response types tailored towards PAV usage [38, 39]. Its “hybrid” configuration was found to be most suitable for PAV usage [14]. Two different settings, one for the low speed regime and one for the high speed regime, are available. Smooth blending occurs in the transition phase between 15 and 25 kts. The intention of this hybrid model configuration is to minimize the number of necessary control inputs for performing typical PAV manoeuvres.

Figure 8.5 shows the response type configuration of the used PAV model. In the longitudinal and lateral axes a Translational Rate Command (TRC) is implemented in slow flight. This response type connects the control deflection to the speed over ground linearly. When the inceptor is returned to the neutral position, the PAV returns to hover. Above 15 kts blending starts towards the forward flight mode which is an Acceleration Command (AcC) in the longitudinal axis. The aircraft’s acceleration is proportional to the inceptor’s deflection in the forward flight mode. This implies that the current airspeed is held when the inceptor is returned to neutral. In the lateral axis an Attitude Command (AC) with attitude hold is implemented for speeds over 25 kts. A lateral control input results in a proportional roll angle. The yaw control is designed as Rate Command (RC) response type in hover and low speed. The yaw rate is proportional to the pedal inputs. In faster forward flight the response type changes to a Sideslip Angle Command (βC) with Turn Coordination (TC). This increases directional stability and allows flying coordinated turns (free of sideslip) in forward flight without additional pilot inputs. The altitude is controlled via TRC response type in hover mode and changes to Flight Path Angle Command (γC) in forward flight. Inter-axis coupling is not present in the selected response type configuration apart from the turn coordination.

The mode change is designed one directional such that the transition phase occurs between 15 and 25 kts when accelerating. In order to return from the fast forward mode to the slow mode, the pilot must bring the aircraft back to hover.

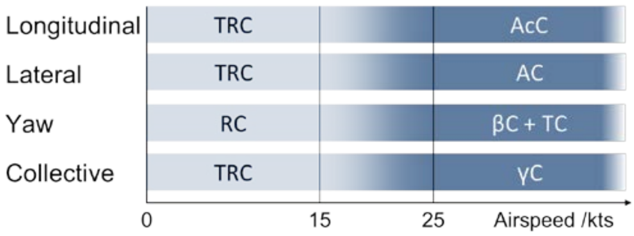

Figure 8.5: Hybrid response type configuration for PAV usage

The described PAV dynamics model has extensively been tested at the University of Liverpool [14, 15, 16]. Both pilots and flight-naïve test participants had the chance to fly a PAV in a motion simulator. The described model configuration generally received very good ratings regarding handling qualities and is foreseen to be most suitable for future PAVs.

9 Flight Controls

The choice of appropriate flight controls clearly depends on the type of vehicle that is flown and the level of automation it incorporates. It was agreed on that VTOL capabilities are a must but that still leaves several possibilities like conventional helicopters with main and tail rotor, multicopters with several rotors, or tilt-rotor aircraft. Although these aircraft differ in their control strategy, the need for controlling the basic degrees of freedom remains the same. When manual control is desired, there must be an inceptor for controlling the heave motion or the power generation and inceptors to control the rotation around the three axes for roll, pitch, and yaw motion. The following table compares different steering systems imaginable for a PAV. The necessity for manual pilot controls vanishes when full (and fail-proof) autonomy of the vehicle is assumed. The PAV user would then use some kind of HMI to set the desired destination but he would not steer the vehicle directly.

Table 9.1: Possible steering systems for PAVs

	Heave / Power	**Pitch**	**Roll**	**Yaw**
Conventional	collective lever (up – down)	centre stick (fore - aft)	centre stick (left – right)	pedals (left – right)
2DoF side stick	conventional collective lever	right hand side stick (fore - aft)	right hand side stick (left – right)	conventional pedals
Two 2DOF side sticks	left hand side stick (fore – aft / up – down)	right hand side stick (fore – aft)	right hand side stick (left – right)	conventional pedals / left hand side stick (twist left – right)
3DoF side stick	conventional collective lever	right hand side stick (fore – aft)	right hand side stick (left – right)	right hand side stick (twist left – right)
4DoF side stick	right hand side stick (push – pull vertically)	right hand side stick (fore – aft)	right hand side stick (left – right)	right hand side stick (twist left – right)
Long pole wheel	long pole wheel (push – pull vertically)	long pole wheel (fore – aft)	long pole wheel (left – right)	long pole wheel (turn left – right)
Car-like	pedals (throttle – brake)	gear shift (up – down – back)	steering wheel / horn (push left - right) or coupled to yaw motion	steering wheel / horn (turn left - right)
Tilt-rotor (ACT-TILT)	two axis inceptor (hover: up – down, forward flight: fore – aft)	conventional centre stick	conventional centre stick	conventional pedals

9.1 Conventional Pilot Controls

Conventional helicopters are controlled with three primary flight controls: cyclic centre stick, collective lever and anti-torque pedals. The cyclic changes the pitch of the main rotor blades cyclically. Thereby it generates lift at a certain position of the rotor disk. Moving the centre stick forward and backward lets the helicopter rotate around its lateral axis and creates a pitching moment. The nose of the helicopter goes down when the pilot pushes the cyclic forward and up when he pulls the stick backwards. Moving the stick to the left and right creates a rolling moment and lets the helicopter rotate around its longitudinal axis.

The collective stick is usually located at the left side of the pilot. When pulled upwards, it increases the pitch of all rotor blades collectively and decreases pitch when pushed downwards. Increased pitch angle at the rotor blades increases the generated lift. From a hovering position the increased lift lets the helicopter ascent while pulling the collective lever upwards in forward flight with the nose pitched down creates a lifting force that accelerates and ascents the helicopter at the same time.

Conventional helicopters are equipped with an anti-torque tail rotor that prevents the helicopter from spinning around its vertical axis due to the moment created by the main rotor. The tail rotor can be controlled with two pedals. Stepping on the left or right pedal increases or decreases the pitch of the tail rotor blades and alters the produced thrust. A change of tail rotor thrust leads to a yawing motion and changes the direction the nose of the helicopter is pointing at. Helicopters with two or more main rotors do not need an extra tail rotor. In this case the pedals control the combination of the created lift coming from the individual rotors in order to control the yawing motion.

The conventional arrangement of controls has been used in several piloted studies throughout the project (WP2, WP3 and WP6).

9.2 Side Sticks

Freely programmable side-arm controllers offer the possibility of creating new pilot control systems that differ from the conventional inceptors. This technology became viable with the integration of fly-by-wire technology into helicopters. Pilot controls do no longer need a mechanical connection to the actuators but can be programmed freely [22, 23].

Depending on the available degrees of freedom (DoF) of the stick, different control arrangements can be realised. For example a two-axis side stick can be used for controlling pitch and roll commands. In this case the yaw and heave axis are controlled via conventional collective lever and pedals.

A second side stick with 2 DoF can be used for left hand commands. Stick deflections in longitudinal direction can then serve as collective control inputs. The remaining lateral axis can as well be used for commanding yaw motion. This configuration of two 2DoF side sticks has intensively been tested on DLR's research helicopter [24].

3DoF side-arm controllers can provide a third degree of freedom in the twisting axis vertically to longitudinal and lateral deflection. Depending on the twisting position, a yaw command can be generated. The heave axis must then be controlled by an additional inceptor, for example a conventional heave controller. Another option for a 3DoF controller is to have roll, pitch and heave control on one stick and separate pedals for heading control. But pilot comments showed that the configuration with a separate heave controller was preferred when using a 3DoF side-arm controller during flight tests [23].

All four axes roll, pitch, yaw, and heave can be controlled via one controller with 4 DoFs. Roll and pitch rates are generated by deflecting the stick laterally or vertically and the yaw axis is controlled by twisting the grip. A movement in vertical direction can then be initiated by pulling and pushing the stick vertically up and down.

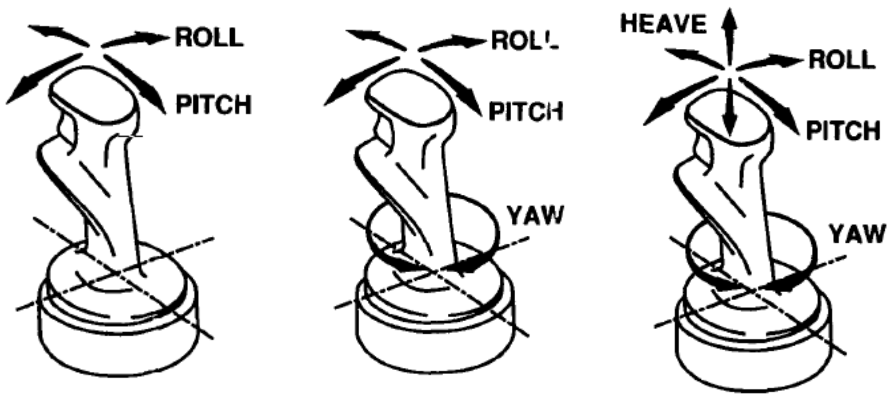

Figure 9.1a, b, c: 2DoF, 3DoF, and 4DoF controller [23]

9.3 Car-like Controls

One idea of making PAV pilot controls more intuitive is to use a well-known control concept from street vehicles. As a typical PAV user would probably already possess a driving licence and would be used to the concept of steering a car, he could probably more easily adapt to a PAV that offers similar controls. The problem that needs to be addressed is the doubling of DoFs in control when entering the third dimension. Driving a car on a street requires commanding only two axes: longitudinal acceleration by using throttle and brake pedals, and yawing motion by turning the steering wheel. In flight additional control over the heave and the roll axis becomes necessary.

The idea of using a steering wheel for controlling a helicopter is not new. Already in the 1940s Hal Lemont constructed the “Gazda Helicospeeder” which had a single wheel as inceptor [25]. The wheel on a long pole worked similarly to a modern 4 DoF side-stick. Pitch and roll axes were controlled by deflecting the pole longitudinally or laterally and heave control was possible by pushing and pulling the pole vertically. The yawing motion was controlled like in a car by turning the wheel.

With car-like controls for a PAV one could as well use pedals for commanding collective inputs. Like the throttle of a car is used for accelerating, a pedal in the bottom of the PAV cockpit would be used to increase thrust. The amount of thrust would remain constant or decrease when the foot is taken off the pedal and another braking pedal could be used for further decreasing thrust.

A horizontally mounted multi-axis gearshift lever could be used not only for commanding forward and backward flight direction but as well for defining the flight path angle. With the lever in neutral position the vehicle would remain in level flight and pulling and pushing up and down would lead to a climbing or descending flight path. Modes for moving the vehicle backwards or into a side-step would be available from a hovering position. A deflection of the gear-shift lever in lateral direction would cause a side-step and pushing the inceptor back towards its pivot point would start the backward flight mode.

The steering wheel would be needed for controlling roll and yaw axis. Controlling both axes separately with a standard car wheel would not be feasible but one could imagine a combination of a wheel and a control horn used in aircraft. At least two DoF are necessary.

One DoF obviously is turning the wheel left and right what could be used for controlling the heading and the other DoF could be deflecting the wheel laterally for commanding roll attitude.

Alternatively, one could limit the DOFs the pilot has to control by coupling the roll motion to yaw commands. The vehicle would then automatically attain a certain roll angle when sharp turns are commanded. This might decrease the pilot’s workload but would at the same time limit the manoeuvrability as a decoupled sideward motion would not be available.

Figure 9.2: Artist’s impression of a PAV cockpit (© Flight Stability and Control)

During the myCopter project several investigations with car-like control concepts for PAVs were conducted. Deliverable D2.3 [39] describes the development of a flight dynamics simulation with thrust vectoring capabilities. So, the, for helicopters typical, pitch and roll motion can be suppressed. This simulation and the previously described hybrid model were also flown with conventional inceptors that were reconfigured for more car-like behaviour. The pedals were used for speed control while the cyclic was configured to replicate a car’s steering wheel. In slow flight a lateral movement of the cyclic was used for yaw control and in fast forward flight for bank angle control. At UoL this automobile configuration was successfully flown by pilots with lower experience [4].

DLR decided to integrate a proper steering wheel into their simulator and research helicopter. The development of the concept together with a historic overview on related developments is documented in [26]. The hybrid control law configuration as described in section 8.7 was adapted for steering wheel usage. The steering wheel is used for commanding coordinated turns – a combination of roll and yaw motion depending on the current airspeed. The pedals are used for controlling the longitudinal movement. The response to inputs from the collective lever does not change compared to the conventional setup. An 8-way switch in the centre of the wheel is used for precision manoeuvring – forward, backward, sideward and diagonally. Steering wheel control for rotorcraft was successfully demonstrated at DLR. The steering wheel configuration generally received slightly better handling qualities ratings and lower workload ratings than the configuration with conventional controls. The complete study is documented in deliverable D6.6 [59].

9.4 Tilt-rotor

Designing pilot controls for a tilt-rotor aircraft is a special case as the control strategy changes when switching from helicopter mode in vertical flight to airplane mode in forward flight. In conventional helicopters power is increased by pulling the collective lever up but conventional fixed wing aircraft use thrust levers that are pushed forward for increasing engine power. The tilt-rotor aircraft BA-609 uses conventional helicopter controls throughout both flight phases [27]. The disadvantage is that in forward flight the pilot still needs to control power with an upward motion of the stick where the direction of motion is not in line with the direction of flight. On the other hand conventional aircraft controls have disadvantages in helicopter mode when the pilot has to control a vertical movement of the aircraft deflecting a lever horizontally.

To overcome these disadvantages of conventional controls, a special power lever was designed during the ACT-TILT project which provides two translational DoFs [28]. When in helicopter mode or vertical motion, power can be controlled by pushing the grip of the lever up and down. During the transition phase from helicopter to airplane mode the control is then blended over to a horizontal movement of the grip to control power. This allows the pilot to always have the axis of stick movement aligned with the direction of aircraft motion.

9.5 Active / Passive Inceptors

Conventional pilot controls are linked mechanically to the actuators for rotor, engine or flaps. This linkage transports control signals not only in one direction from pilot to actuator but as well gives force feedback from the actuator back to the pilot. When fly-by-wire technology is used, this natural feedback is lost but on the other hand new options arise from the implementation of active inceptors.

Active pilot controls can mimic a mechanical linkage and provide additional tactile cueing by adjusting physical parameters of the inceptor like damping or deflection force. This allows creating different force-feel characteristics for different flight scenarios and piloting tasks. The implementation of adequate tactile cues can improve pilot awareness and increase the handling qualities of the entire system [29, 30, 31]. These characteristics can be especially useful for the implementation into a PAV as additional tactile cues can support a minimally-trained pilot to manoeuvre his aircraft.

In WP3 the effects of haptic feedback where investigated for PAV usage. These investigations are further described in the following section.

10 Human-Machine Interfaces

Within a highly automated PAV system, the role of the PAV user is not to pilot the vehicle, but to navigate it in three-dimensional space. Given that we expect training to be minimal, human-machine interface design of PAVs ought to be designed in a way that is intuitive to our everyday capabilities. This can be accomplished by novel interfaces that are designed according to our viewing preferences and appeal directly to our perceptual senses.

10.1 Haptic Feedback

Haptic feedback provides forces to a user via the sense of touch. In common helicopters and aircraft, flight controls are mechanically linked to the control surfaces that interact with the airflow. Thus, the pilot gets a direct feeling for the forces on the control surfaces and the state of the vehicle.

In modern helicopters and aircraft, the mechanical link between the flight control and the control surfaces is generally enhanced with hydraulic actuators, or replaced by a fly-by-wire control system. This is sometimes necessary, such as when the control forces that a pilot has to exert would be too high, e.g., in a large airliner, or when the aircraft has been designed to be unstable, e.g., like a fighter jet.

Haptic cues can be provided to the pilot through the actuated flight control system. Haptic cues could be beneficial by inducing faster pilot responses, because spinal reflexes can be used to respond to an input signal [32]. Haptic cues are generally provided to the human by actuated control devices, which combine a position encoder with an electric motor or hydraulics that can move the control device independently and provide forces to the human. Examples of this type of devices are actuated side sticks, accelerator pedals, or aircraft yokes and pedals. These devices interact with the hands or feet of the human controller.

Haptic cues can also be applied to the human body directly. Tactile vests and bands are worn on the torso, hands, or arms, and are usually equipped with several tactors. Tactors could also be integrated into the pilot seat. These small transducers vibrate on the skin and can be arranged in various configurations. These arrays of tactors can provide, e.g., information on objects that are not in the line of sight, or can provide orientation information. However, the resolution of the skin to tactile information is restricted, which limits the amount of information that can be transferred.

One application of a tactile vest by TNO, The Netherlands, see Figure 10.1, involves tactile cueing for helicopter hover. When the pilot drifts from the desired hover location, the tactors provide an instant cue about the direction of the drift. If a visual display would be used instead, attention could be drawn away from the outside environment.

Figure 10.1: The TNO tactile vest by TNO, The Netherlands

For active control sticks, two types of approaches can be used to supply haptic information. Usually virtual repulsive forces are adopted to avoid collisions with obstacles [33]. These repulsive forces actively deflect the control stick to steer away from the obstacle. Therefore, they provide an informative cue to the pilot about the control actions that need to be taken. Pilots have to adopt a compliant control strategy for this type of haptic cue.

Instead, the haptic cue could be directed in the opposite direction, such that the pilot needs to oppose the forces felt on the control stick. For this, the pilot would adopt a more stiff control strategy to oppose movement of the stick. The informative cue about the control actions that need to be taken is not explicitly provided, but full workspace of the control stick remains available to the pilot.

Within the context of a PAV scenario, there are several options for the use of haptic cues. One of these is the use of haptic cues for flight guidance. In this case, haptic cues would provide information to the pilot about the flight path that needs to be tracked. These can be combined with visual representations of the flight path, such as the Highway-in-the-Sky display that is discussed in the next section.

Another use for haptic cues would be to support the pilot in situational awareness. In this case, haptic cues are used to provide information about the environment that surrounds the PAV. For example, pilots could feel forces on the control stick when the PAV is too close to static obstacles such as buildings and the ground, or flying objects such as other PAVs.

In the myCopter project the use of haptic cues to support an average PAV user in flight were investigated. For this, the MPI used control loading devices that are arranged in a conventional helicopter layout (Wittenstein GmbH, Germany, see Figure 10.2a). These control loading devices can be programmed to mimic a wide range of spring-damper dynamics that can be altered in real-time.

Additionally, an actuated conventional steering wheel is available, see Figure 10.2b. However, this could only be used in investigations with limited degrees of freedom, given the limitations of car-like controls for PAVs presented in Section 9.3.

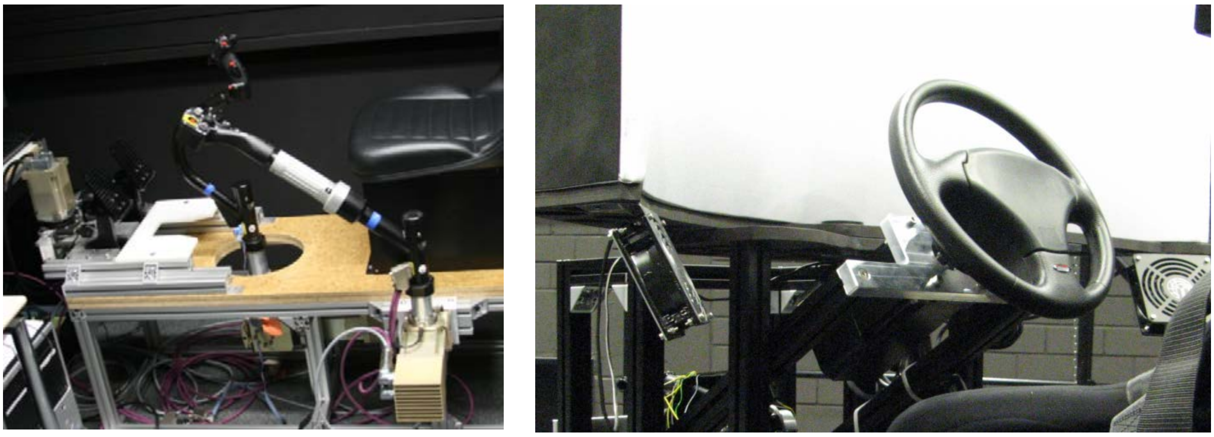

Figure 10.2a, b: Control loading devices at the Max Planck Institute for Biological Cybernetics

After investigating the unintentional interference between inceptors and pilot, also known as biodynamic feedthrough (BDFT) [42], studies on the benefits of haptic aids for PAVs were conducted at MPI. As deliverable D3.4 [43] reports, haptic guidance cues on a side stick allowed pilots to achieve better performance with lower control activity. In a simulated flight the haptic aids were designed to assist the pilots in following a three dimensional flight path shown on a Highway-in-the-Sky display (see section 10.2). This combination of haptic and visual guidance is a promising feature for assisting future PAV users.

10.2 Cockpit Displays

Current display systems in aviation are highly specialised instruments. These require a large degree of training before they can be used to navigate in three-dimensional space. Even though instruments have been integrated into single representations, e.g., the primary flight display, forming a representation of the aircraft surroundings is still cognitively effortful.

One solution would be to include perspective information in the display. A Highway-in-the-Sky (HITS) display integrates flight path information by projecting a 3D representation of the boundaries of the path, see Figure 10.3. It employs perceptually relevant cues such as convergence, texture and optic flow to inform the visual system directly. This representation is intuitively understandable, enhances the situational awareness, and is compatible with other tasks the pilot has to perform [34]. The task of the pilot is to stay within the projected tunnel, which could even be designed for difficult approaches or noise abatement procedures. The HITS display has been proposed several decades ago, but has not been applied yet on a large scale. Other types of information that could be conveyed by a perspective display could include terrain information or surrounding obstacles.

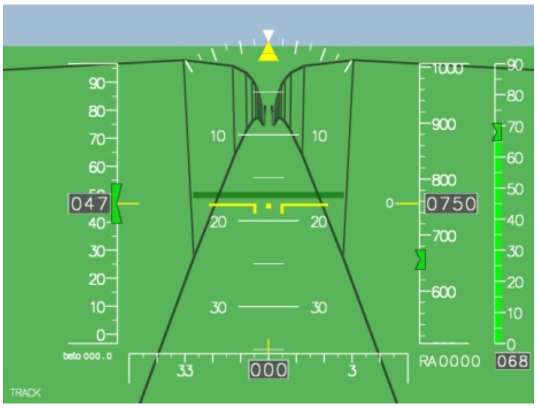

Figure 10.3: A Highway-in-the-Sky display

Future display technologies could include stereo displays. In these displays the image for the left and right eye is different, which preserves the depth information that is observed in the real world. This could provide a more intuitive way of retrieving information from the virtual world on the display. Originally, stereoscopic cues were observed through glasses with either polarised filters or a different lens colour for each eye. However, new types of displays allow for displaying depth information without any type of glasses.

As a next step to display integration, information could be integrated dependent on the current environment and task. The display would adapt its representation of the world by taking into account the current flight phase, e.g. cruise or landing, or weather situation. This requires a thorough understanding of the information that is required by the pilot, and a detailed depiction of the world surrounding the vehicle.

The interaction between the pilot and a display is traditionally done with hardware buttons. This means that displays are surrounded by many physical buttons with a dedicated function that is dependent on the displayed information. Instead, touch screens could be used as a replacement. These could provide a significant improvement as functions such as scrolling and selection can be supported more intuitively. The hardware buttons around the screen can be removed to free up space. Recently, touch screens were introduced into the cockpit of general aviation aircraft with the introduction of the G2000, G3000, and G5000 flight decks by Garmin Inc, see Figure 10.4.

Figure 10.4: The Garmin G2000 flight deck

A possible drawback of this application of touch screens is that intended interactions with the display can be disrupted by interactions of vehicle movement with the limbs of the pilot. Also, a touch screen does not provide the equivalent feedback of pressing a physical button. These issues should be investigated to enhance the usability of touch screens in PAVs.

A HITS display developed by DLR has been used for several investigations throughout the myCopter project. Figure 10.3 shows the display's layout. A tunnel evolves over a plain green and blue background. Overlaid to the three-dimensional design is a two-dimensional primary flight display (PFD). This features conventional indications for attitude, heading, altitude, airspeed and torque. Additionally, target indicators, so called bugs, are implemented for flight parameters such as airspeed and altitude as well as pitch angle and torque. These bugs have a rectangular shape with cut-out triangle in order to provide the pilot with information on the acceptable deviation from the target value. Further details of the display and its usage are to be found in deliverable D4.6 [49]. The display was successfully used in combination with haptic aids as described in section 10.1. The HITS display also proved its flight worthiness in a real aircraft. In 23 approaches to the Braunschweig-Wolfsburg airport, the test pilots of the ACT/FHS research helicopter could follow the displayed flight route with high accuracy. The complete results of the flight tests are documented in deliverable D6.6 [59].

At UoL a head-up display symbology, overlaid to the simulator's outside world scene, was used to inform the pilot about current and target airspeed, heading and radar altitude. An additional marker showed the target hover point [14].

10.3 Monitoring of Pilot State

Physiological responses of a pilot can provide insight into the relationship between a pilot's actions and the cognitive workload during flight manoeuvres. This can be used to develop assistance systems to aid the pilot during flight by combining the relevant information, much like current driver-assistance systems in cars. Such a system could also monitor the pilot's alertness levels.

Relevant measures include galvanic skin response, which is a measure for the electrical conductivity of the skin. Others include heart rate variability and respiration rate. They can collectively contribute to the assessment of arousal and stress levels. Furthermore, electrical activity along the scalp can be recorded with electro-encephalography (EEG), which can provide insight into the processing of neural signals that are relevant to flight performance.

The deliverables D3.1 [40] and D3.2 [41] describe in detail the simulation facilities at the MPI as well as the equipment used for pilot monitoring. Additional to the physiological measurement methods mentioned above, features such as eye-tracking and biodynamic feedthrough measurements were part of the investigations. Latest results will be summarised in deliverable D3.5 “Final publications”.

10.4 Brain-Computer Interfaces

Brain-computer interfaces (BCI) offer a direct communication link between the brain and an external device. They could provide a means for steering a vehicle by measuring brain activity. State-of-the-art technology allows for non-invasive techniques that are particularly suited for applied BCIs (e.g., dry electrodes that do not require long preparation times).

BCIs are often aimed at assisting humans with disabilities by providing a substitute for human cognitive or sensory-motor functions. However, recent developments have shown that BCIs can be used to steer the direction of a car [35], or control the movement of an object through target obstacles in three-dimensional space [36]. Further developments are still required to improve the spatial resolution and latencies of these techniques before these can be used in a scenario that involves personal aviation.

11 Navigation

For a partially or fully automated personal air vehicle new concepts for control and navigation must be developed. One idea is to combine GPS navigation with vision-aided devices in order to improve accuracy of localisation, obstacle avoidance and path planning. Among the more challenging flight phases are take-off and landing. The PAV operator must be supported during these flight manoeuvres especially in confined urban areas with limited space for manoeuvring. Further features and options regarding the control and navigation of a single PAV have been addressed in the deliverables of WP 4.

After selecting an unmanned Micro Aerial Vehicle (MAV) as platform for the investigations of sensors and navigation algorithms in D4.1 [44], the following deliverables D4.2 [45] and D4.3 [46] focused on the development of Simultaneous Localization And Mapping (SLAM) algorithms. Deliverable D4.4 [47] reports on advanced navigation tasks like path planning towards increased autonomy. The final system makes use of a monocular camera as primary navigation sensor for obstacle avoidance. This system can actively aid navigation and collision-free path planning. Due to its generic nature it is applicable to a variety of rotorcraft (see D4.7 [47]). The final algorithms are documented in deliverable D4.8 “Delivery of final system”.

During the challenging phase of landing, PAV users could get help from the landing place selection tool developed in deliverable D4.5 [48]. Featureless polygonal regions are automatically detected as suitable landing sites. This allows detecting for example runways, grass fields or roof tops. The algorithms were successfully applied on video material recorded with the cameras of the ACT/FHS research helicopter.

With a fully operational PATS up to 40 PAVs per km^3 are foreseen to be flying at the same time [37]. The scenario then changes from mainly self-centred operations in sparsely occupied airspace towards the need for a reliable air traffic management. Human based air traffic control will hardly be able to manage the foreseen numbers of vehicles. Instead each vehicle should incorporate a navigation system that allows mid-air collision avoidance without communication. This is necessary to avoid collisions not only with other PAVs but also with non-communicating mid-air obstacles like birds or remote-controlled aircraft. The development of such a navigation system can be divided roughly in three levels. The challenge of the first level will be to facilitate independent navigation with simple collision avoidance. The second step would then be to investigate flocking or formation flying of multiple PAVs and finally in the third level geographic constraints like no-fly-zones or traffic corridors must be taken into account.

The system developed in WP4 copes with the challenge of level one. The MAV has demonstrated to be capable of collision free path planning without relying on external information. The challenges of the second level were dealt with in WP5. Deliverable D5.1 [51] suggests a sensor package that would allow the detection of other aircraft in a swarm or crowd scenario. For small-scale demonstration on Unmanned Aerial Vehicles (UAV) this package is scaled down but still includes radar, vision, GPS and a communication link. Deliverable D5.2 [52] introduces a possible algorithm for vision-based detection of approaching aircraft. Based on the UAV sensor package mid-air collision avoidance strategies are developed for PAV commuting scenarios and demonstrated in flight test with several UAVs. In simulation even hundreds of PAVs could safely navigate through areas with very high traffic density. Formation flying for PAVs was suggested at the beginning of the myCopter project but deliverable D5.4 [54] shows that there are better approaches for a functional PATS. Unlike swarms or flocks of animals, the PAV users in the myCopter scenario do not have a common goal but very individual travel routes. Thus, crowd modelling is suggested to be better suitable. Therefore, the PAV navigation algorithms described earlier are based on crowd modelling.

Geographic constraints or no-fly-zones have not yet been integrated into the navigation algorithms. These features would further assist PAV users and could aid to increase safety when integrated into a PATS. Final findings are reported in deliverable D5.5 “Description and comparison of various global traffic control strategies including formation flying”.

12 Conclusion

This deliverable addresses various aspects and considerations that the different work packages of the myCopter project dealt with. The outcome is a collection of features for PAVs that are beneficial or even essential for the implementation of a functional PATS.

- For the efficient implementation of a PATS point-to-point connections must be feasible with no additional mode changes, e.g. from car to aircraft. Therefore, vertical take-off and landing capabilities are essential for the envisioned PAVs.
- Although the design of a specific vehicle was not the goal of the project, electric propulsion is suggested for further consideration. A short rotorcraft predesign study and a rough estimation of the energy consumption for a reference flight show that the ongoing development in battery technology could make electric PAV flight possible in the future.
- The necessary autonomy of PAVs has been discussed extensively during the project. The consortium as well as the interviewed focus groups came to the conclusion that both (assisted) manual as well as fully autonomous operation are desirable options. Manual flight is suggested for the early adopters as first phase of a possible PATS. Also for sports and leisure flights piloting the own PAV is a wish that was expressed frequently. In the more advanced second phase of the PATS implementation fully autonomous

operation is foreseen to be especially advantageous for tedious routine flights such as the daily commute.

- Daily availability of 90% over the year has been identified to be of utmost importance for a PATS to become a reliable system accepted by the average commuter instead of being a collection of “rich men’s toys”. This means, PAVs have to cope with all kinds of adverse weather conditions.
- Training requirements for future PAV pilots have been investigated. A shorter syllabus comparable to obtaining a driving licence is suggested. This is safely achievable only when the handling of the PAV and the assistance functions it offers are adapted to the limited capabilities of the future user.
- A hybrid control law configuration featuring translational rate command in hover and slow flight and longitudinal acceleration command for higher speeds received the best pilot ratings and is among the investigated response types the most suitable configuration for PAV usage. The lateral response type changes from translational rate command in slow flight to attitude command in fast flight.
- A steering wheel implemented as primary control device has shown to be a good alternative to conventional helicopter controls. Pilot workload could be decreased and handling qualities ratings increased.
- In order to increase the manual path following accuracy, an intuitively understood highway-in-the-sky display was developed. It proved its flight worthiness in flight test on the research helicopter ACT/FHS.
- The combination of the highway-in-the-sky display with haptic cues on an active side stick could further increase flight path accuracy and lower the pilot’s control activity.
- For assistance during the landing phase of a PAV flight a landing place assessment tool is suggested that detects suitable landing areas from visual data.
- Automatic collision avoidance is beneficial for increased safety in PAV operation. Especially when the autonomy of the individual aircraft increases, this capability and independency from ground stations becomes essential.
- In simulations crowd-inspired navigation algorithms have shown to be capable of managing typical PAV commuting scenarios with hundreds of vehicles. These algorithms could successfully be demonstrated in flight test with several UAVs and are expected to be transferrable to autonomous PAV flights.

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Appendix

Power Requirement for a Reference PAV Flight

1 Objective

During the internal myCopter workshop in May 2011, reference missions have been introduced for typical use of a commuter PAV. This document gives an estimation of the power requirements and power consumption necessary for one such reference mission.

One must be aware that the following preliminary design considers only one possible design solution out of many. The calculations are based on basic helicopter theories but as well on statistics, empirical values, and experience. Therefore, the results are affected by uncertainties and can only be seen as reference for the chosen case and not as final design values.

2 Nomenclature

A	disk area, m^2	P_0	profile power, W
a	speed of sound, m/s	P_i	induced power, W
b_{body}	width of body, m	P_p	parasite power, W
C_{d0}	profile drag coefficient	R	rotor radius, m
C_{dp}	parasite drag coefficient	T	thrust, N
C_T	thrust coefficient	ΔT_{duct}	thrust increase due to ducting, %
C_{ref}	power consumption, Ws	t	time, s
c	chord, m	V	velocity, m/s
d	distance, m	κ_W	wake contraction
f_d	equivalent drag area, m^2	λ	inflow ratio
g	gravity, kg/m^3	μ	tip speed ratio
h	height, m	ρ	air density, kg/m^3
h_{body}	height of body, m	σ	solidity of rotor
m	mass, kg	ΩR	rotor tip velocity, m/s
n_b	number of blades		
n_r	number of rotors		
P	power, W	PAV	personal aerial vehicle

3 Preliminary Design

Regarding the design of a reference myCopter PAV only few parameters have been agreed on so far. In order to deduct further necessary parameters, a short preliminary design study is conducted.

The maximum take of weight is set to m = 450 kg in accordance to the outcome of the internal workshop. The necessary rotor disk area A can be determined from the maximum disk loading m/A. Disk loading should not exceed 48.82 kg/m^2 (=10lb/sft). Otherwise the induced velocities under the rotor are very high and can endanger personnel on ground [1]. Minimal disk area is therefore:

$$A_{\min} = \frac{m}{48.82\frac{\text{kg}}{\text{m}^2}} = 9.22\text{m}^2 \quad \textbf{(Eqn 1)}$$

This area can be achieved with a combination of several rotors contributing $A = \pi R^2$ per rotor. In order to keep each rotor small, a total number of $n_r = 4$ rotors is chosen. This leads to a minimal rotor radius of:

$$R_{\min} = \sqrt{\frac{A_{\min}}{n_r \pi}} = 0.856\text{m} \quad \textbf{(Eqn 2)}$$

Choosing a radius of $R = 0.86\text{m}$ leads to a disk area of $A = n_r \pi \text{R}^2 = 9.29\text{m}^2$.

The rotor tip velocity should not exceed 0.65 Ma in hover in order to avoid compressibility effects [2]. Under standard atmosphere at sea level with a speed of sound of $a_0 = 340.29\,\frac{\text{m}}{\text{s}}$ this is equivalent to a maximum tip speed of

$$\Omega R_{\max} = 0.65\text{Ma} = 0.65 a_0 = 221.19\,\frac{\text{m}}{\text{s}} \quad \textbf{(Eqn 3)}$$

The minimum speed is limited by the tip speed ratio $\mu = V / \Omega R$ that must not exceed $\mu_{\max} = 0.5$ to avoid retreating blade stall [1]. A cruising speed of maximal $V = 200\,\frac{\text{km}}{\text{h}}$ had been agreed on. Converted to m/s this leads to the minimum tip speed

$$\Omega R_{\min} = \frac{V}{\mu_{\max}} = 111.11\,\frac{\text{m}}{\text{s}} \quad \textbf{(Eqn 4)}$$

Finally, a speed within this range of $\Omega R = 200\,\frac{\text{m}}{\text{s}}$ is selected.

To further develop the rotors, chord and number of blades have to be selected. The aspect ratio R/c should lie within the range of 8 to 24. A lower ratio produces high tip losses while a higher ratio can lead to blade bending and twisting [1]. In order to allow a wide chord, the aspect ratio is set to 8. Blade chords chosen too thin go along with low Reynolds numbers which are associated with penalties [1]. The chord then results in:

$$c = \frac{R}{8} = 0.11\text{m} \quad \textbf{(Eqn 5)}$$

In order to prevent stall, the specific blade loading C_T / σ should be below 0.12 [3]. The thrust coefficient is defined as:

$$C_T = \frac{T}{\rho A (\Omega R)^2} \quad \textbf{(Eqn 6)}$$

where the thrust T must compensate for the vehicle's weight under hover condition:

$$T_{hover} = m \cdot g \quad \textbf{(Eqn 7)}$$

With $g = 9.81\frac{m}{s^2}$ as gravity and $\rho_0 = 1.225\frac{kg}{m^3}$ as density of air under standard atmosphere at sea level the thrust coefficient is $C_T = 0.0097$. The solidity σ defines the ratio of blade area to disk area:

$$\sigma = \frac{n_b c}{\pi R} \qquad \textbf{(Eqn 8)}$$

With (Eqn 6) to (Eqn 8) and the above requirement $C_T / \sigma < 0.12$ the number of blades can be defined:

$$n_b = \sigma \frac{\pi R}{c} > \frac{C_T}{0.12} \cdot \frac{\pi R}{c} = 2.03 \qquad \textbf{(Eqn 9)}$$

The blade number is then set to $n_b = 3$ and the resulting solidity is $\sigma = 0.12$.

For the later calculation of the profile drag the profile drag coefficient will be needed. Looking at typically used blade profiles, this coefficient lies between 0.008 and 0.010 [2]. An average value of $C_{d0} = 0.009$ is chosen for the preliminary design.

The calculation of parasite drag requires knowledge about the equivalent drag area in forward flight. The area is defined as

$$f_d = C_{dp} \cdot b_{body} \cdot h_{body} \qquad \textbf{(Eqn 10)}$$

where the aerodynamically relevant width and height of the aircraft are estimated to be $b_{body} = h_{body} = 1.2\text{m}$. Layton [2] gives generic data for the estimation of the drag coefficient C_{dp}. For a utility aircraft below 4540 kg (10000 lbs) the given value is $C_{dp} = 0.295$. This leads to an equivalent drag area of $f_d = 0.42\text{m}^2$.

To account for the effects of ducted rotors, the behaviour of the wake below the rotor has to be examined. The available thrust depends on the wake contraction κ_W which is defined by the ratio of wake area above the rotor to wake area below the rotor. $\kappa_W = 0.5$ describes the typical wake contraction of an isolated rotor. When the ducted rotor contracts the wake lesser with $\kappa_W > 0.5$, then the induced power is lower compared to an isolated rotor [3]:

$$P_{i\_ducted} = \frac{P_{i\_isolated}}{\sqrt{2\kappa_W}} \qquad \textbf{(Eqn 11)}$$

Myers et al. [4], Martin & Tung [5], and Akturk & Camci [6] have conducted experiments on the hovering thrust of single and tandem ducted rotors compared to isolated rotors. They found average thrust increases of up to 24% or 38% for different single ducted rotors and up to 35% for the ducted tandem configuration. For the reference PAV a well designed duct with a thrust increase of $\Delta T_{duct} = 38\%$ is assumed. Then the power required when keeping the thrust constant would decrease by $P_{i\_ducted} = (100/138)P_{i\_isolated} = 0.7246 P_{i\_isolated}$ for such rotors. Inserting the experimental results into (Eqn 11) leads to a theoretical wake contraction of $\kappa_W = \frac{1}{2}(P_{i\_isolated} / P_{i\_ducted})^2 = 0.95$.

The outcome of the preliminary design study is summarized in Table 1.

Table 1: Reference PAV parameters

parameter	value	description
m	450 kg	maximum take-off weight
n_r	4	number of main rotors
R	0.86 m	rotor radius
A	9.29 m^2	rotor disk area
n_b	3	number of blades
c	0.11 m	blade chord
σ	0.12	solidity
ΩR	200 m/s	rotor tip velocity
C_{d0}	0.009	profile drag coefficient
f_d	0.42 m^2	equivalent drag area
κ_W	0.95	wake contraction due to ducting

4 Reference Flight

The reference flight consists of a vertical climb up to cruising height, a cruising flight, and a vertical descent. A flight distance of 30 km is selected. As agreed on during the workshop, the cruising altitude is set to 500 m above ground level and the average cruising speed to 48.61 m/s (175 km/h). The velocities of climb and descent are set to 5 m/s and -5 m/s respectively. The flight data and the air density at sea level and at cruising height (assuming a starting point near sea level) are listed in Table 2.

Table 2: Reference flight parameters

parameter	value	description
d	30 km	distance
h	500 m	cruising altitude
V_{cruise}	48.61 m/s	cruising velocity
V_{climb}	5 m/s	climb rate
V_{des}	-5 m/s	descent rate
ρ_0	1.225 kg/m^3	standard air density at sea level
ρ_{500}	1.167 kg/m^3	standard air density at h = 500 m

5 Power requirement in hover

The following formulas are derived from [3].

The power required in hover consists of the induced power and the profile power:

$$P_{hover} = P_{i\_hover} + P_{0\_hover} \quad \textbf{(Eqn 12)}$$

The induced power is calculated by:

$$P_{i\_hover} = \sqrt{\frac{T_{hover}^3}{2\rho A}} \cdot \frac{1}{\sqrt{2\kappa_W}} \quad \textbf{(Eqn 13)}$$

The first term is the induced power for an isolated rotor and the term containing κ_W accounts for the lesser contracted wake due to the ducting as seen in (Eqn 11). Using the design parameters and the thrust from (Eqn 7), the induced power at sea level with ρ_0 results in $P_{i\_hover\_0m} = 44.59\text{kW}$. At cruising altitude with air density ρ_{500} the induced power is $P_{i\_hover\_500m} = 45.68\text{kW}$.

The profile power in hover depends on the profile power coefficient:

$$P_{0\_hover} = \frac{\rho \cdot A \cdot (\Omega R)^3 C_{d0} \sigma}{8} \quad \textbf{(Eqn 14)}$$

At sea level this results in $P_{0\_hover\_0m} = 12.52\text{kW}$ and at cruising altitude $P_{0\_hover\_500m} = 11.93\text{kW}$ respectively.

Thus, the total hovering power is $P_{hover\_0m} = 57.12\text{kW}$ at 0 m and $P_{hover\_500m} = 57.61\text{kW}$ at 500 m.

6 Power requirement for reference flight

6.1 Cruising Flight

During the cruising flight the power required is composed by the induced power, the profile power, and the additional parasite power:

$$P_{cruise} = P_{i\_cruise} + P_{0\_cruise} + P_{p\_cruise} \quad \textbf{(Eqn 15)}$$

The induced power is calculated similar to the hover case but in dependency of the cruising velocity:

$$P_{i\_cruise} = \frac{T^2}{2\rho A V_{cruise}} \cdot \frac{1}{\sqrt{2\kappa_W}} \quad \textbf{(Eqn 16)}$$

For small angles of attack the thrust is of the same magnitude as the weight so the hovering thrust from (Eqn 7) can be used again. The induced power for cruising flight is $P_{i\_cruise} = 13.41\text{kW}$.

The profile power in forward flight is dependent on the flight velocity as well:

$$P_{0\_cruise} = \frac{\rho \cdot A \cdot (\Omega R)^3 C_{d0} \sigma}{8} \left(1 + 3\frac{V_{cruise}^2}{(\Omega R)^2}\right) \quad \textbf{(Eqn 17)}$$

Thus, leading to $P_{0\_cruise} = 14.04\text{kW}$. Finally, the parasite power is calculated by:

$$P_{p\_cruise} = \frac{\rho V_{cruise}^3 f_d}{2} \quad \textbf{(Eqn 18)}$$

Inserting the design parameters, gives a parasite power of $P_{p\_cruise} = 28.16\text{kW}$. The sum of above power requirements gives the total power required for cruising flight: $P_{cruise} = 55.60\text{kW}$.

6.2 Vertical Climb

In vertical flight the parasite power can be neglected due to low flight speeds. Thus, the requirement for vertical climb is composed by:

$$P_{climb} = P_{i\_climb} + P_{0\_climb} \quad \textbf{(Eqn 19)}$$

where the profile power is the same like in hover. The climb takes place in heights between 0 and 500 m. As simplification the power requirement at 500 m is taken for the calculation: $P_{0\_climb} = P_{o\_hover\_500m} = 11.93\text{kW}$.

The induced power in vertical climb can be calculated from the induced power in hover:

$$P_{i\_climb} = P_{i\_hover}\left(\frac{\lambda_{climb}}{2\lambda_h} + \sqrt{\left(\frac{\lambda_{climb}}{2\lambda_h}\right)^2 + 1}\right) \quad \textbf{(Eqn 20)}$$

The inflow ratio in climb is the ratio of climb speed to tip speed: $\lambda_{climb} = V_{climb}/(\Omega R)$ and the inflow ratio in hover can be calculated from $\lambda_h = \sqrt{T/(2\rho A)}/(\Omega R)$. Inserting the design and flight parameters and the air density at 500 m leads to an induced power of $P_{i\_climb} = 54.62\text{kW}$. The total power required for the climbing flight is then: $P_{climb} = 66.54\text{kW}$.

6.3 Vertical Descent

In vertical descent only the induced power changes in comparison to the climbing flight. The induced power for slow descent can be approximated by:

$$P_{i\_climb} = P_{i\_hover}\left(1 - 0.25\frac{\lambda_{des}}{2\lambda_h} - 5.308\left(\frac{\lambda_{des}}{2\lambda_h}\right)^2 - 13.745\left(\frac{\lambda_{des}}{2\lambda_h}\right)^3 - 10.48\left(\frac{\lambda_{des}}{2\lambda_h}\right)^4\right)$$

(Eqn 21)

With the inflow ratio in vertical descent $\lambda_{des} = V_{des}/(\Omega R)$ above formula leads to an induced power of $P_{i\_des} = 39.43\text{kW}$. Adding the hovering profile power like above for the climbing flight, the total power is $P_{des} = 51.35\text{kW}$.

7 Energy consumption

The energy consumption for the reference flight can be calculated from the power requirements and the duration of the flight periods:

$$C_{ref} = P_{climb}t_{climb} + P_{cruise}t_{cruise} + P_{des}t_{des} \quad \textbf{(Eqn 22)}$$

The relevant durations are calculated from velocity and distance: $t_{climb} = h/V_{climb} = 100\text{s}$, $t_{cruise} = d/V_{cruise} = 617\text{s}$, and $t_{des} = -h/V_{des} = 100\text{s}$. With the power requirements calculated in paragraph 6 this leads to a reference power consumption of $C_{ref} = 4.61 \cdot 10^7\,\text{Ws} = 12.81\text{kWh}$.

8 Sensitivity

The above results for power requirement and energy consumption are only reference values for the chosen design parameters. Assuming a different design or slightly other flight data would change the power requirements.

Table 3 gives a summary of a short sensitivity analysis. Several design parameters have been changed by ±10 % (or ±1 for natural numbers) and the resulting changes in power requirement and consumption are listed in percent. One can see that especially the aerodynamic relevant body width and height, the number of blades, the rotor tip velocity, and the mass have a major influence on the consumption. Whereas the other design parameters have minor influence.

Table 3: Sensitivity analysis

parameter		power and consumption changes in %					
		$P_{hover\ 0m}$	$P_{hover\ 500m}$	P_{cruise}	P_{climb}	P_{des}	C_{ref}
b_{body}, h_{body}	+10%	0,00	0,00	10,76	0,00	0,00	8,02
b_{body}, h_{body}	-10%	0,00	0,00	-9,73	0,00	0,00	-7,25
n_b	+1	7,18	6,78	8,23	5,89	7,57	7,82
n_b	-1	-7,18	-6,78	-8,23	-5,89	-7,57	-7,82
ΩR	+10%	7,13	6,73	7,31	5,85	7,52	7,12
ΩR	-10%	-5,84	-5,51	-6,05	-4,79	-6,15	-5,88
m	+10%	12,06	12,24	5,06	11,89	12,27	6,84
m	-10%	-11,47	-11,64	-4,58	-11,38	-11,56	-6,33
C_{dp}	+10%	0,00	0,00	5,12	0,00	0,00	3,82
C_{dp}	-10%	0,00	0,00	-5,12	0,00	0,00	-3,82
n_r	+1	6,75	7,24	1,86	6,14	7,62	3,12
n_r	-1	-2,90	-3,32	1,35	-2,76	-2,99	0,28
c	+10%	2,15	2,03	2,47	1,77	2,27	2,35
c	-10%	-2,15	-2,03	-2,47	-1,77	-2,27	-2,35
C_{d0}	+10%	2,15	2,03	2,47	1,77	2,27	2,35
C_{d0}	-10%	-2,15	-2,03	-2,47	-1,77	-2,27	-2,35
R	+10%	-2,61	-2,97	1,00	-2,47	-2,72	0,09
R	-10%	4,62	4,99	0,96	4,22	5,18	1,90
ΔT_{duct}	+10%	-2,10	-2,13	-0,65	-2,21	-2,07	-1,03
ΔT_{duct}	-10%	2,22	2,26	0,68	2,33	2,19	1,09

9 References

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