

# A DISPLAY CONCEPT FOR UAV AUTOLAND MONITORING: RATIONALE, DESIGN AND EVALUATION

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## Abstract

In manned aviation, the main reason for the development of an autoland capability was to be able to land in reduced visibility. For over thirty years already, the ILS Cat III autoland system provides aircraft with the capability to land under zero visibility conditions. For unmanned aircraft, the main reason for developing an autoland capability is to reduce the mishap rates associated with the landing. This raises the question whether there still is a role for the human operator during the landing, and if so, what this role is. Factors that influence the answer comprise the integrity and reliability of the autoland function and its dependency on operator consent. A UAV autoland concept is discussed that relies on the involvement of a human operator as a conformance and integrity monitor. An analysis of the suitability of a conventional display format and an advanced, perspective display format to support the conformance and integrity monitoring task is presented. In addition, the level of operator involvement is addressed. Finally, an evaluation of the two display concepts and two levels of operator involvement is presented. Results show advantages for the perspective display format with the integrity monitoring task. Differences for the level of operator involvement were less pronounced.

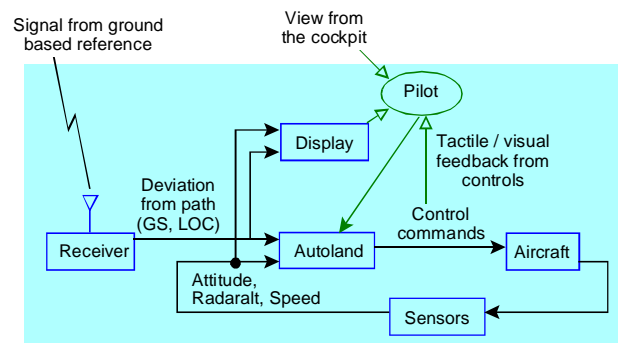
## Introduction

In manned aviation, the main reason for the development of an autoland capability was to be able to land in reduced visibility. For over thirty years already, the ILS Cat III autoland system provides aircraft with the capability to land under zero visibility conditions [1].

For Unmanned Aerial Vehicles (UAVs), *“Automatic launch and recovery operations provide risk reduction for the two most dynamic portions of a UAV’s flight profile. By eliminating the need for an external pilot, this technology helps ensure accurate guidance and control and thus reduces the*

*high mishap rates associated with the UAVs examined in this study.”* [2].

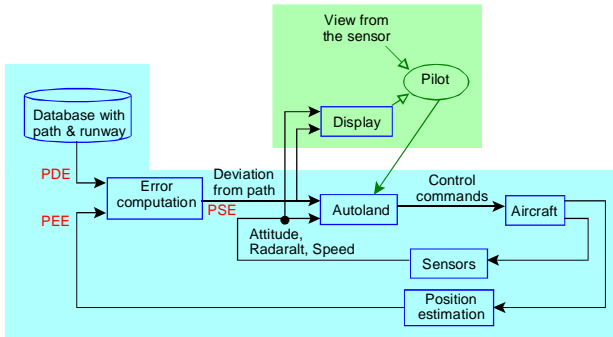
To be able to identify problems and opportunities with automatic landing for UAVs, an understanding of the differences with automatic landing systems used in commercial aviation is needed. A conventional autoland system for commercial aviation consists of a ground based component and an aircraft based component. The ground based component provides an electronic reference path by means of glide slope and localizer antennas. Receivers on board the aircraft use the measured field strength to estimate the horizontal and vertical deviation from the reference path. When using this conventional concept, the integrity of the reference path is determined by the ground based equipment. Figure 1 provides an overview of the main elements of such an autoland function.



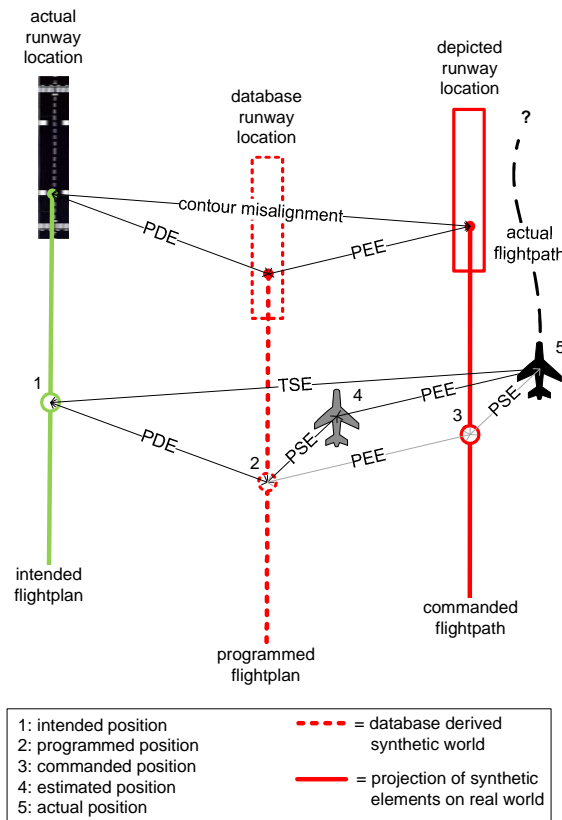
**Figure 1. Autoland function using ground based reference equipment**

Dependency on ground based equipment like the antennas used in commercial autoland systems might limit the UAV system’s deployability. Hence, more autonomous forms of autoland are being pursued. For current systems, this implies that rather than using antennas on the ground to generate an electronic reference path, this path has to be computed from data specifying the location and direction of the runway. Figure 2 shows an overview of the components of such an autoland

function. The difference with the conventional autoland concept is that the integrity of the guidance reference is now a function of the *integrity of the database*. This introduces the possibility of latent failures that cause the UAV to be commanded towards a touchdown position outside of the allowed touchdown area, negatively affecting landing performance.



**Figure 2. UAV autoland function using guidance reference data from a database**



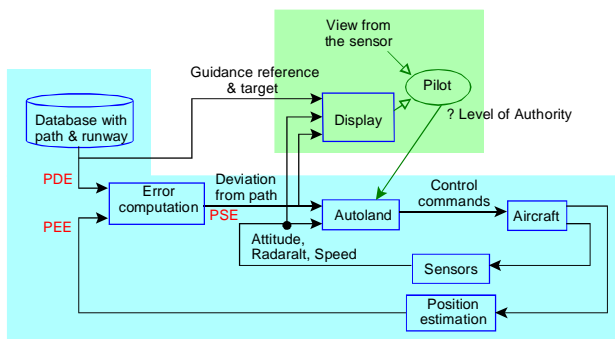
**Figure 3. Schematic overview of RNP TSE components**

### Guidance integrity assessment

The landing performance is typically quantified by the touchdown dispersion. In the Required Navigation Performance (RNP) concept [3], the 95% containment area of the touchdown dispersion represents the amount of Total System Error (TSE) that is used for the specification of the accuracy. The TSE consist of three components, the Path Definition Error (PDE), the Position Estimation Error (PEE) and the Path Steering Error (PSE).

When the reference path is computed relative to locations stored in a database, an error in the database will cause a PDE. The pilot has the possibility to detect such an error by using information obtained from the nose-mounted camera to assess whether the vehicle is being guided towards the desired location in the real world. The ability of the pilot to timely make this assessment is determined by the type and magnitude of the error and the information that is presented to the pilot. With conventional Head-Up Display (HUD) symbology, an important element that supports the pilot in this task is the Flight Path Vector (FPV) which indicates the inertial direction of flight. On the final, straight part of the approach, the FPV should be pointing at the desired touchdown location. However, the relative location of the FPV and runway in the sensor image is influenced by PSE and PSE rate, making it harder for the pilot to distinguish between temporary but acceptable steering errors and an integrity problem.

An opportunity exists to support the integrity assessment in a way not influenced by the PSE component. Rather than using the information about the impact of the guidance reference on elements of the momentary vehicle state (such as the FPV), the guidance reference -or target- itself (i.e., approach path and runway) can be presented in the same reference frame as the sensor image. In the absence of a PDE and a PEE, the depiction of the target (the synthetic runway contour) is aligned with the real runway. Figure 3 provides a schematic overview of the TSE components and their effect on conformally integrated synthetic symbology. Figure 4 illustrates the implementation of this concept in the autoland function shown in Figure 2. In ref. [4] this concept has been explored for manned aviation.



**Figure 4. Integration of guidance reference data to support integrity monitoring**

So, in case of a PDE and/or PEE, the synthetic runway and the real runway do not align. This raises the question how much PDE is acceptable. Although no quantitative requirements for the PDE component are known to exist, an estimate can be made using the RNP concept. The 95% containment area for the touchdown dispersion (touchdown box) has a width of 18.2m [3]. This represents the sum of the PEE, PDE and PSE vectors. The mismatch between the sensor runway and the synthetic runway is caused by the sum of the PEE and PDE vector. A certain error budget is needed to allow for tracking deviations, hence the lateral difference between the real runway and the sensor runway must be smaller than the range [-9.1m, 9.1m]. When half of the available error budget is assigned the PSE component, the pilot must be able to detect deviations between the runway in the sensor image and the synthetic runway of about 4.5m.

### **Level of Authority**

In the envisioned autoland concept shown in Figure 4, the main role of the human operator is conformance and integrity monitoring. Especially with respect to the latter task, the human operator can use the information obtained from the sensor image together with the guidance reference data and the vehicle state to detect PDEs and PEEs which may or even can not be caught by the on-board guidance system.

The way the operator interacts with the system depends on the authority assigned to the autoland function. In terms of Sheridan's eight Levels of Authority (LOAs) [5], two different concepts can be identified. With a lower level of system authority (LOA 4), the autoland function *always* requires the

operator's approval to continue the landing, even when no problems are detected. With a higher level of system authority (LOA 5), the system performs the landing automatically *unless* the operator intervenes. Alternatively, these modes of operation can be classified as *management by consent* and *management by exception* [6].

An autoland function design based on the consent principle might keep the operator more involved in the decision to land. By approving the system to transition from approach mode to landing mode the operator explicitly takes responsibility for the decision to land. On the other hand, compared to the exception principle, it does involve additional operator interaction for a nominal situation. This might lead to perfunctory decisions and increased system opacity.

### **Design and implementation**

To determine the potential of the integration of guidance reference data for integrity monitoring two display formats, a conventional and an advanced one, have been designed and implemented. The conventional display represents the autoland concept shown in Figure 2. The advanced display is a realization of the concept shown in Figure 4. Both display concepts will be discussed on a functional level. A more detailed description of the elements in the designs of the concepts will be presented in future work.

#### **Conventional display**

The conventional approach to support conformance monitoring is to depict the status of the various parameters on a scale with an indication of the margins within which the values need to remain. With respect to integrity monitoring, the operator has to determine whether the control actions of the system guide the vehicle to the desired location. This requires a relation to be established between the sensor image showing the runway and elements of the vehicle state indicating where the vehicle is being guided to. Typically, this is achieved through the depiction of the FPV.

Figure 5 shows an example of a conventional display format. Illustrated is a situation in which the centre of the green FPV symbol is positioned

approximately on the runway-centerline, slightly ahead of the runway identifiers.

### Advanced display

The advanced display format shown in Figure 6 uses conformally integrated guidance reference data to ‘anchor’ the ‘goals’ of the system into the sensor image. This allows the pilot to assess both the conformance to, as well as the validity of parts of these goals. With conventional HUDs, this is achieved by showing a runway outline that is obtained by using the glide slope and localizer signals to compute the required transformations that need to be applied to a 2-D shape representing the runway. In contrast, in the concept presented in this paper, the outline is computed from a 3-D database

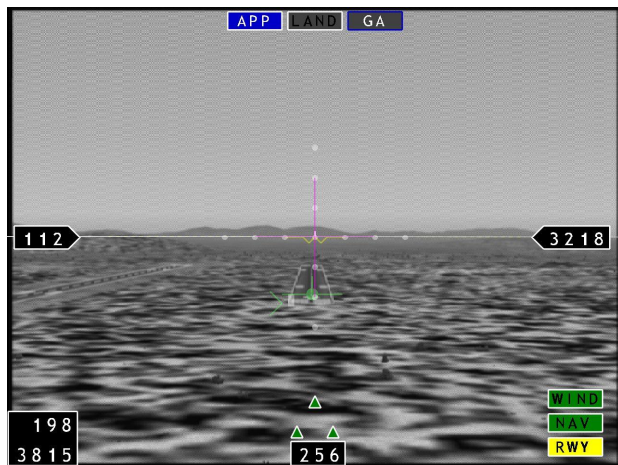


Figure 5. Conventional display ( $D_0$ )

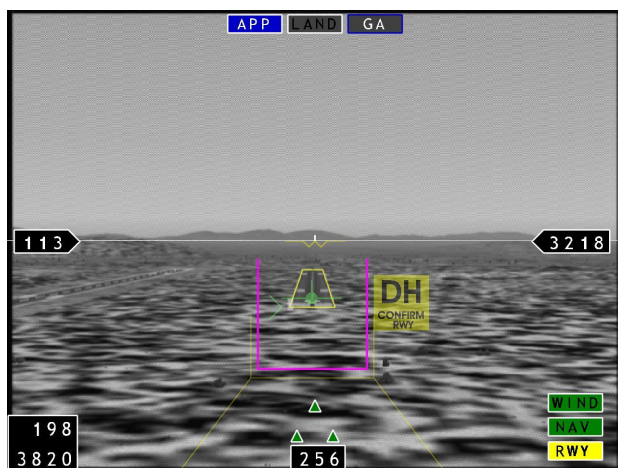


Figure 6. Conformal integration of guidance reference data

containing runway location, based on the position reported by the positioning system, i.e., as it would be seen from the location of the sensor that also provides the image. The depiction of the pathway to the runway is computed from the reference data used by the system that computes the control commands. As exemplified in Figure 3, this concept supports the *detection* of PDEs and PEEs. However, it lacks supporting the *assessment of the severity* of such an integrity problem.

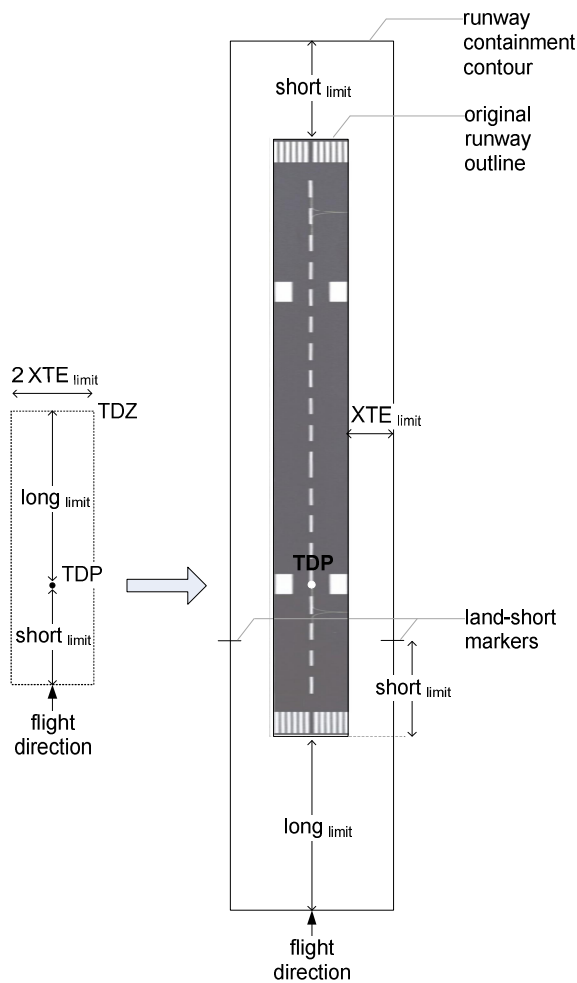
### Integrity Assessment

Basically, assessment of the integrity of the reference path used by the autoland function involves two steps:

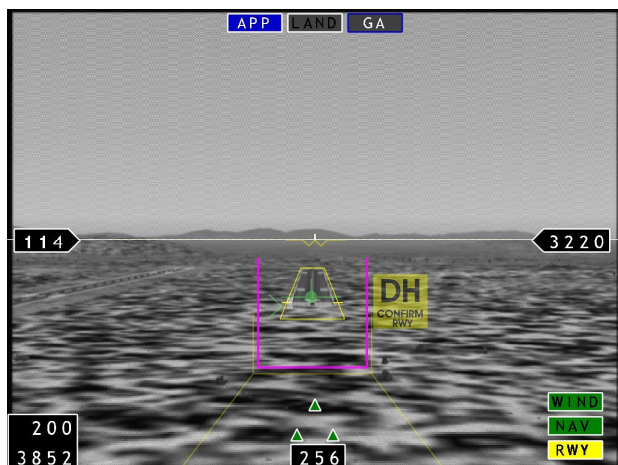
1. detecting potential discrepancies between the runway depicted in the nose-cam video and the associated HUD-symbology;
2. deciding whether detected discrepancies exceed the applied landing performance criteria, or Touch Down Zone (TDZ) limits.

Thus, to support the operator in this assessment task, information on the applied TDZ limits should be provided. One way of achieving this is to graphically depict an ‘aiming zone’ with the dimensions of the allowed TDZ on the runway surface. In this concept, the vehicle is heading towards a Touch Down Point (TDP) within the TDZ when the FPV is pointing within the ‘aiming zone’. However, even this might not provide the desired level of decision support since, compared to world based reference points, the FPV is rather dynamic. Additionally, this concept depends on specific markers on the runway surface, something which might not be desirable.

Another option is to integrate the applied limits into the synthetic runway outline of the concept illustrated in Figure 6, to form a synthetic ‘runway containment contour’. This runway containment contour replaces the original runway outline. In the resulting concept, the vehicle is heading towards a position within the allowed TDZ when the runway depicted in the nose-cam video is enveloped by the synthetic contour. To address potential issues with the perceptibility of the type of position errors causing short-landings, additional markers can be implemented that bring the required cues more into the foreground of the perspective world. This idea is exemplified in Figure 7. Figure 8 presents the



**Figure 7. Integration of TDZ limits into a runway containment contour**



**Figure 8. Conformal integration of the guidance reference and landing criteria ( $D_1$ )**

implementation of the runway containment contour into the advanced display format that was subject of the study presented in this paper. The advanced display format features a conformal integration of the guidance reference and landing criteria with the sensor image. Instead of the first option (described above), this concept uses symbology with the same dynamic behavior as the world based reference points contained by the video and does not depend on specific markers on the runway surface.

### Additional operator support

The main purpose of the advanced display design was to provide increased operator support with respect to integrity assessment of the guidance reference. This aspect primarily employs the runway containment contour.

Additionally, the conformal integration of the pathway to the runway was implemented to support the conformance monitoring task i.e., determining whether the autoland function is actually following the commanded reference path. The perspective pathway also supports anticipation of mode-changes, such as the transition from the approach path to the glide path. Finally, conformally integrated signs were applied to support anticipation of decision points. These 'billboards' were, for instance, placed along the glide path to indicate the decision height (DH) before which the decision to land should have been taken.

### Feasibility

The perspective pathway and runway outline are rendered by means of a wireframe representation, as can be observed from Figures 6 and 8. All required transformations, the perspective projection and the clipping are performed in software. Consequently, these elements of the overlay concept can be implemented on any graphics system that is capable of rendering 2-D vectors. Implementation of the billboards requires a graphics system that is also capable of texture mapping.

### Evaluation

The analysis associated with the design process raised several questions:

- Are the display concepts suitable for the intended integrity monitoring task?

- To what extent do representation and level of authority affect the performance? Does the proposed depiction of the error margins indeed improve performance?
- What objective and subjective measures provide a valid indication of this performance?
- How do the type and magnitude of the error affect performance: is the relevant range of potential errors detectable and what are the associated false alarm rates?
- To what extent does the performance depend on operator background? Are there any differences between e.g., licensed pilots, controllers and novices?

To address these questions, an experiment has been conducted in which participants monitored an automatic landing of a UAV using the two different display concepts and two different levels of authority.

### Participants

Participants in the experiment included naval helicopter pilots, a commercial airline pilot, a general aviation pilot, Command and Control (C2) personnel, Military Air Traffic Control (MilATC) personnel and non-operational personnel (both military and civilian). Table 1 provides the number of participants from each of the different backgrounds.

**Table 1. Participant backgrounds**

Background	No. of participants
Helicopter pilot	4
Commercial airline pilot	1
General aviation pilot	1
C2	28
MilATC	6
Non-operational, military	7
Non-operational, civilian	5
<b>Total</b>	<b>52</b>

### Simulation environment

The experiments have been conducted on the UAV Control Station (UCS) research simulator at the Royal Netherlands Naval College (RNLNC) and, on a mobile UCS concept demonstrator, at the Air Operations Control Station Nieuw Milligen

(AOCS NM). Both set-ups contained a head-level display and a touch-screen multi-function display. The head-level display provided the participants with simulated monochrome video imagery from the UAV's fixed, nose-mounted camera, along with guidance and status symbology overlay [7]. The simulated imagery was created from a realistic model representing the Mojave Desert region; field-of-view was 32 × 24 degrees. The touch-screen display below the head-level display provided elementary status indications and served as a control panel. Figures 9 and 10 depict both UCS simulators.



**Figure 9. Pilot position of the UCS research simulator at the RNLNC**



**Figure 10. UCS concept demonstrator at the AOCS Nieuw Milligen**

**Task and scenario**

Participants acted as the operator in charge of the UAV. The task of the operator was to monitor the integrity of the guidance reference data used by the autoland function. This required the operator to judge whether the UAV was guided towards a TDP within the allowed TDZ, by using information from the sensor imagery and the data presented in the overlay.

Approaches were flown according to the schematic flight plan depicted in Figure 11. In some of the approaches, deliberate position database errors were introduced, some of which causing the vehicle to be commanded to a position outside of the allowed TDZ. In case the vehicle was believed to land outside of the allowed TDZ the operator had to abort the landing; otherwise the landing should have been continued.

The applied touchdown criteria are given in Table 2. As a reference, these values represent about 1/5<sup>th</sup> of the usable part of the runway. Of the longitudinal errors, only discernment of short-landings has been evaluated since these were considered to be more critical than ‘long-landings’.

**Table 2: Applied TDZ limits**

XTE <sub>limit</sub>	±4.5m
short <sub>limit</sub>	58m

**Independent variables**

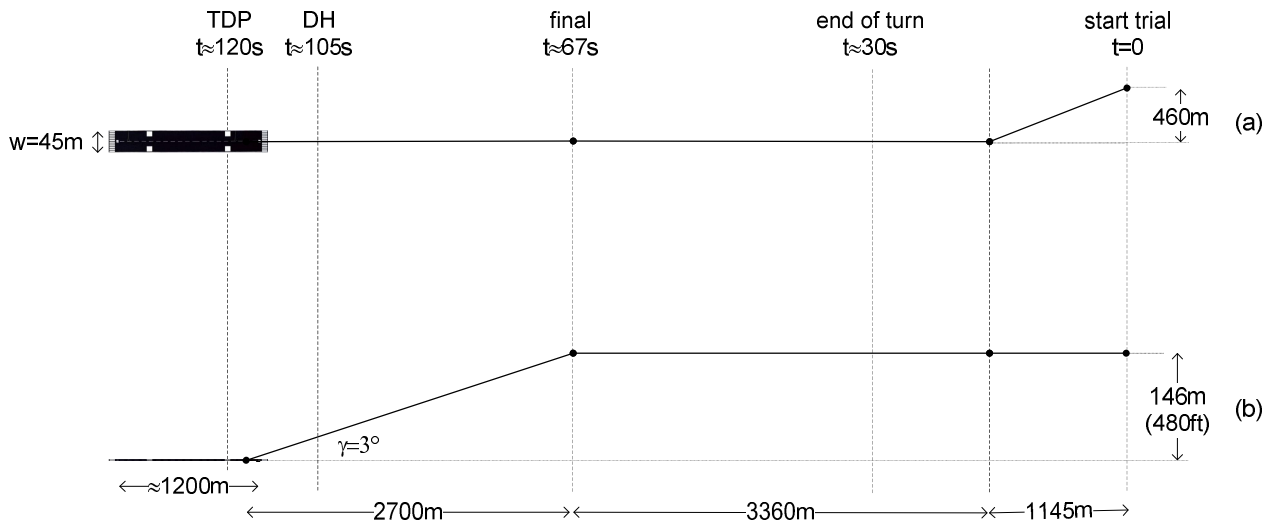
The integrity monitoring task had to be performed using two different display concepts and two different interaction concepts.

**Display concept**

With the baseline display (condition D<sub>0</sub>, Fig. 5) the operator was presented with a flight director command display providing path deviation indicators and a FPV. With the advanced display (condition D<sub>1</sub>, Fig. 8), the planned path and landing margins were presented using a conformal overlay.

**Interaction concept**

The evaluated interaction concepts differed in the dependency on operator consent. In LOA 4 (condition A<sub>0</sub>), when the operator believed the UAV would land within the allowed TDZ the runway had to be confirmed to switch to the final landing mode. When no runway confirmation was given, the system would automatically switch from the approach mode to the go-around mode upon passing the DH of 100ft above ground level. In LOA 5 no confirmation was required for the transition from the approach mode to the final landing mode. Both interaction concepts required the operator to initiate a go-around when the UAV was believed to land outside of the allowed TDZ. Table 3 provides an overview of these required operator responses.



**Figure 11. Schematic flight plan: (a) top view, (b) side view**

**Table 3: Required operator responses**

		Level of Authority	
		LOA 4, $A_0$	LOA 5, $A_1$
Decision	Land	confirm runway	no action
	Go-around	initiate go-around	

**Table 4: Independent variables**

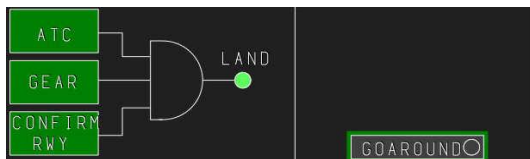
Display format, D	Level of Authority, A
‘Conventional’: condition $D_0$ , Fig. 5	LOA 4, ‘Consent’: condition $A_0$ , Fig. 12
‘Advanced’: condition $D_1$ , Fig. 8	LOA 5, ‘Exception’: condition $A_1$ , Fig. 13

**Table 5: Decision rating**

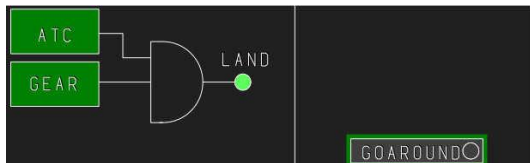
		PDE condition	
		$PDE < applied\ limits$	$PDE > applied\ limits$
Decision	Land	correct landing	miss
	Go-around	false alarm	detection

Besides the go-around option, common elements in the evaluated interaction concepts comprised ATC-clearance and a gear-down status as prerequisites to transition to the landing mode. Both of these conditions had to be met before the glide slope intercept in order not to interfere with the actual decision whether to land or go-around. Figures 12 and 13 illustrate the control panels of both LOA conditions. The control panel was presented on the touch-screen display. Activating the required landing prerequisites and initiating the go-around was achieved by touching the associated buttons.

Table 4 provides an overview of the independent variables, with references to the figures illustrating these conditions.



**Figure 12. Control panel LOA 4 ( $A_0$ )**



**Figure 13. Control panel LOA 5 ( $A_1$ )**

### Dependent variables

The rating criteria that were used to compare the display and interaction concepts are:

- the correctness of the PDE related decisions to proceed or abort the landing, see Table 5;
- timeliness of these decisions: the heights at which the decisions were taken.

If, in the consent mode, the operator does not take action before the DH, the go-around is initiated automatically. In case this happens when a non-marginal PDE is present, such a ‘non-landing’ could be interpreted as a correct action performed by the overall system. However, since the operator cannot be attributed any credit for such actions, these cases were rated as misses as well.

### Procedure

Participants were first briefed on the purpose of the experiment. Next, an instruction was given on the task, the applied landing criteria, the display concepts and the interaction concepts. The instruction was followed by several familiarization / practice runs in which the participants were confronted with different types and magnitudes of PDEs using the different display and interaction conditions. After the participant had shown to sufficiently comprehend the task and concepts, the experiment started.

The magnitudes of the PDEs that were used in the experiment were chosen based on experiences gained in validating the experimental software design, such that both correct and incorrect decisions were expected. This resulted in a PDE range of [0,.5,.8,1.2,1.5,2] times the landing criteria provided in Table 2. Approximately half of all trials contained a PDE of the magnitude requiring the operator to decide to go-around. Lateral and longitudinal PDEs were never combined.

Each participant performed between 36 and 44 trials, each trial lasted two minutes at maximum. Trials were organized in two separate sessions, based on LOA ( $A_0/A_1$ ). These sessions were sequenced in such a way that half of the participants started with the  $A_0$ -session. The sequence of trials within the sessions was randomly determined once; half of the participants performed this sequence in a reversed order.

The experiment was followed by a discussion in which participants were asked to comment on their experiences with the different concepts. Together with the instruction and discussion, the experiments required about three hours per participant.

## Results and discussion

### Correctness of the decisions

The type and number of *incorrect decisions*, as well as the contributions of the different PDE magnitudes to these incorrect decisions are provided in Figure 14. The numbers above the bars represent the amount of incorrect decisions relative to the total number of performed -or associated- trials.

The data show that using  $D_1$  the participants made less incorrect decisions. The data indicate that the performance gains achieved by  $D_1$  result primarily from a decrease of the number of misses; false alarm rates with  $D_1$  are lower than with  $D_0A_1$ , but higher than with  $D_0A_0$ . For  $D_1$ , the data show no apparent difference between  $A_0$  and  $A_1$ . For  $D_0$  however,  $A_0$  showed a higher miss rate and a lower false alarm rate than  $A_1$ . The contributions of the different PDE magnitudes indicate that for  $D_0$  the longitudinal landing criterion seems more likely to be missed than the lateral criterion.

Regarding the detection of guidance reference integrity problems that require the landing to be aborted, the proposed advanced display format shows a reduction in misses of about a factor six to seven. The false alarm rate remained about the same but these will only lead to a missed approach, a missed detection can result in a loss of vehicle.

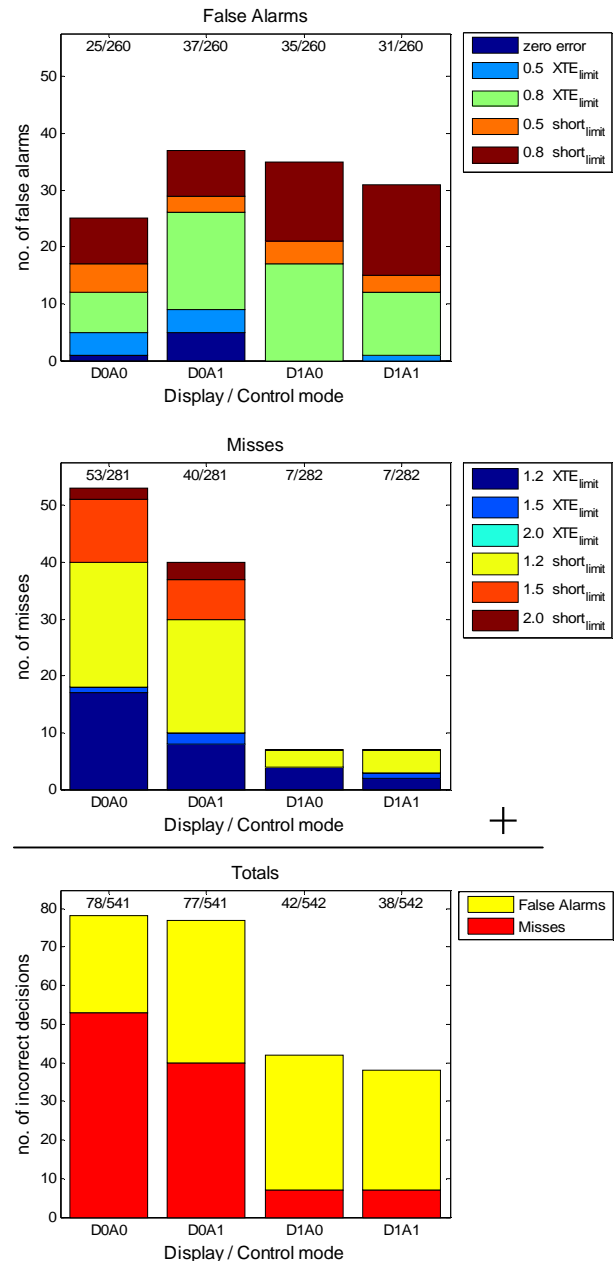


Figure 14. Incorrect decision data

### Timeliness of the decisions

Participants were briefed that besides the correctness of their decisions, the timeliness of their decisions was also important. Figure 15 shows the heights at which both the correct and incorrect decisions were taken. These data indicate that, on average, the advanced display concept enables earlier decisions than the conventional display. No considerable differences were found between the interaction concepts.

### Participant comments

#### Display concept

Some participants with piloting experience found the conventional display format to be “more natural”, as they experienced the presentation of the runway in the video to be less cluttered than with the advanced display.

Other participants indicated that with the conventional display format, detection of errors

required quite some skill since the FPV is rather dynamic and the concept is lacking the explicit depiction of the applied landing criteria. As a result, some indicated to believe to have been less consistent in making decisions with the conventional display format than with the advanced display format. It appeared that the lack of the explicit depiction of the landing criteria might allow too much room for own interpretations (variability) in the operator’s judgments. In case of stress, fatigue, inattentiveness or lack of experience, it might be harder to exactly remember how to apply the instructed landing criteria, possibly making the conventional display more susceptible to confusion. Regarding this, a participating instructor indicated to have experienced what he called: “replacing the instructed criteria with his own reality”, a behavior he said to observe with his trainees occasionally, when they become saturated in training scenarios.

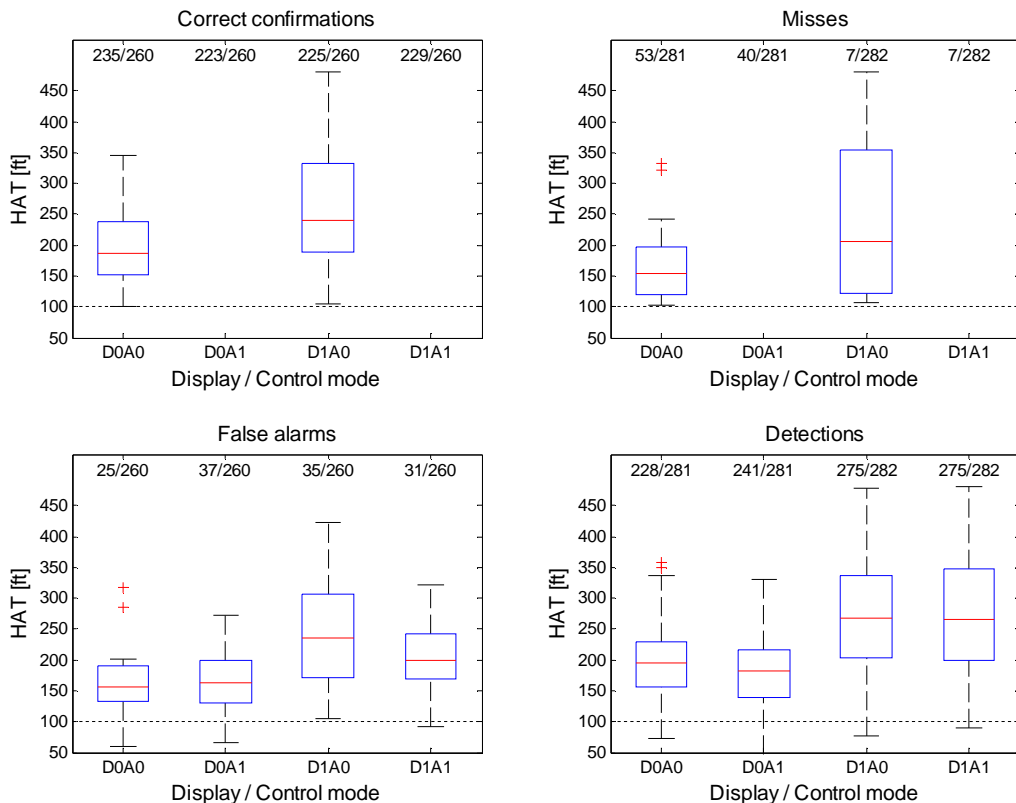


Figure 15. Heights Above Threshold (HATs) at which decisions were taken

## Interaction concept

Some participants appreciated the fact that the consent mode allows the decision chain to be broken into several steps, first filtering out obvious errors (confirm / no confirm) and then focusing on smaller errors (go-around / no go-around).

Other participants argued that, in practice, standard procedures will probably require the operator's approval to transition to the approach phase anyway. Depending on the time between this transition and actual landing, it might be overdone to explicitly require landing approval as well.

Additionally, several participants seemed to be disinclined to initiate a go-around when a confirmation given earlier appeared to be incorrect, often openly marginalizing the observed integrity problem. This complacent type of behavior might have caused several misses; especially in the conventional display format since it does not explicitly depict the landing criteria, allowing the perceived errors to be incorrectly justified more easily.

## Summary and Conclusion

An advanced display concept for UAV autoland integrity monitoring is presented. In this concept the system goals and landing criteria are explicitly anchored into the outside world using a conformally integrated depiction of the guidance reference data and the available margins. In addition, the level of operator involvement is addressed.

Results of an evaluation of the advanced display format with a conventional display format indicate that the explicit depiction of the available margins reduces the variability in the decision whether to continue or abort the automatic landing. For the scenarios tested, performance data show the advanced display concept provides a reduction of the miss rate with a factor six to seven without an increase in false alarm rate. Differences for the level of operator involvement were less pronounced. However, comments from the subjects indicate that the intended type of operator should not be neglected when deciding on the LOA assigned to the autoland function.

The advanced display concept relies on simple transformations and can -except for the billboards-

be realized on any platform capable of drawing 2-D vectors.

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