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Evaluation of landing procedures for a high-altitude platform with skid-type landing gear based on pilot-in-the-loop simulations

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Abstract
In the context of the project *HAP*, the German Aerospace Center (DLR) is currently developing a solar-powered high-altitude platform. The underlying vehicle is a fixed-wing aircraft that is supposed to be stationed in the stratosphere for 30 days. Due to, among others, low achievable rates of descent, the use of skids as landing gear and its high susceptibility to wind, landing this aircraft is a very challenging task. Hence, it requires a landing procedure specifically tailored to the aircraft's particularities. Furthermore, this procedure needs to be easy to follow by pilots especially in adverse atmospheric conditions. This paper deals with a pilot-in-the-loop simulation campaign conducted to assess a landing procedure developed for the high-altitude platform in earlier works. Within this campaign, the pilots are supposed to land the aircraft following this developed procedure in atmospheric turbulence conditions. In addition, they also land the aircraft following a second procedure, which is based on a conventional landing. In doing so, the altitude at which a flare is performed and/or the propellers are shut down is varied. Finally, the novel procedure's overall feasibility from a piloting point of view and its potential to reduce the risks during landing are assessed. The results show that the procedure proves to reduce the risk of inadvertent ground contact of the aircraft payload compartment, which is associated with serious damage to aircraft structure and payload. However, since the novel procedure is challenging for the pilots, some improvements to the procedure are proposed.

Keywords High-altitude platform · Flight mechanics · Pilot-in-the-loop simulations · Landing procedures · Skid-type landing gear · Desktop simulator

List of symbols

x, y, z	Coordinates
c_1, c_2	Spring constants
d	Damper constant
h	Altitude
i_H	Stabiliser deflection
N	Number of samples
N_{Prop}	Propeller RPM
L	Scale length
m	Aircraft mass
R	Skid force
V_{TAS}	True airspeed

Abbreviations

6DOF	Six-degrees-of-freedom
CG	Centre of gravity
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
HAP	High-altitude platform
LAPL(A)	Light aircraft pilot licence (aeroplane)
LWG	Left wing gear
MG	Main gear
HTP	Horizontal tailplane
VTP	Vertical tailplane
PC	Payload compartment
PIO	Pilot-induced oscillations
PPL	Private pilot licence
RPM	Revolutions per minute
RWG	Right wing gear
SPL	Sailplane pilot licence/sport pilot licence
TG	Tail gear
UDP	User datagram protocol
USB	Universal serial bus

Greek symbols

Φ, Θ, Ψ	Euler angles
μ, μ_S	Kinetic friction coefficients
ξ	Aileron deflection

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ζ	Rudder deflection
σ	Standard deviation
χ	Track angle

Indices

AGL	Above ground level
b	Body-fixed coordinate system
max	Maximum value
min	Minimum value
RWY	Runway
TD	Touchdown
W	Value for wind

1 Introduction

In recent years, the research on so-called high-altitude platforms (HAPs, *sg*. HAP) has increased significantly [1–4] with many prominent examples of aircraft that have already performed successful flights [5–7]. HAPs are air vehicles designed to operate at high altitudes for a relatively long time. In principle, HAPs can stay airborne permanently. In practice, the operation for several weeks has already been demonstrated [8, 9]. This prolonged operating time, together with the high operation altitude, makes HAPs suitable candidates for typical satellite applications. These applications include general Earth observation missions [10] and telecommunications [11]. Compared to satellites, HAPs have the advantages of a higher flexibility in use since they are not dependent on their orbit. In addition, their lower altitude brings benefits with respect to image resolution.

The German Aerospace Center (DLR) is currently developing a HAP system in the context of the DLR-internal project *HAP*. The HAP system includes the aircraft itself, the flight control system and the full operational concept, the ground segment, the flight termination system and two interchangeable instruments as payload with a mass of up to 5 kg. The aircraft is designated to perform Earth observation missions carrying either a high-definition camera or a synthetic aperture radar. The aircraft development process is currently in the detail design phase. Within the further project term, the manufacturing, a comprehensive flight test campaign and a final high-altitude mission demonstration using the instruments will follow. The primary aim of the DLR project *HAP* is to obtain, generate and publish knowledge about such aircraft rather than to compete with existing HAP aircraft developed by industrial companies.

The high operating time and altitude of HAP aircraft bring challenging demands with respect to the design and operation of solar-powered HAPs. The flight needs to be as efficient as possible due to the limited availability of solar power and battery storage capacity. For fixed-wing HAPs, this leads to the need for a very high aerodynamic efficiency, low structural weight and extremely low operating airspeeds. As a consequence, HAP aircraft are very susceptible to wind perturbations, especially in ground proximity and have limited control authority. In addition, due to the need for a very low aircraft weight, air brakes are usually excluded. Together with the aircraft's high glide ratio, the achievable stable rates of descent are low. In addition, the aircraft is equipped with small non-retractable skids used as landing gear. Its propellers need to be shut down and set parallel to the wing leading edge at a certain altitude above ground due to the lack of ground clearance, which impedes the possibility of a go-around after that point during landing. Furthermore, it has a very narrow allowable pitch band to touch down. Altogether, landing the aircraft is a very challenging task.

In recent works, a landing procedure has been developed for the DLR HAP aircraft which subdivides the landing until touchdown into different phases [12]. This procedure has multiple aims. First, it provides a stabilisation altitude at which the decision of performing a go-around or to land can be safely made. Second, it separates different tasks, e.g. energy management and maintaining a certain pitch angle, into different phases in order to not overburden the pilot. Third, it allows more focus on the moment of touchdown. In Ref. [12], a very high number of simulations were performed following this procedure to position the main skid and to estimate the potential of the procedure to reduce the risk of aircraft damages during landing. In these prior works, a flight controller has been used that generated the control inputs. However, at the beginning of the flight test campaign, the aircraft will be piloted remotely. Different controller loops will be activated gradually as soon as more information about the aircraft's flight physics is available and the underlying models are validated. Hence, it must be ensured that the aircraft can be landed remotely. Therefore, it needs to be investigated whether the procedure can easily be followed by pilots likewise, especially in adverse wind conditions. For instance, varying lateral wind, even of small magnitude, is critical during the final phase of landing as it impedes the already difficult task of aligning the aircraft with the runway.

This paper deals with the landing of such type of aircraft. It investigates whether novel landing procedures have the potential of increasing the safety during landing compared to conventional landing procedures. Furthermore, it deals with the question whether such a novel landing procedure can be easily followed by pilots who remotely control the aircraft and whether this procedure can be improved in this regard. For this purpose, a pilot-in-the-loop simulation campaign using a desktop simulator is conducted. In this campaign, the pilots are supposed to perform landings in the presence of atmospheric turbulence following the described procedure and a rather conventional one. In addition, the procedures are varied in such a way that prescribed altitudes at which the pilots are supposed to, e.g. perform a flare, are varied.

2 The DLR HAP aircraft

Figure 1 provides a sketch of the HAP aircraft, designed by DLR within the last years. It is an extremely lightweight aircraft with high aspect ratio and dihedral of 12° in the outer wing sections. It is capable of carrying payload of up to 5 kg in the payload compartment which is located inside the aircraft nose. The aircraft is equipped with two propeller engines and it generates control moments using two ailerons, an all moving horizontal stabiliser and a rudder. The aircraft has a total mass of around 140 kg, a wing span of roughly 30 m and a wing area of about 40 m^2.

Due to its comparatively high weight, the DLR aircraft is too heavy to be launched and collected by hand. For take-off, a launch vehicle is used. However, for landing, a landing gear is required. Since a retractable gear would lead to an excessive weight penalty, small non-retractable skids are used instead, which cause only little additional drag but bring some risks with respect to the landing, e.g. concerning possible rollovers and the allowable pitch band at touchdown. Figure 2 shows the top view of the aircraft and depicts all relevant points with respect to landing. The blue dot represents the centre of gravity (CG), which is somewhat aft of the wing quarter chord line. The green dot represents the lowest point of the payload compartment (PC), which could make ground contact in case of an unsuccessful landing. The red dots represent the positions of the four skids. The tail skid (denoted TG for tail gear) is positioned below the horizontal tailplane (HTP) quarter chord line and the centreline of the fuselage. The left wing skid (LWG) and right wing skid (RWG) are placed below the kinks of the wing and are dimensioned such that they just make ground contact if the aircraft is in standstill and on ground. The position of the main skid (MG) was determined based on a multitude of simulations in recent works [12]. Herein, a position of 40 cm forward of the CG was found to offer the best compromise between payload compartment ground contact risk and bending loads.

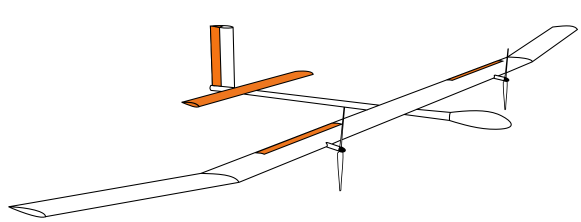


Fig. 1 Sketch of the DLR HAP aircraft [13]

In addition, Fig. 3 shows a side view of the DLR HAP aircraft and provides a conceptual sketch of the skid relations. While the payload compartment contains the very sensitive payload, being a radar or a camera, it must never make ground contact because this would very likely result in structural damage with a high possibility of a loss of the instruments. This is a hard limit. In addition, the main skid is supposed to touch down first, because for very large landing shocks the tail gear structure might not be able to withstand it. However, this is rather a soft limit. Hence, during touchdown, the aircraft must remain within a very small allowable pitch band. Moreover, during the final slideout, the aircraft must not fall below the lower pitch limit. The limits for the current HAP configuration are

- *Minimum allowable pitch angle* $\Theta_{\mathrm{TD,min}} \approx -2.5°$
- *Maximum allowable pitch angle* $\Theta_{\mathrm{TD,max}} \approx 0.8°$

Furthermore, the propellers need to be shut down and brought into a position parallel to the wing's leading edge at a certain minimum altitude before touchdown due to the lack of ground clearance. This impedes the possibility of a go-around after this point. To sum it up, landing the DLR HAP aircraft is a very demanding task that needs thorough

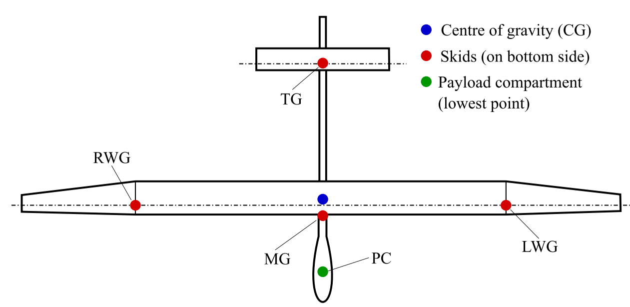


Fig. 2 Top view of the HAP aircraft and the four skid positions; main skid (MG), tail skid (TG), left wing skid (LWG) and right wing skid (RWG), based on Ref. [12]. The payload compartment stores sensitive instruments and must, therefore, not make ground contact during a landing. Its lowest point thus defines the minimum allowable pitch angle during touchdown and has an influence on the difficulty of the landing task

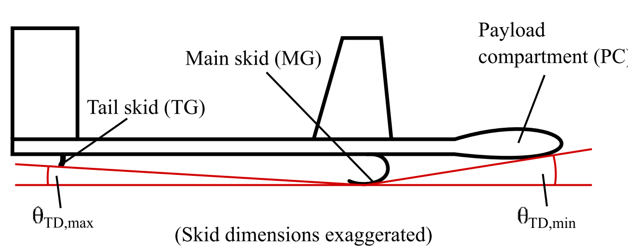


Fig. 3 Side view of HAP aircraft and approximate allowable pitch angles at touchdown, based on Ref. [12]

Fig. 4 Simulator environment

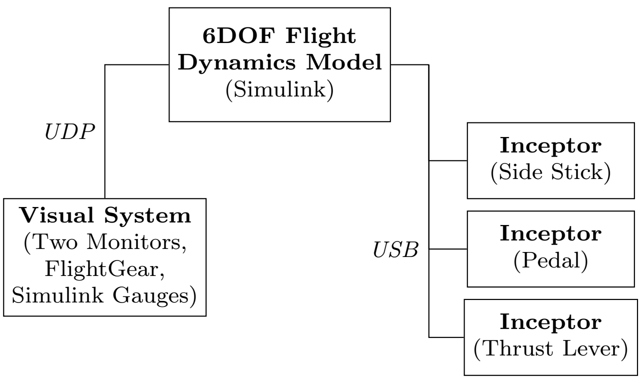


Fig. 5 Sketch of the desktop simulator environment

prior investigation and a dedicated landing procedure that copes with the HAP-specific flight mechanic characteristics.

3 Simulator environment

This section describes the environment of the simulator used for this study. The simulator used is a desktop simulator with a rather simple infrastructure. It is intended to be used to generate knowledge and to evaluate, challenge and improve aircraft design decisions, operational concepts and flight procedures, rather than to prepare the pilots for the real flight. Therefore, elements that help to make the circumstances alone as realistic as possible compared to real flight only play a minor role. Instead, the focus is on the flight physics, hence the aircraft behaviour and its handling. Therefore, significant effort has been put into modelling the HAP aircraft's flight dynamic characteristics, while other elements like a sound system are simply omitted.

Figure 4 provides a photograph of the vision system. In addition, Fig. 5 shows the structure of the simulator environment. It consists of a 6-degrees-of-freedom (6DOF) flight dynamics model, which is implemented using MATLAB®/Simulink®. For the vision the visual system provided by the open-source simulator *FlightGear Flight Simulator* [14] is used and displayed on a single monitor. In addition, instruments are displayed on a second monitor. For pilot inputs, three inceptors are used. These include a side-stick, located at the pilot's right hand side, which is used to generate roll and pitch commands, a pedal used to generate yaw commands and a thrust lever, which is located to the pilot's left hand side. No differential thrust is provided and both thrust levers need to be controlled together. In order to shut off the engines and to set the propellers parallel to the wing leading edge, which is required before touchdown, the thrust levers must be set to the most rearward position, slightly be pulled and then be moved further backwards. All inceptors do not provide hinge moment-dependent force feedback.

3.1 Flight dynamics model

The flight dynamics model forms the core of the simulator environment. It has been continuously enhanced during the different design stages of the project *HAP* [13, 15]. It includes geometry, aerodynamic, structural, and aeroelastic data provided by the complete flight physics team in the project. Even though, a model including the structural dynamics has been developed within the project *HAP*, for this study a 6-degrees-of-freedom (6DOF) model is used for consistency with the analyses performed in Ref. [12]. In order to account for flexibility, a dynamic pressure-dependent quasi-static approach is used. Herein, sets of aerodynamic derivatives are given for four characteristic equivalent airspeeds. For intermediate airspeeds, interpolation is performed [13].

The flight dynamics model includes a three-point aerodynamic model, signifying that the aerodynamic forces and moments are calculated for the HTP, the vertical tailplane (VTP) and the wing-fuselage section independently. Lag effects for downwash and wind are included and main wing stall and VTP stall are modelled [15]. A ground effect model is included that accounts only for effects in longitudinal direction, i.e. pitching moment, lift and drag [12].

3.1.1 Skids

The skids are modelled with standard linear solids as shown in Fig. 6. More information about the used skid modelling approach can be found in Ref. [12].

All skids are modelled using the same viscoelastic properties. For the spring constants c_1 and c_2 a value of 40,000 N/m is assumed, which represents very soft skids. For the damper constant, a value of 500 Ns/m is used, which was adjusted manually, such that a seemingly realistic

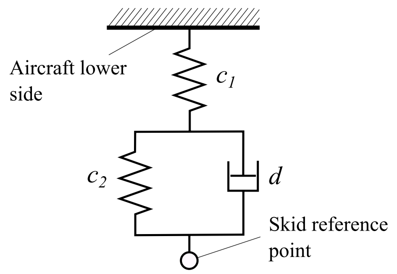


Fig. 6 Skid modelled as standard linear solid in Kelvin–Voigt representation [12]

touchdown behaviour is obtained. In Ref. [12], it could be shown that this approach yields skid force results that agree fairly well with those obtained with a dynamic aeroelasticity simulation for the touchdown.

For the kinetic friction coefficient, a value of $\mu = 0.4$ is used, derived as an average value from measurements for metal skids on a dry lakebed [16–18]. Experiments made within the project *HAP* showed that this value also agrees well with the friction coefficient of metal skids on grass. Note that in this study landings on a runway were performed, which would yield smaller friction coefficients. However, for the flight test campaign it is also conceivable to land on unfortified ground like grass in order to perform a landing into the wind direction. While the slideout distance is small in both cases, the higher friction coefficient increases the risk of a rollover and a payload compartment ground contact. For this reason, the more conservative value of $\mu = 0.4$ is used here. For the lateral kinetic friction coefficient a somewhat higher value of $\mu_S = 0.55$ is assumed. Note that this is a very simplified approach to account for the form of the skids, which have better slide properties in longitudinal direction than in lateral direction.

3.1.2 Turbulence model

Continuous turbulence is modelled for the translational wind components as proposed in Ref. [19]. In doing so, white noise is passed through forming filters such that approximate Von Kármán velocity spectra are obtained. These forming filters require scale lengths L and velocity standard deviations σ for all three axes. These values are obtained based on Ref. [20], which provides data for altitudes above ground under 1 km only for severe turbulence [20, Table 2.70] and for light, moderate and severe turbulence for an altitude range of 1–200 km [20, Table 2.71]. The scale lengths are taken from both tables. In the case of the velocity standard deviations, these are not available for light turbulence at very low altitudes. Therefore, these are obtained by extrapolating the light turbulence values at 1 km to lower altitudes based on the gradients for severe turbulence at low altitudes. The resulting values then yield the light turbulence parameters for the works presented here. For moderate turbulence, these values are doubled. Note that, consequently, the resulting parameters for the standard deviations and scale lengths and thus the turbulence strength definitions for "light" and "moderate" derived in this work deviate from those provided by the CS-AWO [21]. Table 1 shows these parameters. At simulation startup, the white noise seed is varied at random to ensure that the wind profile changes for each run.

3.2 Vision system

The vision system consists of the *FlightGear* vision and virtual instruments, each displayed on different monitors (compare Fig. 4). The monitor showing the instruments is located somewhat below the monitor showing the aircraft.

Since it is not the purpose of these works to prepare the pilots for the real flight, for these pilot-in-the-loop simulations, the instruments are simply gathered on a single page as shown in Fig. 4. It is probable that the landing task becomes easier from a piloting point of view if the instruments are arranged in a more convenient way. The instrument panel includes both gauges and numeric value displays for equivalent airspeed, bank angle, altitude, vertical speed, angle of sideslip, thrust and pitch. In addition, altitude above ground, heading and track are provided by numeric value displays. It should be noted during a real flight, the pilot does not have access to altitude above ground information due to the lack of a radar altimeter. Instead, he might get the information

Table 1 Standard deviations and scale lengths used within this work to model turbulence

Range	Light turbulence			Moderate turbulence			Scale length		
h_{AGL} (m)	σ_u (m/s)	σ_v (m/s)	σ_w (m/s)	σ_u (m/s)	σ_v (m/s)	σ_w (m/s)	L_u (m)	L_v (m)	L_w (m)
0–10	0.129	0.093	0.065	0.259	0.187	0.129	21	11	5
10–20	0.144	0.111	0.082	0.289	0.222	0.164	33	19	11
20–30	0.154	0.123	0.096	0.308	0.246	0.192	43	28	17
30–40	0.167	0.139	0.115	0.322	0.264	0.212	52	35	23
40–50	0.172	0.146	0.123	0.334	0.279	0.230	61	42	29
50–60	0.176	0.152	0.130	0.344	0.292	0.246	68	49	35

The definitions for "light" and "moderate" turbulence differ from those provided by the CS-AWO [21] verbally from a second pilot who will be positioned besides the runway.

3.3 Latency measurements

As described in detail in Ref. [15], latency measurements have been performed with the present desktop simulator. Latencies are around 300 ms for the displayed instruments and around 200 ms for the view. These values are of a similar size as the maximum allowable latency values for the flight test as defined in the project *HAP*. Therefore, it can be concluded that the most relevant latency-induced effects with respect to flight safety like, e.g. pilot-induced oscillations (PIO) can be reproduced.

4 Test program and execution

This section presents the test program and the general approach followed during the execution of the tests.

4.1 Objective

As already stated, landing the HAP aircraft is a very challenging task due to a multitude of aircraft-specific characteristics. In recent works [12], a landing procedure has been developed that is supposed to cope with these challenges and to reduce the general risks of damages to the aircraft structure or single components or even of a complete loss of aircraft during landing. If followed appropriately, this procedure has already proven to be reliable at light turbulence conditions. In Ref. [12], a landing controller has been used to test the procedure within 1000 landing simulations. However, due to the lack of radar altimeter, the HAP aircraft needs to be landed remotely by a pilot. Therefore, it needs to be investigated whether the landing procedure can be easily followed by a pilot as well. In addition, possible improvements to the procedure and underlying parameters are supposed to be made.

4.2 Landing tasks

The procedure developed in Ref. [12] and a rather conventional landing are investigated. Both are described below. All landings are performed with an approach from base leg and always with the exact same starting point. The pilots are neither requested to land the aircraft as close to the runway centreline as possible, nor to try to minimise required runway length. Landing on any position the runway and not leaving it until standstill is considered sufficient.

4.2.1 Landing procedure 1 (tailored to HAP-specific needs)

Landing procedure 1 was developed and specifically tailored to aircraft with similar characteristics as the DLR HAP aircraft. Its main purposes are to subdivide three different piloting tasks and to integrate them into different phases of landing. These are to

1. reduce airspeed and to establish a safe pitch angle,
2. to provide a dedicated time interval before touchdown within which the decision whether to perform a go-around or to land can be made in a well-considered way and
3. to shut off the engines and to set them parallel to the wing leading edge.

The latter will henceforward be called to “retract the propeller” for the sake of simplicity. Figure 7 shows a sketch of landing procedure 1. Please note that compared to the definition in Ref. [12], the final slideout is here also defined as a phase. Nevertheless, the procedure is identical.

Landing procedure 1 consists of four different phases. All phases take place during the final leg, while the aircraft’s track is already aligned with the runway. Thus, the procedure does not provide any specifications on the approach itself. The four phases are:

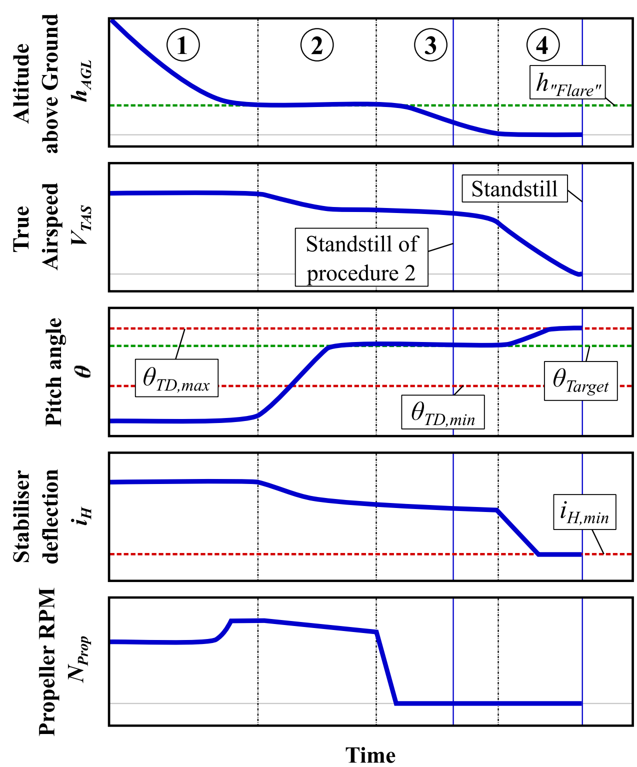


Fig. 7 Landing procedure 1

1. *Phase 1—Descent and capture of* $h_{\text{“Flare”}}$: the landing starts by a descent up to $h_{\text{“Flare”}}$. It should be noted, that the aircraft does not perform a flare in the typical sense here. It is crucial that this altitude is high enough to offer enough ground clearance that both the engines can still be used and a light gust does not directly lead to ground contact of any part of the aircraft. At the same time, it must not be too high as a go-around will not be possible anymore after descending from this altitude (see phase 3). At altitude $h_{\text{“Flare”}}$, the pilot needs to stabilise the aircraft in an unaccelerated horizontal flight. This signifies that a thrust increase becomes necessary if the prior descent was stabilised.
2. *Phase 2—Deceleration while maintaining* $h_{\text{“Flare”}}$ *and capture of target pitch attitude* Θ_{Target}: as already stated, the main skid needs to touch down first, while the payload compartment must never make ground contact. As a result, the allowable pitch band at touch down is very narrow (cf. Fig. 3). The third plot of Fig. 7, showing the pitch angle Θ, illustrates this schematically. It shows the minimum allowable pitch angle ($\Theta_{\text{TD,min}} \approx -2.5°$) at touchdown, limited by the payload compartment, and the maximum allowable pitch angle ($\Theta_{\text{TD,max}} \approx 0.8°$) at touchdown, limited by the tail skid. The target pitch angle is defined to be $\Theta_{\text{Target}} \approx 0°$. It is closer to $\Theta_{\text{TD,max}}$, because this is the less critical limit. In addition, choosing this value makes it easier for the pilots to track the target pitch angle. In this phase, the altitude $h_{\text{“Flare”}}$ is maintained while the aircraft decelerates. In doing so, the angle of attack increases along with the pitch angle, while the flight path angle is zero. As soon as the target pitch angle Θ_{Target} is reached, the flight is stabilised and continued for a couple of seconds.
3. *Phase 3—Depletion of remaining kinetic and potential energy while keeping safe pitch attitude* Θ_{Target}: this phase is initiated by retracting the propellers. Subsequently, Θ_{Target} needs to be maintained while the aircraft descends to the ground. The remaining kinetic and potential energies decrease simultaneously. This phase is critical in terms of gusts or system faults as no go-around manoeuvre can be initiated anymore.
4. *Phase 4—Pitch-up during final slideout:* as soon as the main skid touches down, the stabiliser is slightly pulled to ensure that the payload compartment does not make ground contact. The pitch-up needs to be sufficiently soft in order to prevent the aircraft from becoming airborne again or from inducing too high loads on the tail skid. At the same time, it must the strong enough to counteract the aircraft's tendency to pitch down due to the skid friction forces.

4.2.2 Landing procedure 2 (reference procedure)

Landing procedure 2 is kept as close as possible to conventional landings while not restricting the pilots more than necessary. The aim is to define a landing procedure that feels somewhat natural to the pilot. Figure 8 provides a sketch of this landing procedure.

It consists of three phases:

1. *Phase 1—Stabilised descent until* h_{Retract} *is reached* The landing starts by a descent until h_{Retract} is reached. Different from landing procedure 1, this altitude is only passed. Hence, the rate of descent needs to be maintained. If a go-around is to be initiated, this must be done before reaching h_{Retract}.
2. *Phase 2—Retraction of propellers upon reaching* h_{Retract} As soon as h_{Retract} is reached, the propellers need to be retracted. The descent is continued. Before touchdown, a flare needs to be performed, such that the target pitch angle Θ_{Target} is established as soon as the aircraft makes ground contact. The pilot is free to decide about exact altitude and type of execution of the flare. This way, it is ensured that the pilot performs it the way it feels the most natural and secure to him or her.
3. *Phase 3—Pitch-up during final slideout* Analogous to landing procedure 1, as soon as the main skid touches

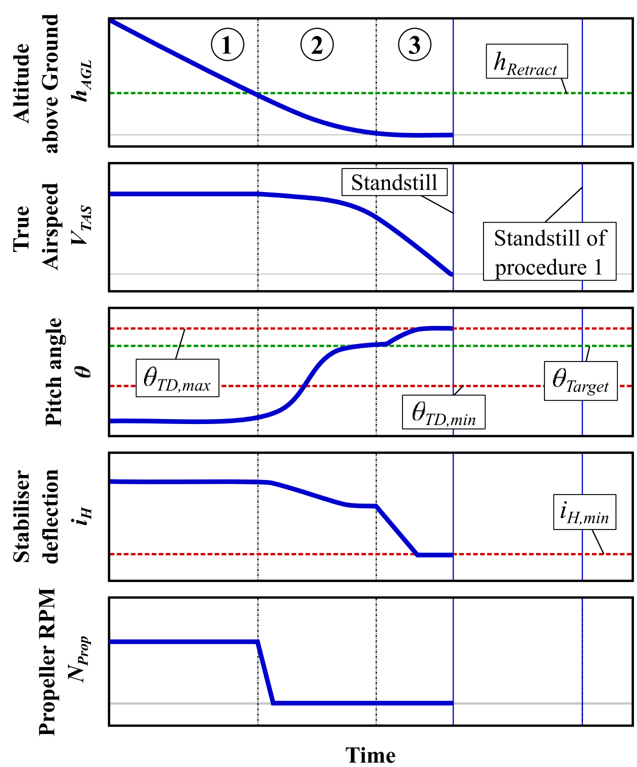


Fig. 8 Landing procedure 2

down, the stabiliser is slightly pulled to ensure that the payload compartment does not make ground contact. The pitch-up needs to be sufficiently soft in order to prevent the aircraft from becoming airborne again or from inducing too high loads on the tail skid.

For both procedures, the characteristic altitudes, being $h_{\text{“Flare”}}$ for procedure 1 and h_{Retract} is varied between 2.5 and 5.0 m within the simulator campaign.

4.3 Wind conditions

All landings are performed in the presence of continuous turbulence alone. This signifies that no constant wind, requiring the pilot to, e.g. perform crabbed approaches, is applied. Two different turbulence levels are applied, (1) light turbulence and (2) moderate turbulence. It is modelled as described in Sect. 3.1.2 and with the underlying modelling parameters as documented in Table 1. It should be noted that the notations “light” and “moderate” turbulence do not match those defined in the CS-AWO [21] regarding the magnitude of the resulting wind perturbations.

4.4 Test points and execution

In the context of the simulator campaign both landing procedures, two different characteristic altitudes (parameters of the landing procedures) and two different levels of turbulence are combined. This yields the eight test points summarised in Table 2.

Five pilots participated at the campaign, yielding five sessions. Each session took around 3 to 4 h. Every session started with a 10 min preparation phase within which the pilot was supposed to familiarise with the aircraft. Subsequently, the core of the session started. Every test point of Table 2 was performed, whenever applicable, three times consecutively and in the given order. Every landing execution is henceforward called a “run” in this paper. Landings with an approach from base leg were performed. In this connection, the starting point always remained the same and the horizontal flight time until the descent was initiated took around 3 min. The focus of this study was on the final leg and the described landing procedures. For this reason, no specifications were given to the pilots about how to perform the approach. Some pilots preferred to reach the final leg first before starting the final descent while others performed a curved descent.

This approach was chosen deliberately for multiple reasons. First, the given order of test points is in favour of landing procedure 2. The aim of this study was especially to use procedure 2 for comparison to assess and possibly improve procedure 1 and its potential to increase the safety at landing for aircraft similar to the DLR HAP. This approach thus yields more conservative results with respect to the assessment of landing procedure 1. Second, the repetitions were performed to include the learning effect both over each single test point and over the complete session. It was a major goal to estimate the potential effect training can have with respect to the pilot’s capability of following the procedures. It has to be noted, however, that this approach also has a drawback with respect to estimating the effect of the characteristic altitude on landing procedure 1 within the first round (test points 611 and 612). However, in this regard, more focus is put on the second round and the pilot’s comments. Third, the longer horizontal flight segment adds to the learning effect with respect to the HAP aircraft’s flying properties. Even though it is associated with a different level of complexity compared to the final landing segment, it trains the pilots in terms of understanding and controlling the aircraft. Furthermore, it gave the pilots a small recuperation phase before the demanding higher precision terminal flight phase started.

After each run, the pilots were supposed to assess the complexity of landing the aircraft using the prescribed procedure. This included only the final legs (as shown in Figs. 7, 8), not the approaches from base leg. They were asked to use the following grades:

1. The task was easy to execute.
2. The task had an acceptable level of complexity.
3. There were minor control issues executing the task.
4. There were major control issues executing the task.
5. The difficulty of the task was not acceptable.

In addition, during and after each run, the pilots could give feedback and make comments concerning the aircraft handling qualities and the feasibility of the task. The comments were collected and included in the analysis. Furthermore, the pilots were allowed to ask about the physical background of the aircraft’s behaviour and use the responses in order to improve their performance. For instance, due to the very small ground clearance of the aircraft, the ground

Table 2 Test points performed within the simulator campaign

Test point	Procedure	$h_{\text{“Flare”}}/h_{\text{Retract}}$ (m)	Turbulence
611	1	2.5	Light
612	1	5.0	Light
621	2	2.5	Light
622	2	5.0	Light
711	1	2.5	Moderate
712	1	5.0	Moderate
721	2	2.5	Moderate
722	2	5.0	Moderate

effect-induced pitch-up very close to ground is very strong. Two pilots realised this and asked about it. When they learned that this effect was not turbulence-induced but due to ground effect, and thus reproducible, they included this knowledge into their way of establishing the target pitch angle right before touchdown.

Figure 9 shows the distribution of the test points and also gives some insights about the number of failed landings. All pilots except one performed all test points. Due to time restrictions, the implied pilot performed test points 711, 712, 721 and 722 only twice. Altogether, 116 test points were performed by five pilots.

4.4.1 Discussion on the used rating scale

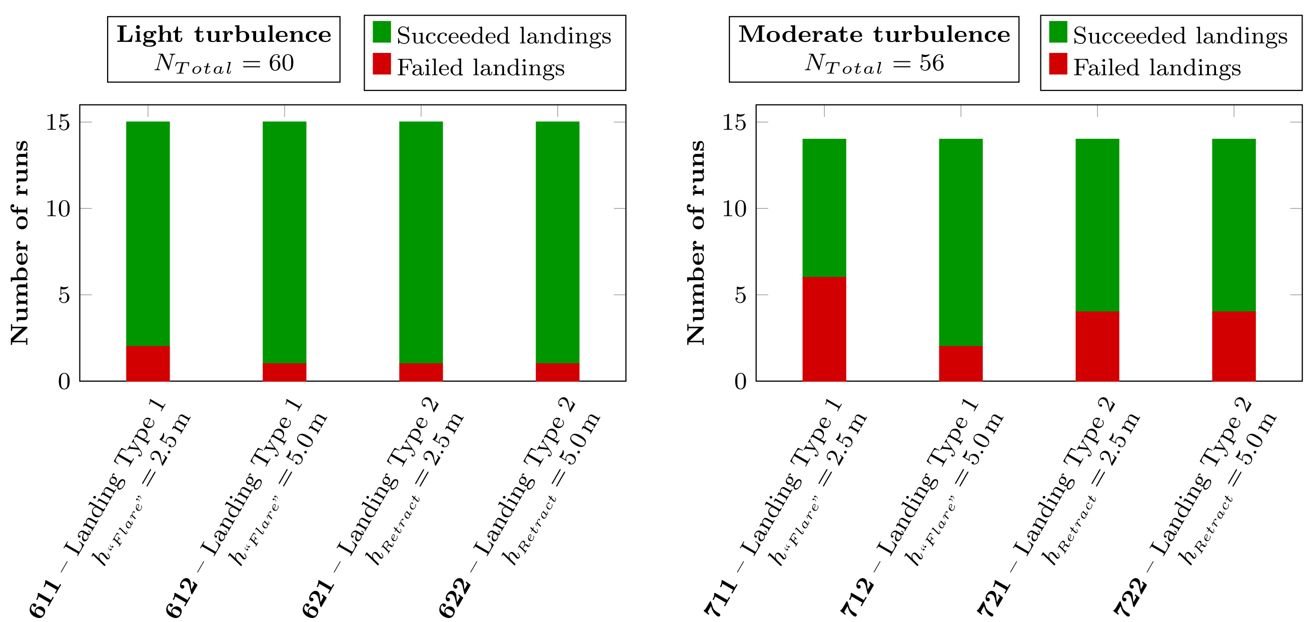
In spite of the existence of well-established evaluation scales like, e.g. the Cooper–Harper rating, Bedford workload rating scale or the NASA Task Load Index, a very simple custom rating scale was used deliberately in this work. Hereby, simplicity was sought over complexity. Not all of the pilots who participated at the campaign are familiar with the existing rating scales and therefore do not have experience in their use. In addition, in the present case the use of the established rating scales would not bring significant benefits mainly for two reasons:

1. For all landings, factual criteria about success and failure are available (for instance the fact whether the payload compartment made ground contact or not). For this reason, the examination of the time histories with respect to these criteria is the most important in order to evaluate the suitability of the landing procedures. The ratings by the pilots are merely used as an accompanying element.
2. The present aircraft has very unconventional flying qualities and the experience the pilots have with flying this aircraft differs. For this reason, an absolute assessment of the task is not possible anyway and therefore not aimed at. Instead, the trend over test points for the same pilots, respectively the relative difference of the ratings for the different procedures, is of interest to get an idea of the potential of the learning effect and the pilots' general acceptance of the task. These are also represented by the simple rating scale used in this work.

Indeed, the significance of the obtained pilot ratings is limited. For this reason, a lot more attention is put on the analysis of the time histories and the remarks pilots make after each run. Nevertheless, the rating differences between test points still provide valuable information about the learning effect, or at least the pilots' adaptation and familiarisation with the aircraft and the task, and furthermore about the pilots' preference with respect to the procedures.

4.5 Pilots

Five pilots participated in the test campaign. This section shortly specifies their backgrounds and piloting experience.



(a) Base landing test points with light turbulence

(b) Base landing test points with moderate turbulence

Fig. 9 Overall distribution of test points; altogether 116 test points were performed

- *Pilot 1* The first pilot has the light aircraft pilot licence for aeroplanes LAPL(A) since September 2015. His experience covers around 285 flight hours with single engine piston aeroplanes and about 70 h with touring motor gliders. Furthermore, he has the German sport pilot licence (SPL) for ultralight aircraft since July 2021. This pilot has participated at three HAP simulator sessions prior to this one and thus has some experience with flying the DLR HAP in the desktop simulator.
- *Pilot 2* The second pilot has been flying sail planes for 10 years and touring motor gliders for 4 years. Combining both classes the pilot has performed around 600 take-offs and landing and has accumulated approximately 350 flight hours. Furthermore, the pilot has some experience with open class sailplanes, flying an aircraft that, according to him, showed some similarities with the DLR HAP aircraft concerning flight properties. This pilot has not participated at a HAP simulator sessions prior to this one.
- *Pilot 3* The third pilot has around 10 years of experience flying single engine and 2 years flying twin engine aircraft. Altogether, he has around 280 flight hours as a commercial pilot. He has already flown a tail wheel aircraft. This pilot has not participated at a HAP simulator sessions prior to this one.
- *Pilot 4* The fourth pilot flies model aircraft in his private life since 1995. His experience as a safety pilot covers around 37 flight hours, including 19 flight hours flying fixed-wing aircraft. He has the civil drone licences A1/A3 and A2. In addition, he obtained the licence to operate large aircraft and rotorcraft models with a mass of more than 25 kg in April 2021. This pilot is rather used to flying air vehicles from a third person view than from a first person view and the use of pedals is rather unfamiliar to this pilot. This pilot has participated at three HAP simulator sessions prior to this one.
- *Pilot 5* The fifth pilot has the private pilot licence PPL for aeroplanes with class rating for single engine land class aircraft up to 2 tons since 2011. He has around 120 flight hours of experience flying single engine aircraft. In addition, he has the sailplane pilot licence (SPL) since 1989, having accumulated around 1250 flight hours. This pilot has participated at one HAP simulator session prior to this one.

5 Results

This section presents the results obtained within the desktop simulator campaign. Figure 10 shows the averaged pilot rating and failure rate for all test points. Both are obtained by averaging over all runs of the respective test points. This plot provides some general insights. First, it is obvious that the pilots tend to prefer landing procedure 2 over procedure 1.

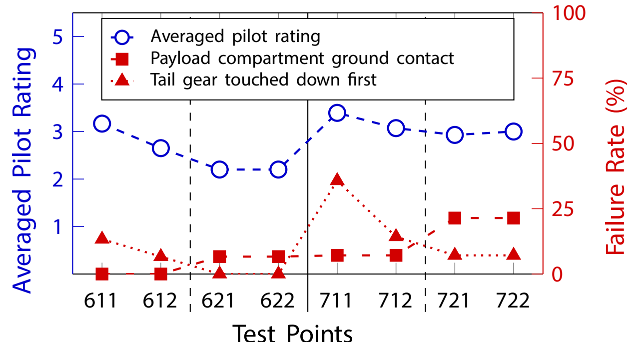


Fig. 10 Averaged pilot rating and failure rate over all test points (from 1: easy to 5: not acceptable)

This is comprehensible since procedure 2 was designed with the intention to have it feel more natural to the pilots. At a higher degree of turbulence, however, the rating difference becomes less distinct. Second, increased turbulence is remarkable. The pilots gave a worse rating to the test points with a higher degree of turbulence and the probability of a failed landing increases, too. Third, there is a correlation between procedure and type of failure. While tail-gear-first landings are more common with landing procedure 1, the risk of a payload-compartment-ground-contact landing is higher with landing procedure 2.

In order to give an impression about the landing tasks, Fig. 11 provides a three-dimensional view of the flight paths from beginning of the task until touchdown. Hence, the final slideout is not depicted. For every test point, all runs flown by all pilots are averaged in the plot. This is done by subdividing every run's flight path into four segments. Segment 1 is from start until the moment the characteristic altitude is reached or the propellers are retracted, whatever comes first. Segment 2 is until the respective other event, segment 3 is until touchdown, and segment 4 is from touchdown to standstill. Subsequently, segment 1 from all runs of the respective test point are brought to the same size with respect to data points. In doing so, intermediate flight path points are interpolated. In the following, an average flight path for segment 1 is obtained by forming the mean value at every data point of the flight path. The same is performed for the other segments and all segments are strung together.

As shown, every test point starts at the same position with an altitude above ground of 50 m. The runway is at Cochstedt Airport (EDBC). The required runway lengths for landing procedure 1 is longer on average than for procedure 2. This is not surprising since this procedure includes an additional horizontal flight phase at which the aircraft needs to be stabilised. Nevertheless, it can also be seen that the required runway lengths decreases for test points that were conducted later in the test program. It is particularly visible that the pilots started the descent earlier. Indeed, reducing

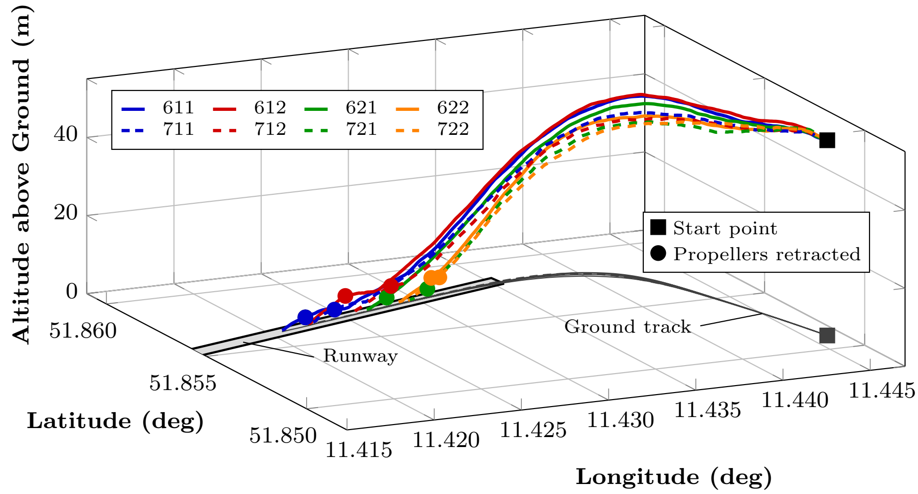


Fig. 11 Paths for all test points obtained in the simulator campaign, averaged over all runs of the respective test point

required runway length was not a goal for the pilots. However, this indicates that the pilots gained some experience and confidence flying the DLR HAP aircraft. While at earlier test points they first concentrated on track before starting to descend, at later test points they most often did both simultaneously.

5.1 Learning effect and concentration

The learning effect is often important when experiments involving pilots are performed. In this study, it even plays a major role because the aircraft's flight dynamics are very uncommon and the pilot's individual experiences with flying the DLR HAP aircraft are very different. In addition, the investigated landing procedure 1 is rather unconventional and it requires some training until it can be followed adequately. For this reason, the test program was designed such that the learning effect is facilitated by a lot of repetitions and long flight phases.

In the simulator campaign the learning effect arose in two different forms. First, the pilots gained experience and improved their understanding of the aircraft. This led to a better pilot performance. As a consequence, after a couple of runs, the pilots more easily performed the quarter turn to align with the runway, improved stabilisation of the aircraft both in longitudinal and in lateral direction, used the control surfaces and followed the procedures more accurately. Second, a kind of adaptation of the pilots occurred. This means that the pilots adapted their own expectation to the situation and the controllability of the aircraft. For instance, within the first runs, it usually took the pilots quite a while to catch the characteristic altitude and to stabilise the aircraft. They then realised that this is indeed a really challenging task. Therefore, at later test points, they decided earlier that the aircraft is stabilised and tended to go on to the next phase earlier. In addition, they increased their tolerance about altitude deviations from the characteristic altitude.

Figure 12 shows the averaged landing tracks per test point. As shown, in all cases with a higher degree of turbulence (711, 712, 721 and 722), the landings are completed earlier than in the cases with their equivalent test points with lower turbulence (611, 612, 621 and 622). Indeed, the turbulence might also play a role here, but it is more likely that the learning effect is the main driver.

The learning effect is even more observable in case of the test points involving landing procedure 1. The segment from reaching the characteristic altitude (marked with a square) until propeller retraction (circle) shows it best. The distance between both events can be considered an indicator for the learning effect. From test point 611 to 612, this distance decreases. This signifies that the pilots either managed to stabilise the aircraft more easily, or they earlier considered the degree of stabilisation

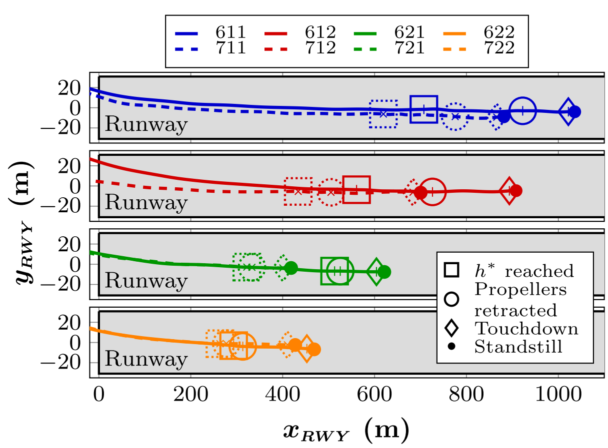


Fig. 12 Ground paths for all test points obtained in the simulator campaign, averaged over all runs of the respective test point

as sufficient, or both. From 612 to 711, the distance decreases again and at test point 712, it is already very short. This also shows the potential of comprehensive pilot training with respect to reducing required runway length even for landing procedure 1, which is not really effective in this regard. Finally, it can be seen that the final slideout length is fairly short, which is not surprising since skids are used.

Figure 13 shows the pilot ratings and failure rate averaged over every run. As shown, according to the averaged pilot rating, thus their own perception, there is a learning effect or at least an adaptation of the pilot to the task and the aircraft. This effect decreases along with the flight time, which is natural for a learning effect. It can also be observed that, speaking of the test points with lower degree of turbulence, the failure rate is a lot higher at earlier runs of a test point. In case of test points with a higher degree of turbulence, there is no such correlation suggesting that the reactions due to turbulence dominate and a successful landing is less likely in general. Another effect that cannot really be evaluated is the pilot's concentration. The sessions took around 3 to 4 h with breaks according to the pilot's needs. However, it is expectable that the concentration decreased in the end and some pilots even stated this.

5.2 Evaluation of the landing

Using the global results depicted in Fig. 10, it can already be concluded that landing the DLR HAP aircraft is a very challenging tasks, regardless of the landing procedure used. At higher turbulence, the rate of failure is comparatively high and even at lower turbulence, a failure is not completely unlikely. Nevertheless, the major goal of this work is to reduce the risk associated with the landing as much as possible rather than to completely eliminate it.

5.2.1 Assessment of the landing procedures

Judging by the pilot assessment, the pilots tend to slightly prefer landing procedure 2 over procedure 1. Besides the already mentioned fact that procedure 2 feels more natural to the pilots, the test point order was also in favour of landing procedure 2 because this procedure was performed after landing procedure 1.

However, as shown by Fig. 10, while the probability of a tail-gear-first landing is more probable for procedure 1, the payload compartment makes ground contact more often in case of procedure 2. The payload-compartment-ground-contact landing is the by far more severe failure case. For this reason, the target pitch angle was set to 0° for both procedures. This signifies a clearly larger margin to the minimum allowable pitch angle $\Theta_{\mathrm{TD,min}}$ than to $\Theta_{\mathrm{TD,max}}$. Nonetheless, the probability of a payload compartment ground contact is high for procedure 2 in spite of the larger margin to $\Theta_{\mathrm{TD,min}}$. This indicates that controlling the pitch angle until touchdown is more difficult with this procedure. For procedure 1, on the other hand, it is more likely that the tail gear touches down first, which is statistically plausible because its limit is closer to Θ_{Target}.

Altogether, landing procedure 1 performs better than procedure 2. This is true in spite of the test point order in favour of procedure 2 and even though it is rated lower by the pilots. At this point, it should be noted that no structural damage effects are modelled in the flight dynamics model, and therefore, it was not always clear to the pilots that the payload compartment made ground contact. This would have surely had an effect on the pilot ratings.

Nevertheless, in order to improve landing procedure 1, it is worth investigating why the pilots gave a worse rating to this procedure compared to the reference procedure. There are some aspects that basically make flying the DLR HAP aircraft challenging. With landing procedure 1, these are more emphasised:

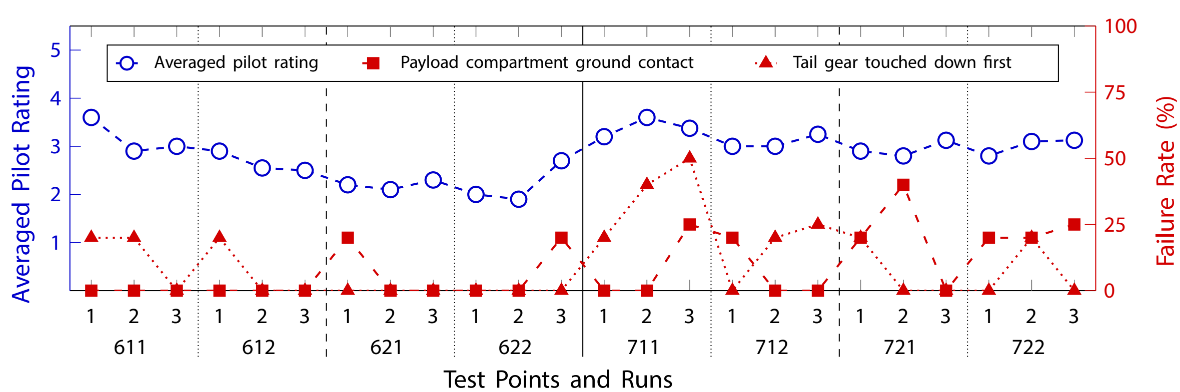


Fig. 13 Averaged pilot rating and failure rate over all runs (from 1: easy to 5: not acceptable)

1. Altitude captures are not easy with the DLR HAP aircraft. Since the "flare" altitude needs to be captured and a horizontal flight is to be established, a thrust increase is required. The pilots stated that it is not easy to estimate the right amount of thrust such that the aircraft does not climb again.
2. A major challenge of the HAP aircraft is lateral-directional control. While stabilising the aircraft in a horizontal flight at $h_{\text{“Flare”}}$ after the descent is already demanding, stabilisation of heading is fairly difficult. This will be explained in Sect. 5.3 in more detail. Therefore, aligning with the runway takes away a large amount of pilot capacity. This phase is stressing in both procedures, but with procedure 1, the phase simply lasts longer.
3. With procedure 1, the aircraft is supposed to capture an altitude while already being in ground effect. In contrast, for procedure 2, the aircraft only descends until touchdown. The ground effect leads to, besides others, an additional altitude-dependent pitching moment, which, if not properly compensated by the pilots, causes pitch deviations. For the HAP aircraft, this more easily causes deviations of the flight path angle than for more conventional aircraft.

Figure 14 shows the vertical profiles for all performed landings relative to each landing's respective touchdown point. As shown, in most of the cases with landing procedure 1, the $h_{\text{“Flare”}}$-capture and stabilisation phase is not easy for the pilots. It takes some time and the aircraft covers distances up to 500 m and is oscillating around $h_{\text{“Flare”}}$ until the propellers are finally retracted.

To conclude, even though landing procedure 1 is challenging for the pilots and it takes longer than the reference procedure, this procedure proves to be beneficial with respect to reducing the risks during landing. Nevertheless, there is still some potential to improve the landing procedure.

5.2.2 Influence of the characteristic altitude

The test points also include a variation of the characteristic altitude, being either 2.5 m or 5.0 m. For landing procedure 1, the characteristic altitude is the so-called "flare altitude", which needs to be captured and at which the aircraft needs to be stabilised in a horizontal flight. The pilots preferred a characteristic altitude of 5 m over 2.5 m, as also shown by Fig. 10. This has multiple reasons. First, since stabilising the aircraft and aligning it with the runway at the same time is a challenging task, which is stressing for the pilot, the lower altitude adds to the risk perception of the pilot because mistakes can more easily lead to crashes. Second, the ground effect, and especially its gradient with respect to altitude is stronger in the lower altitude, which also impedes stabilisation. Accordingly, Fig. 14 shows that it takes less time to stabilise at 5.0 m compared to 2.5 m in most of the cases. Indeed, the learning effect also plays a role here, but this tendency is not only visible comparing 611 and 612, but also comparing test points 711 and 712, where it is likely that the learning effect is not that strong any more. Third, for 2.5 m the time between propeller retraction and touchdown seems to be somewhat too short, such that the subdivision of different tasks as intended when developing landing procedure 1, does not really apply.

Nevertheless, capturing an exact altitude and maintaining it, also poses a challenging task. Therefore, some pilots suggested to allow an acceptable altitude band, e.g. 3 m to 5 m rather than to specify an exact value.

For landing procedure 2, the characteristic altitude is the propeller retraction altitude. The pilots' opinion on this altitude diverged. Some stated that it hardly made a difference while others preferred 5 m since this altitude provides more time for setting up the desired pitch angle for touchdown. However, there is no correlation between type and/or quantity of failure cases and retraction altitude in the test points.

5.2.3 Influence of turbulence

The effect of increased turbulence is observable both in the pilot ratings as in the failure rate (cf. Fig. 10). Figure 15 shows box plots for the bank angle, pitch angle and crab angle at the moment of touchdown for all runs.

As shown, at the test points with a higher degree of turbulence, both the variation of pitch angle and the deviation of the median from the target pitch angle are higher than for the test points with lower turbulence. Test point 611 forms an exception here, but it must be considered that this was the first test point and the pilots were still getting used to the procedure and the aircraft. For moderate turbulence, the question whether the landing is performed successfully or not seems to be driven by the wind profile and thereby by coincidence to a significant extent. Besides the wind-induced aircraft reaction, a major complication was that the pilots could not distinguish any more between ground effect, requiring a pitch-down command, and the reaction due to turbulence, which would not necessarily require a counteraction. Altogether, it can be concluded that for moderate turbulence the use of a pitch damper would be highly beneficial.

Figure 15 furthermore shows touchdown values for bank angle (top plot) and crab angle (bottom plot). The influence of increased turbulence on these values is not distinct. The maximum allowable bank angle at the moment of touchdown depends on the flight shape and thus on airspeed. At a bank angle of approximately ±4°, a wing gear would have touched down first. Thus, it can be seen that this never occurred within the simulator campaign. As a guide value the pilots were told to touch down with less than 2° bank angle in any direction, which they apparently did not always

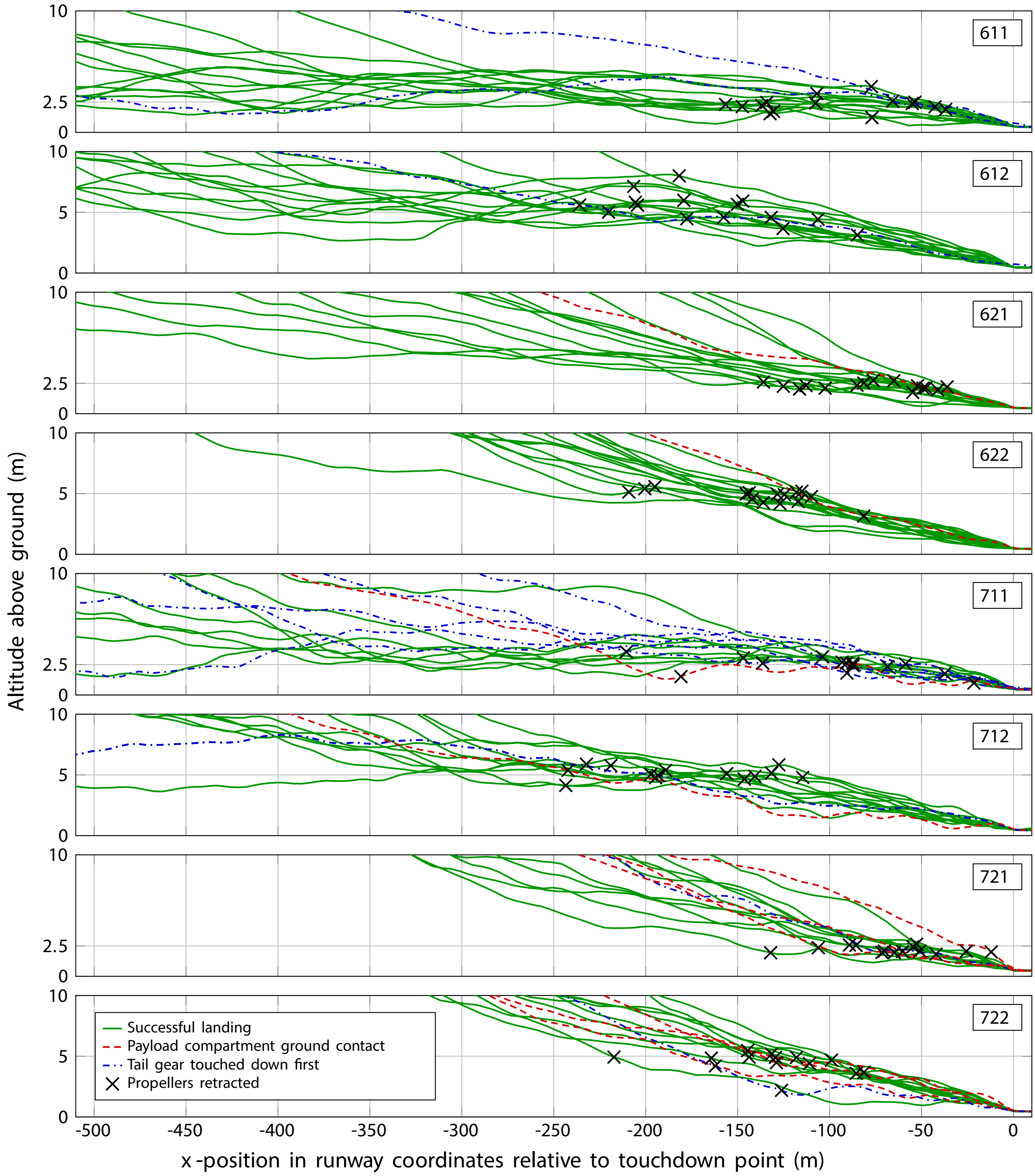


Fig. 14 All altitude profiles obtained in the simulator campaign

achieve. As shown by the third plot, the aircraft most often touched down with less than 10° crab angle. This is a comparatively small value and it can be assumed that this skewness is still acceptable for a landing with skids.

5.3 PIO (pilot-induced oscillations) tendencies

As already described in Sect. 5.2.1, stabilisation of the DLR HAP aircraft in longitudinal direction is complicated due to the aircraft's lateral-directional control characteristics. Figure 16, showing the time histories of a selected section of a run of test point 711, illustrates this.

The aircraft has weak weathercock stability and does not stabilise itself fast with respect to yaw. In addition, the response to lateral-directional control inputs is sluggish. As a result, the aircraft tends to overshoot an aimed heading. At low-precision tasks like steady horizontal or even turning flight, this aircraft tendency is less critical. At high-precision

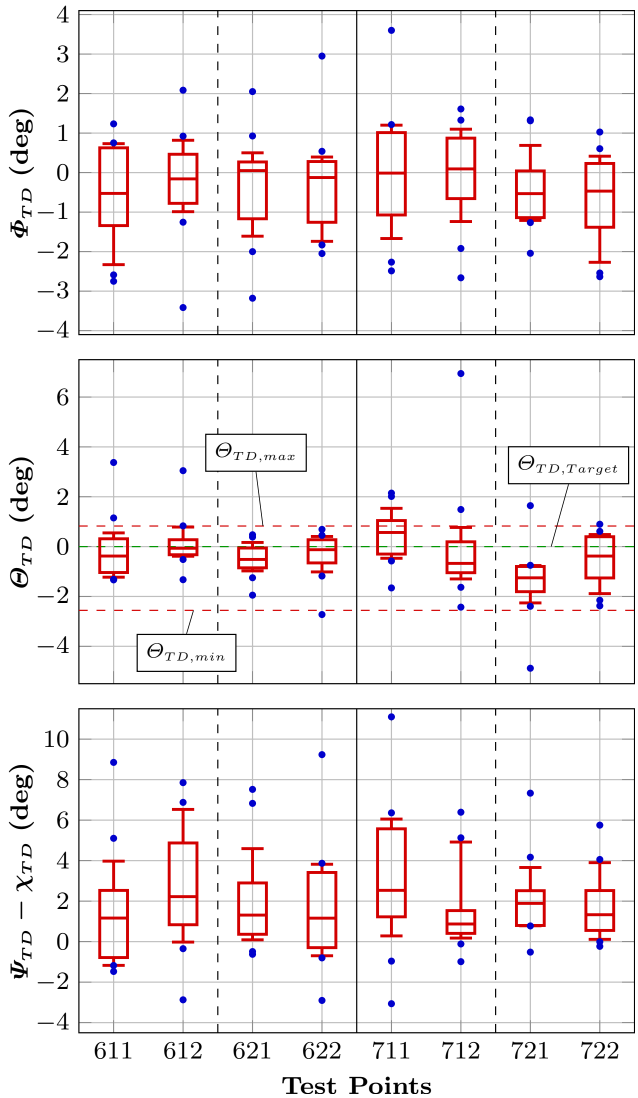


Fig. 15 Box plots for bank angle, pitch angle and crab angle at the moment of touchdown

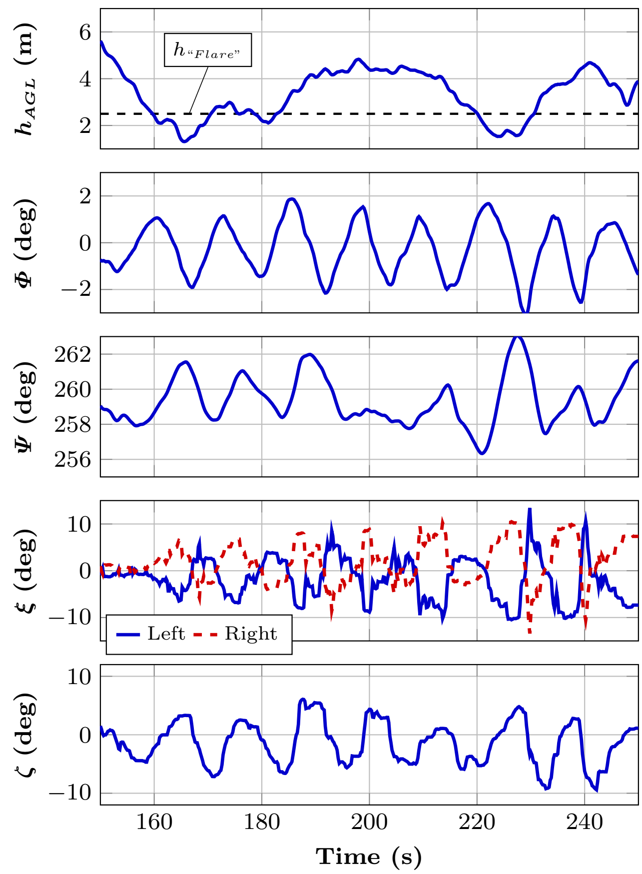


Fig. 16 Time histories for a selected landing (test point 711, type 1, $h_{\text{“Flare”}}$ = 2.5 m, moderate turbulence) showing difficulties of the pilot to align with the runway in the final stabilisation phase at $h_{\text{“Flare”}}$

tasks, however, this behaviour is distracting. A proper piloting approach would thus be to "just let the aircraft fly" as much as possible, to only use small control inputs and to anticipate the aircraft's yaw reaction. In the context of this simulator campaign it was observed that all pilots accustomed themselves with this DLR HAP-specific behaviour and improved their technique of flying the aircraft. However, if high-gain inputs are applied to keep aligned with the runway during the final landing phase, the pilot is prone to evoke pilot-induced oscillations (PIO).

As shown, the aircraft reaches $h_{\text{“Flare”}}$ at around 160 s, slightly undershooting it. While the pilot tries to gain altitude again to capture and maintain $h_{\text{“Flare”}}$, the aircraft's heading slightly diverges, leading to a misalignment with the runway, which has a heading of approximately 259°. The pilot reacts with excessive rudder and aileron input. However, this leads to an undershooting of the desired heading. In order to stop the movement, the pilot applies strong inputs again, which in turn leads to an overshooting of heading. This continues for around half a minute overburdening the pilot and taking away part of his concentration. As a result, the aircraft gains altitude again and thus deviates from $h_{\text{“Flare”}}$ by more than 1 m. Subsequently, the whole course of events repeats itself. This example shows that the aircraft is prone to PIO. Hence, it needs to be piloted carefully with anticipation and with small control inputs especially at high-precision tasks.

6 Conclusion

This paper investigates the potential of a novel landing procedure to increase safety and its feasibility from a piloting point of view. This landing procedure is intended for very slow aircraft with high susceptibility to wind disturbances, low ground clearance and a small allowable touchdown pitch band. For such aircraft, the landing usually poses a comparatively high risk of a loss of aircraft or at least serious aircraft damage. The DLR high-altitude platform is such an aircraft. The procedure subdivides the landing into four different phases with the aim to separate different piloting tasks. For this purpose, pilot-in-the-loop simulations were carried out using a desktop simulator. The novel landing procedure and a rather conventional one were performed. Within 116 runs, eight different test points were performed by five pilots.

Within the tests, it turned out that for light turbulence, the developed procedure indeed provides more control over pitch during touchdown. For the DLR HAP aircraft, this manifests in a reduced occurrence of the most severe failure case, being the payload compartment, located in the aircraft nose and carrying sensitive payload instruments, to make ground contact. However, the simulator campaign also showed that this procedure is challenging and does not feel natural from a piloting point of view and, therefore, needs improvement. This particularly refers to the stabilisation phase, at which the aircraft is stabilised at a predefined altitude in a horizontal steady flight. A possible improvement could be to define an allowable altitude band at which the aircraft can be stabilised instead of an explicit altitude to facilitate this phase. Facilitating the piloting task in this phase is especially important if the lateral-directional control already requires a great portion of the pilot capacity for aligning the aircraft with the runway as it is often the case for extremely slow aircraft like the DLR HAP.

At moderate turbulence, the failure rate is quite high for both procedures, such that it is questionable whether the risk of an accident during landing can be reduced to an acceptable level at this wind condition using the developed procedure alone. For this purpose, the use of supporting systems should be considered.

In the desktop simulator used in this pilot-in-the-loop campaign, the instruments were gathered on a single panel that was displayed on a different monitor located below the monitor showing the aircraft vision. This position was not optimal and all pilots complained about it. It is thus probable that this representation of the instruments aggravated the landing task in the study and might even have led to some of the failed landings. However, it can be assumed that the results obtained in the campaign still hold true because this circumstance was given for both landing procedures, the developed one and the rather conventional one, which was used as a reference. Thus, the assessment of the procedure relative to the conventional one is expected to be valid. On the other hand, it is arguable whether the results obtained here are significant to assess the risk of the landing during a real flight. Nevertheless, it can be assumed that the instruments' non-optimal location in these studies led to a more conservative assessment. With a better position of the instruments, it is thus possible that the landing tasks becomes easier than in this simulator campaign.

In this work, a very simple rating scale is used instead of an established one. Together with the differing experience, the pilots have with flying the DLR HAP aircraft, a general and absolute evaluation of the task load of the landing cannot be made. For this reason, the assessment of the time histories with respect to compliance with the prescribed limits is mainly used to assess the success of the landings and to make the comparison between both procedures. Regarding the pilot ratings, only the trends and the differences for the procedures are used to draw some supplementary conclusions.

To sum it up, the results indicate that the novel landing procedure indeed has the potential to increase the safety of the landing for very slow aircraft with high susceptibility to wind disturbances, low ground clearance and a small allowable touchdown pitch band. Nevertheless, more pilot-in-the-loop studies using established rating scales and involving pilots that have much experience in flying such aircraft should be performed to consolidate this result and to provide a more sophisticated assessment of the associated landing task load.

7 Future work

The results obtained in the presented simulator campaign directly provide tasks for future works. First, the landing procedure needs to be modified by replacing the characteristic altitude by an allowable altitude band. Within another simulator campaign, it then needs to be investigated if this yields significant improvement from a piloting point of view. In these investigations, a more sophisticated rating scale will be used. Furthermore, the benefits of simple pitch and yaw dampers will also be investigated and more focus will be put on the instruments' positions. Another future task is the investigation of the landing of the DLR HAP in dedicated lateral wind conditions. This will include the improvement of the skid modelling for strongly skewed landings and the development of a procedure that copes with lateral wind conditions.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The author has no conflict of interest to declare that are relevant to the content of this article

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