Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

Executive summary

Predictive Landing Guidance in Synthetic Vision Displays

Problem area
Little research has been conducted on how synthetic vision displays can support pilots in manual control during the final phase of the landing. While perspective flight-path displays and the use of display augmentation to improve path-following accuracy have been subjected to many investigations, there has been relatively little attention for the landing phase. Perspective flight-path displays allow high-precision manual trajectory following and interception of different trajectory sections, for which performance can be improved by introducing display augmentation that provides the future position. Still, it has been questioned whether this type of display is useful during the final phase of the landing and especially during the flare manoeuvre. This paper tries to provide an answer to whether these doubts are justified or if they can be rebutted.

Description of work
After analysing the final phase of the landing itself, the use of synthetic vision during this flight phase was examined. The results of this investigation suggested that the synthetic vision display needed to be augmented with predictive guidance. Two types of predictive guidance were examined. The first was the Flight-Path Predictor that indicates the aircraft's future position a certain prediction time ahead. The second was the Flight Trajectory Predictor that presents an entire future trajectory by interpolating a number of sequential predicted positions. A theoretical investigation into the characteristics of these types of predictors reduced the amount of variables and resulted in an optimized predictive guidance system for the final phase of the landing. Naturally, there were a number of variables and/or side effects that could not be optimized and/or ascertained using theory alone. An experiment with ten airline pilots and the GRACE moving base flight simulator was used to fill this gap.

Results and conclusions
The experiment revealed that predictive guidance, to certain extends, supports pilots in manually controlling the final phase of the landing during low visibility conditions. With regard to the flare manoeuvre, that ultimately determines the performance during the landing, the addition of predictive guidance enhances the pilot's ability to determine the correct flare initiation time instance. The same effect could be noticed by

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rendering (ground)textures on the synthetic vision display without the addition of predictive guidance. Even though the flare initiation timing was improved by the addition of predictive guidance, the flare control after initiation was not sufficiently supported and there was no noticeable performance increase. Comparing landings that were conducted using synthetic vision and landings that were conducted using the outside vision revealed a significant difference between the sinkrate at touchdown. Landing using synthetic vision as sole means of visual information resulted in a much higher sinkrate. Analysis of the pilot's control strategy after flare initiation revealed a cause of this high sinkrate. Pilots tend to pull back the control column much faster after flare initiation when using synthetic vision. Probably the lack of cues on the relatively small synthetic vision display and/or the unnatural field-of-view caused this control behaviour. Future research should include an investigation of the effect of field-of-view.

Comparing the two predictive guidance concepts with each other leads to the conclusion that the Flight-Path Predictor should be preferred over the Flight Trajectory Predictor. The first allows a lower pilot workload, while the path-following accuracy is superior. Unfortunately, neither of the two concepts could provide enough support to the pilot when controlling the flare after initiation.

Applicability

This research project was conducted as part of a master thesis work and has no direct application. Still, synthetic vision displays are already available in some private aviation aircraft. The addition of predictive guidance can be used to support manual trajectory following. However, more research is needed to be able to assist pilots in manual landing during low visibility conditions while using synthetic vision.

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Predictive Landing Guidance in Synthetic Vision Displays

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Summary

In order to improve performance during manual control, synthetic vision displays were augmented with predictive guidance. Little is known on how these predictive guidance concepts can be applied to the landing flare manoeuvre. This paper discusses the investigation into the applicability of 3D predictive guidance in synthetic vision displays during the final phase of the landing. Two types of predictive guidance were examined, the Flight-Path Predictor that indicates the aircraft's future position a certain time ahead, and the Flight Trajectory Predictor that presents the future trajectory by interpolating a number of sequential predicted positions. A theoretical investigation and an offline simulation were used to optimize the system for the landing. A pilot-in-the-loop experiment, conducted in a moving-base flight simulator, indicated that predictive guidance supports pilots in manual control. Also, the addition of predictive guidance enhances the pilot's ability to determine the correct flare initiation time in a way that is comparable to providing a more realistic synthetic vision display with textured surfaces. Even though the flare initiation timing was improved by the addition of predictive guidance, the flare control after initiation was not sufficiently supported and there was no noticeable improvement in landing performance.

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Contents

Symbols

γ	=	Flight-path angle
d_{td}	=	Runway consumption till touchdown
δ_a	=	Aileron deflection angle
δ_e	=	Elevator deflection angle
h_{init}	=	Flare initiation height
$\dot{h}_{td}$	=	Sinkspeed at touchdown
θ_{td}	=	Pitch angle at touchdown
K_p	=	Pilot gain
K_q	=	Pitch rate deviation feedback gain
q	=	Pitch rate
T_{PR}	=	Prediction time
$T_{PR\ opt}$	=	Optimal prediction time
$T_{PR\ max}$	=	Maximum prediction time
T_q	=	Lag time constant
x_e	=	Horizontal track error
y_e	=	Vertical track error
Y_{ac}	=	Aircraft system
Y_p	=	Pilot system
Y_{PR}	=	Predictor system

1 Introduction

Little research has been conducted on how synthetic vision displays can support pilots in manual control during the final phase of the landing. While perspective flight-path displays and the use of display augmentation to improve path-following accuracy have been subjected to many investigations, there has been relatively little attention for the landing phase. Perspective flight-path displays allow high-precision manual trajectory following[1] and interception of different trajectory sections[2], for which performance can be improved by introducing display augmentation that provides the future position[3]. Still, it has been questioned whether this type of display is useful during the final phase of the landing and especially during the flare maneuver. This paper tries to provide an answer to whether these doubts are justified or if they can be rebutted.

In essence, the flare maneuver is the transitioning between following the glide path during the approach and following the runway after touchdown. The purpose of this maneuver is to decrease the vertical velocity and allow a smooth landing. The (auto)pilot normally executes the flare by exciting the phugoid motion of the aircraft by gradually increasing the elevator deflection (pull up), and by reducing thrust to assure that touchdown will occur. When the autopilot is engaged during the flare, the autoland system generally executes a preprogrammed pitch rate command profile (that is dependent on the descent velocity) from a certain predetermined initiation height until the aircraft touches the runway[4]. More advanced autoland systems also control the thrust, brakes and spoilers to reduce total velocity. One of the most important differences between automatic and manual landings is the greater consistency of automatic landings[5]. Manual flare executions are performed in more or less the same way as automatic ones. Although it is possible to perform the flare with the steering column as single control, using the throttle as secondary control offers better performance in the presence of disturbances and better recovery from errors[6]. Normally, human pilots initiate the flare at a certain instance by gradually pulling back the control column (or stick) to increase the elevator deflection[7]. After flare initiation, the already small engine thrust is generally reduced even further to an idle throttle setting at touchdown[6]. This makes a manual executed flare a multivariable control task that requires precise coupling between timing (initiation) and action (force on the control(s))[7]. A beneficial effect of the coupling between timing and action is that it allows for one element to compensate the other. A late (or early) timing can be compensated by the application by a larger (or smaller) force on the control column[7]. The flare initiation is based on at least two different timing strategies, the altitude perception strategy and the Time-To-Contact (TTC) strategy[7]. The disadvantage of the altitude perception strategy is that it is susceptible to ambiguity, especially if few visual cues are available. The TTC is defined as the time remaining to collision if no pilot control action is taken, and a strategy using this variable offers a more robust flare timing strategy[7]. In theory it can be registered by relating the distance to the aiming point and its time derivative, or by relating the visual angle (field from the eye(s) to both runway edges) and its time derivative. Evidence suggests that the TTC or optical variable tau, that describes the relative velocity of an optical image expanding across the retina, can be registered directly by the human eye[7,8]. Normally, pilots can obtain many (visual) cues to adopt a correct timing and control strategy. However, during low visibility conditions the number of visual cues decreases and manually keeping up performance becomes more difficult[9] or even impossible.

Providing synthetic vision with three-dimensional (3D) guidance during low visibility conditions while on approach or during landing procedures enables pilots to control the aircraft with high precision[10] and "*to fly complex curved approaches and missed approaches that cannot necessarily be flown with current instrumentation*"[11]. Even without available outside visibility pilots can manually conduct safe landings with these types of instruments[12]. It is possible to facilitate the anticipation behavior of pilots by augmenting the synthetic vision display with the visualization of the aircraft's predicted future position[3]. Research indicates that predictive guidance can help to minimize trajectory errors[13,14] and that it is possible to acquire a system that is relatively insensitive to turbulence[14]. However, the transition between two straight trajectories (glide path and runway surface) while allowing a smooth landing is more difficult. Presenting the future aircraft's position is said to allow a smooth anticipation of trajectory changes[9], but as mentioned before, there are doubts concerning the use of this type of display (augmentation) during the final phase of the landing.

This paper presents the development and testing of two predictive guidance concepts with respect to the final phase of the landing including the flare. It is structured as follows. First, the two predictive guidance concepts that were examined are discussed. Then, the optimization procedure of these two concepts using an offline simulation will be presented. Finally, the results of a pilot-in-the-loop experiment, conducted in a moving-base simulator, are discussed. The goal of this experiment was to study pilot performance and workload when using synthetic vision that is augmented with the two predictive guidance concepts during the final phase of the landing.

2 Two predictive guidance concepts

The first predictive guidance concept that was examined is the Flight-Path Predictor (FPP)[3,14]. This concept presents the future aircraft's position a certain prediction time T_{PR} ahead. Assuming that the prediction is accurate, the pilot's task when following a straight trajectory is changed into a two-axis pursuit tracking task[9]. Controlling the predictor to minimize the error between the predicted and reference trajectory will result in an even smaller position error when the aircraft reaches this predicted position after the prediction time T_{PR} has passed. It also allows a smooth anticipation of changes in the trajectory to be followed[9]. The final phase of the landing is essentially a sequence of two straight trajectories and just before touchdown the pilot makes the transition between the two by executing the flare to allow a smooth landing. This transition is normally started by pulling back the control column and initiating the flare at a certain height. When using predictive guidance the transition is started at the moment the symbol predicting the future position of the aircraft starts to deviate from it reference trajectory. If the aircraft is accurately following the glide-path, this moment will occur when the prediction time of the symbol is equal to the Time-To-Contact with the runway if no pilot action would be taken. This implies that the chosen prediction time is of great importance to the flare initiation. On the other hand the prediction time also influences the pilot-predictor-aircraft system's performance[15], and of course to the prediction accuracy itself as it is based on assumptions of unknown future inputs. Determining the right type of predictor laws and the optimal prediction time is, therefore, crucial to the success of using a FPP during the final phase of the landing and this will be discussed in the following chapter.

The second predictive guidance concept that was examined is the Flight Trajectory Predictor (FTP). This concept does not only present the aircraft's position a certain prediction time ahead, but displays a future trajectory till a certain maximum prediction time $T_{PR\,max}$. It is possible to obtain the predicted trajectory using the same prediction techniques as the FPP, but for a prediction time range. By connecting the sequential predictions and presenting them on each tunnel side the future flight-path angle is directly visualized. It is assumed that the pilot uses the trajectory prediction and combines the furthest visible prediction of position and flight-path angle to control the aircraft during the flare. The intersection between the predicted path and the runway indicates the point where touchdown will occur if no pilot control action is taken, and the difference between predicted flight-path angle and runway inclination indicates the predicted sinkspeed at touchdown. These two variables are assumed to be the main factors that determine the success of the landing maneuver and pilots may be able to perceive and control both directly with this predictive guidance concept.

3 Optimizing the predictive guidance concepts for the final phase of the landing

3.1 The extended predictor concept

The extended predictor concept, as proposed by G. Sachs for enhancing the guidance and control capabilities for perspective flight-path displays[14], seems to offer great potential to fulfill the requirements for a suitable predictor during the final phase of the landing. This predictor concept requires minimum pilot compensatory effort, is relatively insensitive to turbulence, and provides a high degree of face validity, as shown by theoretic findings and pilot-in-the-loop simulation experiments[14].

By controlling the predicted future aircraft position to decrease path deviations, the predictor-aircraft system minimizes the actual deviation after the prediction time has surpassed[14]. The primary goal when optimizing this pursuit tracking task is to minimize the compensatory effort that needed while maximizing performance[14]. This introduces requirements for the dynamics of the controlled system that can be specified using manual control theory[16]. Accordingly, the predictor-aircraft $Y_{PR}Y_{ac}$ system should approximate a pure integration K/s with sufficient phase margin around the cross-over frequency[14, 16] ω_c. Other essential requirements to the pilot-predictor-aircraft system $Y_pY_{PR}Y_{ac}$ are system stability and low turbulence sensitivity. The extended predictor concept is capable of satisfying these requirements and can be expressed as[14]:

$$\Delta h_{PR}(s) = \frac{K_q}{1+T_q s} q(s) + \frac{VT_{PR}s + V}{s^2} \dot{\gamma}(s) \qquad (1)$$

Δh_{PR} in equation (1) represents the predicted height error, K_q resembles the pitch rate q deviation feedback gain, T_q resembles the lag time constant of this feedback loop, V represents speed, T_{PR} represents the prediction time, s is the Laplace operator, and $\dot{\gamma}$ is the first time derivative of the flight path angle. A block diagram of the system using this extended predictor is illustrated in Fig. 1.

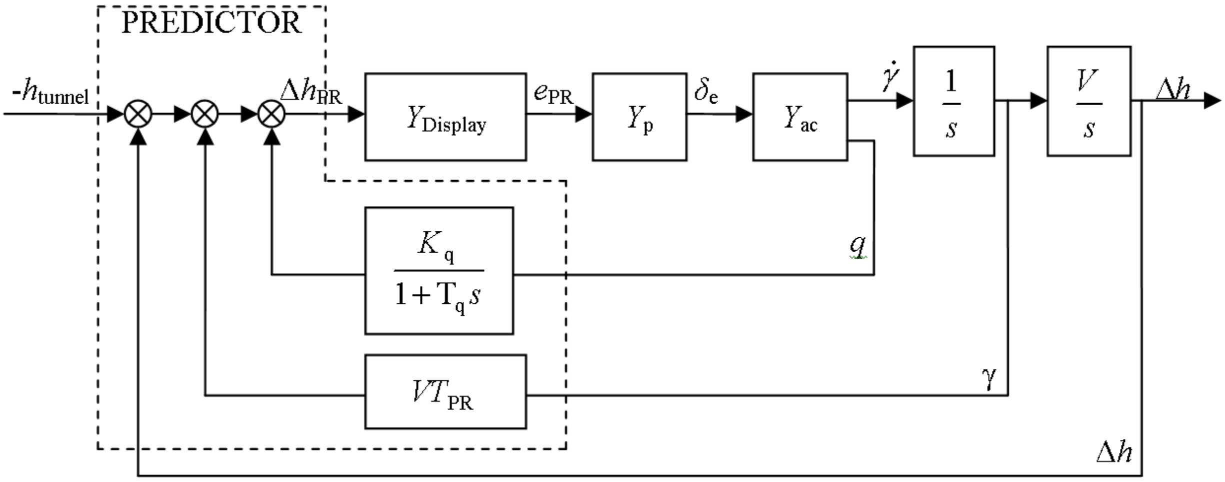

Fig. 1 Extended predictor diagram[14]

To examine if the predictor-aircraft system $Y_{PR}Y_{ac}$ approximates a pure integrator K/s and satisfies the consistent requirement, the aircraft dynamics in the frequency region of concern should be determined. It is assumed that the Short Period (SP) mode of the aircraft dynamics is dominant in the frequency region of concern and where the pilot-predictor-aircraft crossover can be expected[14]. By selecting the lag time constant T_q to be equal to the negative reciprocal of the stability derivative Z_α ($T_q = -\frac{1}{Z_\alpha}$) and selecting the pitch rate feedback gain K_q to be equal to VT_{PR}/ω_{SP}, it can be assured that the system to be controlled by the pilot approximates a pure integrator[14] K/s. Still, the prediction time T_{PR} remains to be tuned to optimize the predictive landing guidance concepts for the final phase of the landing.

3.2 Optimizing the predictive guidance concepts

As stated, the prediction time T_{PR} still needs to be optimized. A MATLAB/Simulink simulation of the pilot-predictor-aircraft system was used to investigate the system in the time domain for different values of prediction time to acquire the most favorable setting.

For the simulation, the aircraft model Y_{ac} represents a linearized Boeing 747 for which lateral movement is neglected. It is assumed that the model, which is linearized around a stationary descending flight along the flight-path, is valid during the final approach and flare maneuver until touchdown. The only control input that is used during this simulation is the elevator. Adding the throttle as second control input would have offered better performance in the presence of disturbances[6], but the goal of this simulation is to optimize the predictive guidance concepts for the flare maneuver and not for the recovery from disturbances.

The pilot model Y_p that is used for this simulation consists of a pilot gain K_p (the system to be controlled already approximates a pure integrator, so no equalization is necessary) and a model that represents the pilot's intrinsic limitations. In the following equation (2) the pilot model is given:

$$Y_{\mathrm{p}} = \frac{\delta_{\mathrm{e}}\left(s\right)}{e_{\mathrm{PR}}\left(s\right)} = K_{\mathrm{p}} e^{-j\omega T_{\mathrm{e}}} \frac{1}{T_{\mathrm{N}} s + 1} = K_{\mathrm{p}} e^{-0.3 j\omega} \frac{1}{0.1 s + 1} \tag{2}$$

The symbol δ_e in equation (2) represents elevator deflection, e_{PR} is the normalized predicted error in relation to the reference trajectory, T_e and T_n are respectively the effective (information processing) time delay and the neuromuscular lag[15]. The only variable in the pilot model that can deliberately be altered is the pilot gain K_p that effectively determines the balance between stability and performance for the system as a whole.

Stability is generally considered to be the most stringent requirement for system control. Using root locus design, a stable pilot gain K_p region can be determined for different values of the prediction time T_{PR} in the pilot-predictor-aircraft system $YpY_{PR}Y_{ac}$. The result is a stable pilot gain region with a maximum gain of approximately 2 for prediction times larger than two seconds and this stays roughly constant for larger prediction times.

After taking care of the stability requirement, the performance comes into play. To establish the optimal prediction time $T_{PR\,opt}$, certain performance requirements must be determined. It is assumed that the two most important subjective measures that determine the landing performance are the runway consumption until touchdown d_{rw} and the descent velocity at touchdown $\dot{h}_{td}$. Therefore, it is stated that the landing maneuver is successful when these two measures are within the following limits[17]:

$$\begin{aligned} d_{td} &< 366m \\ \dot{h}_{td} &< 0.914\,{}^{m}\!/_{s} \end{aligned} \tag{3}$$

Using these limits, the following optimization procedure is defined:

1) Run multiple simulations for different stable pilot gains and prediction times.

2) Evaluate if the performance of the simulated landing fulfils the requirements specified in equation (3) and can be labeled as successful.

3) Count the number of successful landing over the whole range of stable pilot gains and prediction times to obtain the landing score.

In Fig. 2 the results of the optimization procedure, the landing score, is illustrated. It can be observed that for both the predictive guidance concepts (FPP and FTP) the optimal prediction time is located at approximately five seconds. Now the system is optimized using manual control theory and offline simulations, the human interaction with this control system needs to be examined to complete the investigation.

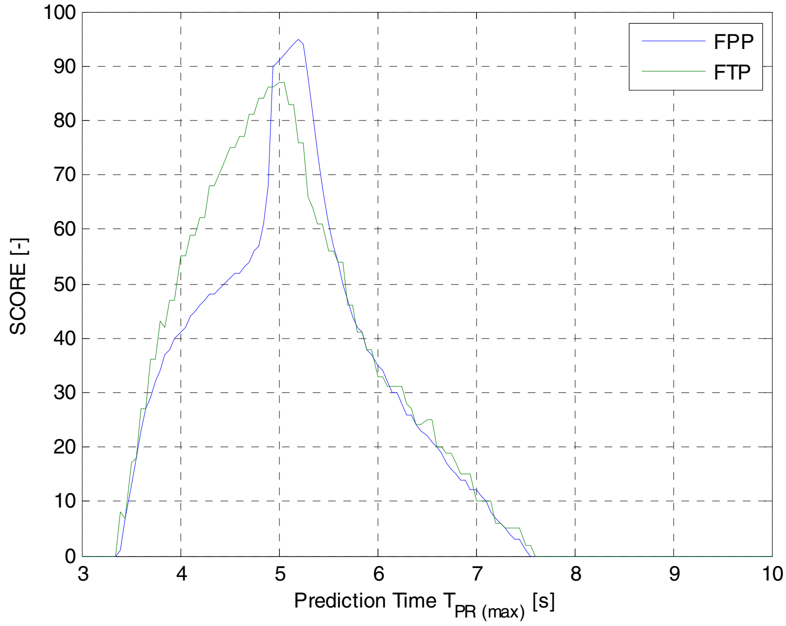

Fig. 2 Landing score, the summation of successful simulated landings versus prediction time T_{PR}

4 Experiment

The goal of the experiment was to evaluate the usefulness of 3D predictive landing guidance in synthetic vision displays during the final phase of the landing.

4.1 Method

4.1.1 Apparatus

The experiment is conducted in the NLR Generic Research Aircraft Cockpit Environment (GRACE) reconfigurable moving base flight simulator. For this experiment the GRACE simulator is configured to simulate a Boeing 747-400 for both hardware (steering column and Boeing throttles) and software components.

4.1.2 Subject and Instructions to Subjects

Ten professional airline pilots participated in the experiment. The mean age of the pilots was 39 and they had an average flight experience of 7237 hours (Table 1). All pilots were instructed to fly the final phase of the landing as they would normally do during a manual landing, with the exception that they could manually land the aircraft using instruments only.

Table 1 Characteristics of the pilot subjects in the experiment

Pilot	Sex	Age	Hours	Types of aircraft
A	M	42	11700	B747-300, B767-300
B	M	34	6015	B737-200/300/400/500/700, A330, A320
C	M	42	8900	NF-5, F-16, B747-300, B737-300/900
D	M	33	6700	Fokker 100, B767, B747-300, B777, B737
E	M	53	13000	DC-9, DC-10, B737-400, B747-400
F	M	36	3000	BAe 146 / Avro RJ
G	M	40	5100	Cessna Citation II, Fairchild Metro II, Fokker 100, B767, A330
H	M	24	1150	Cessna 172 / 206 / 208 / 182, Piper Pa28, B777
I	M	56	13000	F5, F104, DC-10 Fokker F27, A310, B747-300, B747-400
J	M	30	3800	MD-80, MD-11, B737

4.1.3 Independent variables

One independent variable was varied in the experiment: the type of visual information provided to the pilot. There were five different conditions in which the type of provided visual information is varied (the flight displays of each condition are shown in Fig. 3 to Fig. 7):

a) Conventional PFD with degraded but still available outside visibility.
b) Synthetic vision display with Flight-Path Predictor (FPP), but without available outside visibility.
c) Synthetic vision display with Flight Trajectory Predictor (FTP), but without available outside visibility.
d) Synthetic vision display with Flight-Path Vector (FPV), but without available outside visibility.
e) Synthetic vision display with Flight-Path Vector (FPV) with textures, but without available outside visibility.

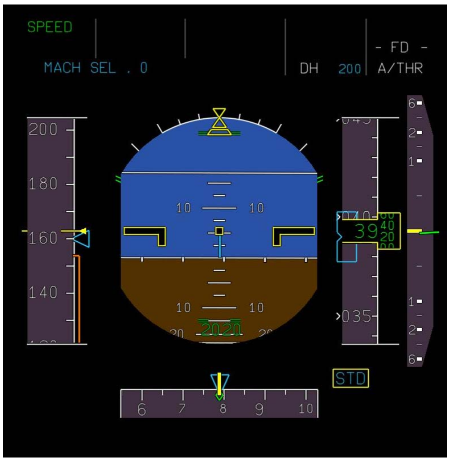

Fig. 3 Conventional PFD.

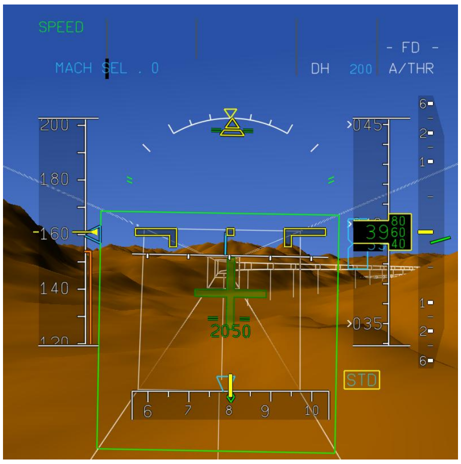

Fig. 4 Synthetic vision display with FPP

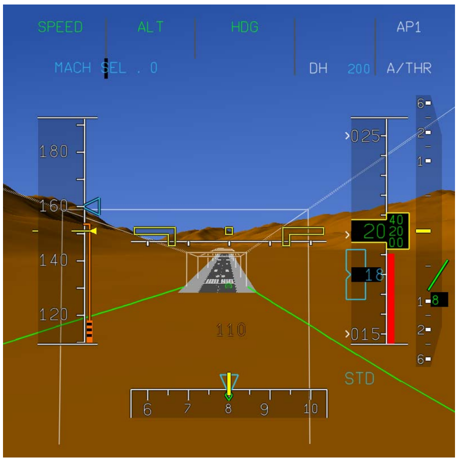

Fig. 5 Synthetic vision display with FTP

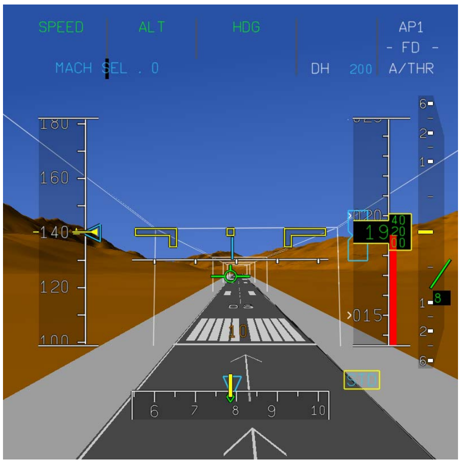

Fig. 6 Synthetic vision display with FPV.

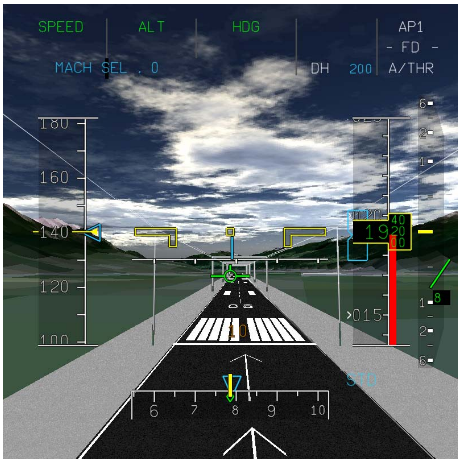

Fig. 7 Synthetic vision display with textures and FPV

4.1.4 Experimental design and procedure

The five experiment conditions were randomized over each experiment day in blocks of five runs. On each day a crew of two pilots was invited to participate in the experiment. After conducting several training runs for each experimental condition they were asked to complete five replications of all conditions that served as measurements. Each run started at a height of 1000 feet and it took about 90 seconds for pilots to complete the landing. After each landing, the pilot in control was asked to complete an ‘end of run questionnaire’ which examines the mental workload using the NASA TLX Subjective Workload Scale. Subjective landing performance was determined by asking the pilots to rate the main performance parameters, touchdown distance from threshold and sinkrate, after touchdown. After all runs for a condition were completed, the participants were asked to fill in an ‘end of block questionnaire’ that was used to obtain comments about that specific experiment condition. At the end of the day when all experiment cases were conducted, the participants were asked to complete the ‘end of day questionnaire’ to explain their strategies, rate each condition and comment on the experiment.

4.1.5 Dependent Measures

Six types of variables acted as dependent measures: 1) pilot control activity, that is, aileron deflection δ_a, and elevator deflection δ_e; 2) pilot workload (the TLX rating); 3) path-following performance, that is track position error x_e, and y_e; 4) landing performance variables, that is, runway consumption until touchdown, and sinkrate at touchdown; 5) flare initiation variables, that is flare initiation height and Time-To-Contact; 6) flare control variables after initiation, that is, pitch angle at touchdown θ_{td}, maximum elevator excitation, time to maximum elevator excitation, and flare excitation rate. The Standard Deviations (STD) of these variables represent the experimental results.

4.2 Experiment hypotheses

It was hypothesized that the addition of predictive guidance to the synthetic vision displays would result in lower pilot control activity, lower workload, and better (path-following) performance compared to synthetic vision displays without augmentation. For the difference between the FPP and the FTP, it is expected that the FPP has better path-following performance, while the FTP has better landing performance. The addition of textures to the synthetic vision display was hypothesized to have positive effects on landing performance. The conventional display with available outside visibility is expected to result in overall better landing performance and is mainly included for comparison purposes.

5 Results and discussion

The main results of the experiment are summarized in this section.

5.1 Statistical Analysis of the Dependent Measures

The means and 95% confidence limits of the dependent measures are shown in Fig. 8 to Fig. 19.

5.1.1 Pilot control activity

For elevator control inputs (Fig. 8), the control activity tends to be larger for condition with PFD and FPP ($F_{4,36} = 0.483$; not significant). This indicates that the predictive guidance concepts cause the pilot to control the aircraft in pitch direction more actively as compared to the other experiment conditions that do not use predictive guidance.

Newman-Keuls (NK) post-hoc analysis ($p = 0.05$) indicates that the aileron control activity (Fig. 9) is evidently largest for the condition with FPV without textures. The difference between condition with and without textures (FPV+T and FPV respectively) is interesting, because it indicates that the addition of textures to the synthetic vision display resulted in less control activity by pilots. The results for the conditions with predictive guidance (FPP and FTP) indicate that the addition of predictive guidance supports pilots in lateral control and allows them to adapt a less active control strategy compared to the FPV condition that provided neither predictive guidance nor additional visual information using textures. Between these two conditions the control activity with FPP tends to be smallest, while both use the same predictor laws and related symbology. Still, the differences in symbology are likely to have caused the difference in control activity. For lateral control, the FTP provides a small circular symbol and this small size and coherent saliency may be important factors in the amount of support it can offer.

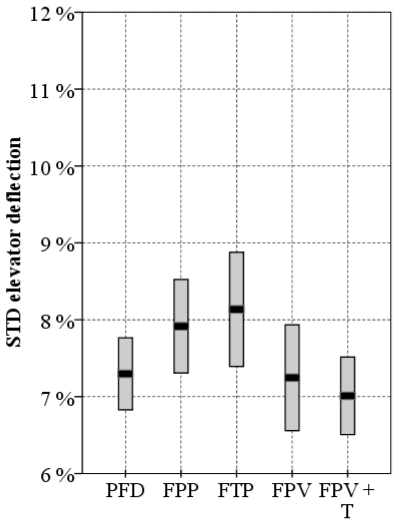

Fig. 8 STD elevator deflection δ_e

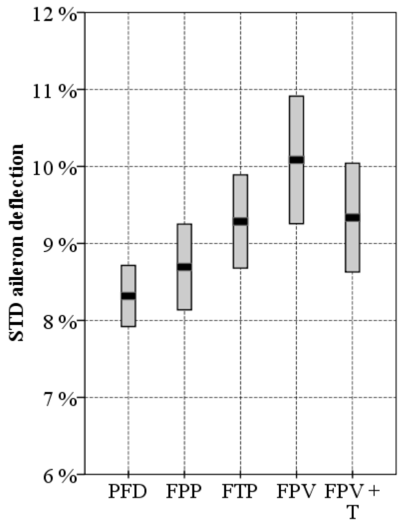

Fig. 9 STD aileron deflection δ_a

5.1.2 Pilot workload

The workload for PFD condition with conventional Primary Flight Display and with degraded but still available outside visibility was rated lower than the other cases that provide synthetic vision without the availability of outside vision (Fig. 10). With the exception of the experiment condition with Flight Trajectory Predictor (FTP), the differences in workload for the conditions that use synthetic vision are small. The FTP is specifically designed to support the flare maneuver and does not provide much assistance before this moment. Pilots commented that a better option would be to enable the FTP just before the flare initiation to prevent the added symbology from becoming a nuisance. This nuisance effect is probably the main cause of the higher rated workload, because the frustration level component of the TLX rating was generally rated higher for the FTP.

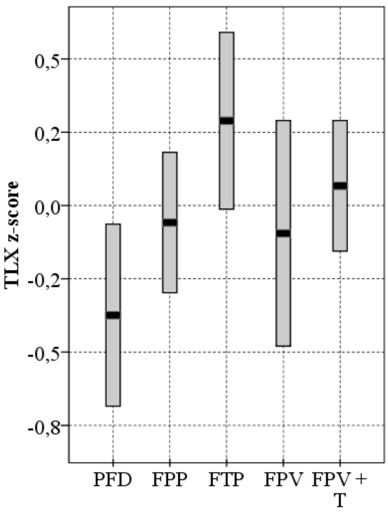

Fig. 10 TLX workload rating (z-score)

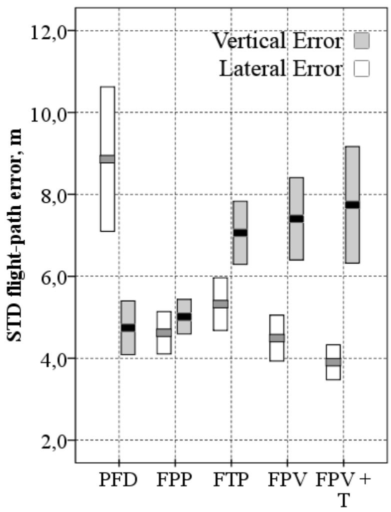

Fig. 11 STD lateral and vertical flight-path error x_e and y_e, m

5.1.3 Path-following performance

The pilot controls the aircraft from a height of 1000 ft to touchdown and the flare is generally initialized at a height of 50 ft. The pilot has to control the aircraft for 95 % along the glide-path to approach the runway and, as the old saying goes: "*A good landing requires a good approach*", it is an important part of the landing. The path-following performance is, therefore, illustrated in Fig. 11. Post-hoc analysis (NK; $p = 0.05$) revealed that the vertical path-following performance is significantly better for experiment condition with PFD and with FPP ($F_{4,36} = 4.025$; $p < 0.01$). Observing the elevator control activity for these experiment conditions from Fig. 8 and comparing this to the path-following performance indicates that the higher control activity for the experiment case with FPP did not result in a increased accuracy. Still, a synthetic vision display with FPP is clearly able to assure a vertical path following accuracy that can be compared with conducting a conventional landing with available outside visibility. For the experiment case with FTP, the control activity tends to be even larger, while the path-following performance decreases. As mentioned before, the FTP is designed to support the pilot during the flare maneuver and during the approach the pilot has to control the aircraft through the tunnel without much additional support. This has probably resulted in the lower path-following accuracy for this predictive guidance concept.

The lateral path-following performance is clearly less accurate for the conventional experiment condition with PFD ($F_{4,36} = 18.35$; $p < 0.01$). Still, the aileron control activity does not vary much between experiment conditions (especially not between experiment case with PFD and FPP) (Fig. 9). This difference may be caused by the relatively small sized tunnel that is used on the synthetic vision displays compared to the larger ‘lateral tolerance’ that is ‘allowed’ during conventional approaches. Pilots commented that for the tunnel size for the synthetic vision concepts was too small at high altitudes. This tunnel size was optimized for the flare maneuver and kept constant during the approach, but a larger tunnel that narrows with decreasing height may be more practical.

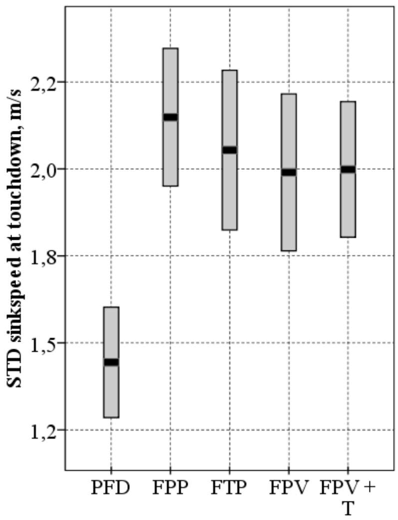

Fig. 12 STD sinkrate at touchdown $\dot{h}_{td}$, m/s

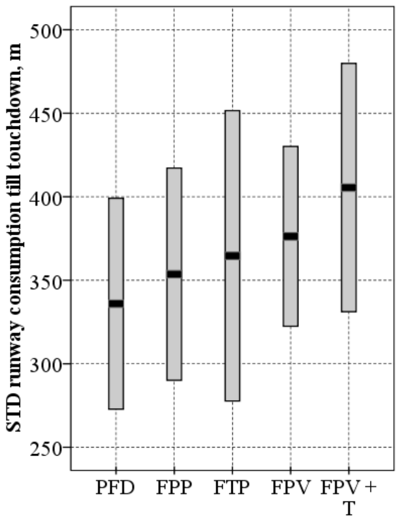

Fig. 13 STD runway consumption till touchdown x_{rw}, m

5.1.4 Performance variables

As mentioned in paragraph 3, it is assumed that two subjective measures are of main importance to the flare maneuver. These two measures are: the runway consumption until touchdown; and the vertical descent velocity at touchdown. In paragraph 3 two requirements for these measures are introduced to determine if a landing is successful or not.

First, the runway consumption until touchdown is considered. In Fig. 13 the means and confidence limits indicate small differences between experiment conditions ($F_{4,36} = 0.686$; not significant). The runway consumption for successful landings is required to be smaller than 366 meters. Fig. 13 shows that the runway consumption during the actual experimental runs lays around this requirement and the runs that are represented by area below this requirement can be labelled as successful. When comparing the different experimental conditions, the general trend seems to indicate that the runway consumption is smallest for the conventional condition with PFD and increases for the subsequent conditions, resulting in fewer successful landings.

Second, the sinkrate at touchdown will be discussed. Fig. 12 shows that none of the confidence limits are below the maximal sinkrate requirement of 0.914 m/s for successful landings. Still it is clear from post-hoc analysis (NK; $p = 0.05$) that the sinkrate for the conventional experiment condition with PFD is significantly smaller compared to the other conditions, as was hypothesized ($F_{4,36} = 7.514$; $p < 0.01$). What causes this striking difference in sinkspeed between 'normal' landings with available outside vision and landings using synthetic vision as sole means of visual information? Is this caused by a wrong flare initiation or is the flare control after initiation more likely to be the cause? To answer this question, the flare maneuver is examined in more detail in the following paragraphs.

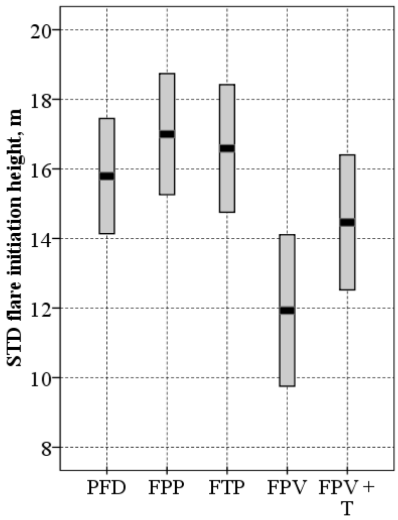

Fig. 14 STD flare initiation height, m

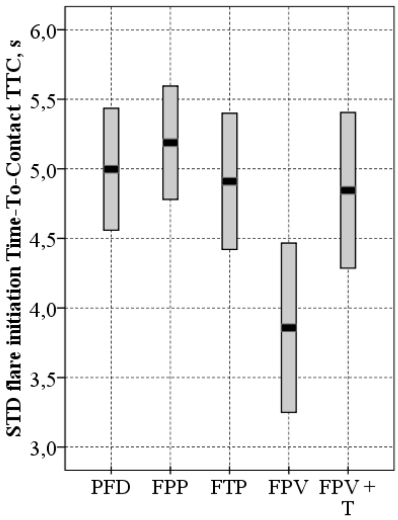

Fig. 15 STD flare initiation Time-To-Contact, s

5.1.5 Flare initiation variables

Obviously, the flare initiation time instance has to be determined in order to obtain an indication of whether this contributes to the difference in sinkrate. The technique that is developed to determine the flare initiation moment is thoroughly explained in the appendix. In short, this technique uses the elevator angle to reveal the moment when the pilot pulls back the control column to excite the phugoid eigenmotion of the aircraft.

As mentioned in paragraph 1, the pilot uses at least two different flare initiation timing strategies; one based on the perception of altitude and one on the notion of Time-To-Contact (TTC). For this reason, the flare initiation time instances were converted to the flare initiation height and TTC. By illustrating the means and confidence limits (Fig. 14 and Fig. 15) for these two important variables, an indication of the likelihood that the flare initiation influences the sinkrate at the end of the entire maneuver can be derived.

Starting with initiation height, as expected the flare initiation height is located between 15 and 18 m (or 50-60 ft) on average (Fig. 14). This is noticeable for all experiment conditions with exception of the condition for synthetic vision displays with FPV but without textures. Post-hoc tests (NK; p = 0.05) showed that the flare initiation height for this experiment case is clearly smaller than the other experimental conditions. Notice that there is no distinct difference between the conventional experiment condition with PFD and the two experiment conditions with synthetic vision and predictive guidance (FPP and FTP).

Equivalent to the theoretically determined optimal time to initiate the flare maneuver, the observed flare initiation TTC is approximately 5 seconds (Fig. 15). Although there are no significant differences between the experiment conditions ($F_{4,36}$ = 1.883; not significant), the general trend can be compared with the trend in the flare initiation height (Fig. 14). Pilots tend to initialize the flare maneuver later and at a lower height when no predictive guidance or textures are displayed on the synthetic vision display (FPV condition without textures).

Consequently, there are no indications that the moment of flare initiation contributes to the difference in sinkrate between the conventional condition, with PFD and outside visibility, and the other conditions that provide synthetic vision. The general trends of the moment of flare initiation do not seem to match to the trend in sinkrate over the experimental conditions. In the following paragraph, the flare control after initiation will be examined to determine if there are indications that this aspect contributes to the differences in sinkrate.

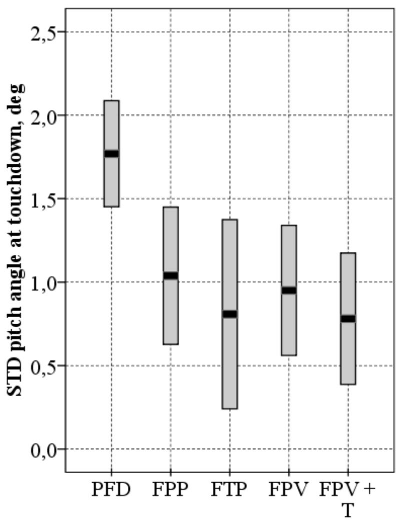

Fig. 16 STD pitch angle θ_{td} at touchdown, deg

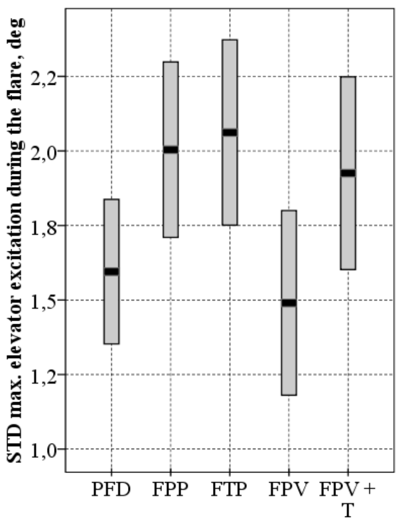

Fig. 17 STD maximum elevator excitation during the flare, deg

5.1.6 Flare control variables after initiation

After initializing the flare, the pilot controls the aircraft until touchdown finalizes the maneuver. The pilot rotates the aircraft in pitch direction and the resulting pitch angle at touchdown is illustrated in Fig. 16. Post-hoc test (NK, p= 0.05) showed a clear difference between pitch angle at touchdown for the conventional experiment condition with PFD and the other conditions ($F_{4,36} = 2.869$; $p < 0.05$). To increase the understanding of how this pitch angle is achieved and how the flare is controlled during the experiment, the change in elevator deflection is examined. Pilots normally initialize the flare maneuver by gradually pulling back the control column to increase the elevator deflection. It is assumed that the maximum elevator deflection after initiation and the time between initiation and reaching this maximum deflection are of strong influence to the flare maneuver. To establish these two variables, the original elevator control signal is processed by a Moving Average Filter (MAF) with an interval length that equals the period of the short period eigenmotion (also see the appendix). This processed signal is used to determine the difference between maximum elevator deflection and the elevator deflection at flare initiation. Also the time difference between these two occurrences is ascertained. The means and confidence limits of both of these differences are given in Fig. 17 and Fig. 18.

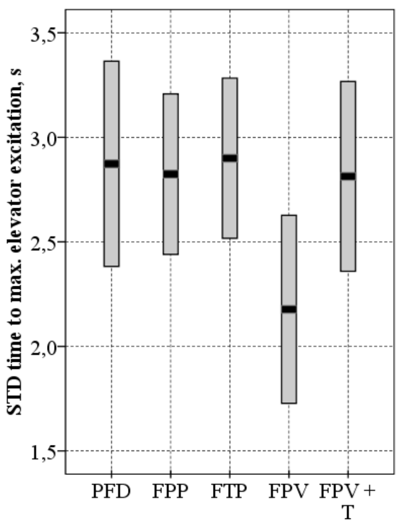

Fig. 18 STD time to maximum elevator excitation during the flare, s

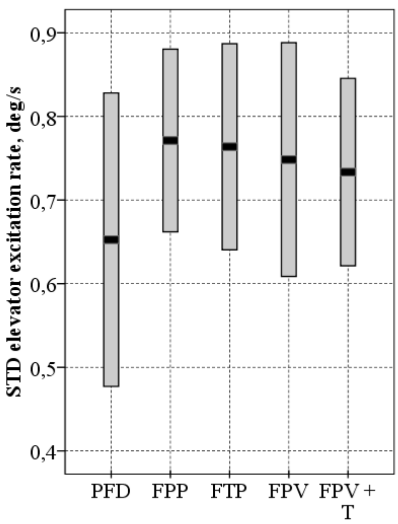

Fig. 19 STD elevator excitation rate, deg/s

The maximum elevator deflection tends to be smaller for the conventional experiment condition with PFD and the condition with FPV ($F_{4,36} = 1.636$; not significant) (Fig. 17). For the time to maximum elevator deflection, however, only the experiment condition with FPV seems smallest ($F_{4,36} = 1.129$; not significant) (Fig. 18). Thus, for the condition with FPV both the maximum elevator deflection and time to reach this maximum tend to be relatively small. Combining these two variables by dividing the maximum deflection with the time to obtain this maximum from initiation will provide an elevator deflection rate, which may contribute to increasing the understanding of the flare control after initiation. The means and confidence limits of this rate are given in Fig. 19. This figure indicates that the elevator excitation rate tends to be smaller for the conventional experiment condition ($F_{4,36} = 0.359$; not significant). In other words, the pilot tends to pull back the control column more gradually when outside vision is available (like for the conventional condition with PFD), compared to landings with synthetic vision as a sole means of visual information.

Notice the similarities between the elevator excitation rate (Fig. 19), the pitch angle (Fig. 17), and sinkrate at touchdown (Fig. 12). Comparing these three figures provides indications that the flare control after initiation is indeed the cause of the differences in sinkrate at touchdown for landings performed using outside vision and landings using a synthetic vision display only. It seems that pilots pull back the control column too abruptly when only synthetic vision is provided. A more gradual control strategy is likely to enhance the performance during the flare maneuver.

5.2 Pilot questionnaire

Almost all pilots suggested that the pitch ladder and banking angle indication should be included in the synthetic vision displays. These were left out to prevent clutter, but the pilots disliked this and it is, therefore, suggested that this symbology should be included in future synthetic vision displays that focus on the landing.

Two pilots suggested that the size of the tunnel-in-the-sky should be larger at greater heights to prevent pilots from controlling the aircraft with too much precision when it is not absolutely necessary. Two other pilots even suggested that the tunnel-in-the-sky in the synthetic vision displays should be removed, or replaced by a 2D indication of the flight path to be followed.

Three participants suggested that the conditions with FPP and FTP symbology should only be displayed below an altitude of 200 feet. Also, one pilot indicated that a target symbol for the FPP and FTP within the tunnel should be included. According to one pilot, adding wind information (direction and intensity) to the PFD may be helpful during the final phase of the landing. One participant indicated the need for more training and would have liked to fly more experimental runs with the displays that include FPP and FTP symbology.

Concerning the experimental setup, it was mentioned that the experiment day was very intense. The experiment consisted of a large amount of manual performed landings. This large amount caused a few pilots to be quite tired at the end of the day.

For future research on this subject, all pilots were asked if they could think of any other way to support the manual execution of the flare maneuver. Three pilots think that presenting the synthetic environment and symbology on a Head-Up-Display (HUD) would be very advantageous. Surprisingly, three pilots mentioned that they would prefer direct control commands, like those given by a Flight Director (FD) but in this case related to the flare maneuver.

5.3 Discussion on the experimental results

For very few landings the performance requirements from paragraph 3 were satisfied. The consumed runway distance generally stayed within limits (Fig. 13), but the landings were simply too hard during this experiment (see Fig. 12). For this reason it is not possible to assess the number of successful landings and to compare these for the different experimental condition as was done in paragraph 3 during the optimization procedure. As was hypothesized, the performance (especially the sinkrate) at touchdown of conventional experimental condition with outside visibility was better than the conditions that provided a synthetic vision display as only visual information for conducting the landing. Although this was expected, the difference was quite large. A possible reason for this large difference was the application non-conformal field-of-view on the synthetic vision display. In order to present more information on the synthetic vision display, the field-of-view was chosen to be relatively large (60^o). This synthetic field-of-view did not match the pilot's field-of-view, which was less than 20^o when one was focusing on the 14.1 inch display at a distance of 90 cm. The pilot may have (unconsciously) assumed that the synthetic vision display resembled the view when looking out of a window that is the same size as the display. The perceptual bias that results may have caused objects to appear to be located on a different place than in actuality. Another probable reason was the relatively small sized display with respect to the outside vision and proportional lower visibility of rates and accelerations on both sources. These two reasons are believed to have influenced the pilot control strategy and may explain the performance differences. By analyzing the pilot's control actions it was noticed that the pilot control strategy after flare initiation was the main cause of the harder landings. Pilots pulled back the control column too abruptly when using the synthetic vision display. A more gradual control action was likely to improve the landing performance, but the synthetic vision display probably did not provide enough visual information to allow pilots to adopt such a control strategy.

Fig. 15 indicates that the flare maneuver was initialized at lower height and smaller Time-To-Contact for the experimental condition with FPV compared to the other cases. This experimental condition provided no predictive information (FPP or FTP) or (ground)textures. The absence of this additional information may have caused the pilot to initialize the flare at lower height. Fortunately, pilots generally compensated for this late flare initiation by pulling back the control column faster (see Fig. 18) to reduce the sinkrate at touchdown to a level that was comparable with the other experimental conditions that did not provide outside visibility.

Still, this indicates that a FPV by itself did not provide enough visual information for conducting a flare maneuver and augmentation is preferred.

This experiment clearly indicated significant performance differences between manual landings that are executed with and without available outside vision. When considering manual performed landings with synthetic vision display as only useful source of visual information (no available outside visibility) it was noted that the addition of predictive landing guidance supports pilots in performing landings under these conditions. Also, the additional information provided by the addition of (ground)textures to the synthetic vision display supported pilots in a similar way. Still, the provided support by augmenting the display with predictive guidance or by the addition of (ground)textures was not very effective. Pilots appeared to perform better timed and controlled flare maneuvers, but the main performance measures (consumed runway distance and especially sinkrate at touchdown) did not improve.

6 Conclusions

To conclude, although the experiment indicates that it is possible to manually land an aircraft without available outside visibility and using synthetic vision, the vertical velocity at touchdown is simply too high. With regard to the flare maneuver, that ultimately determines the performance during the landing, the addition of predictive guidance enhances the pilot's ability to determine the correct flare initiation time instance. The same effect was noticed when more pictorial detail is displayed by rendering (ground)textures on the synthetic vision display. Although the assessment of the correct flare initiation time could be supported by augmenting the synthetic vision display with predictive guidance, the flare control after initiation is not sufficiently supported and as a result there is no significant performance increase. Comparing the FPP and FTP predictor concepts leads to the conclusion that the FPP performance is better and pilots have indicated that this type of predictive guidance is proffered. A possible improvement to the display that is used in this experiment is the application of synthetic vision with a more conformal Field Of View (FOV). The FOV was chosen larger than conformal based on previous research, but a FOV on the display that mimics the view when one would be looking through a window of the same size and location may increase performance. Also, more research is recommended on the application of Head-Up-Displays (HUD) while landing during low visibility conditions. Advanced tunnel design and/or the application of control augmentation with landing as main focus may prove to be very interesting subjects as well.

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Appendix: Determining the moment of flare initiation

The final descent consists of a straight approach along the glide-path. The pilot constantly controls the aircraft and small perturbations and deviations from the desired flight path are corrected using control inputs. At an altitude of approximately 50-60 feet, the flare is initialized by gradually pulling back the control column to increase the elevator deflection and exciting the phugoid eigenmotion. This change in control strategy can be used to determine the flare initiation time instance. Still, the highly frequent fluctuating elevator deflections conceals the exact flare initiation time. Therefore, a Moving Average Filter (MAF) is applied to provide a reliable solution[18].

First, the original elevator control 'signal' is processed by a MAF with an interval length that equals the period of the short period eigenfrequency (Fig. 20). Then, the original signal is processed by a MAF with an interval length that equals the period of the phugoid and the standard deviation of the original signal within the phugoid interval is calculated. Combining the calculated standard deviation with the phugoid MAF, by subsequent addition and subtraction, establishes a deflection range. It is assumed that the control strategy is changed when the short period MAF signal exits the phugoid MAF ± standard deviation range.

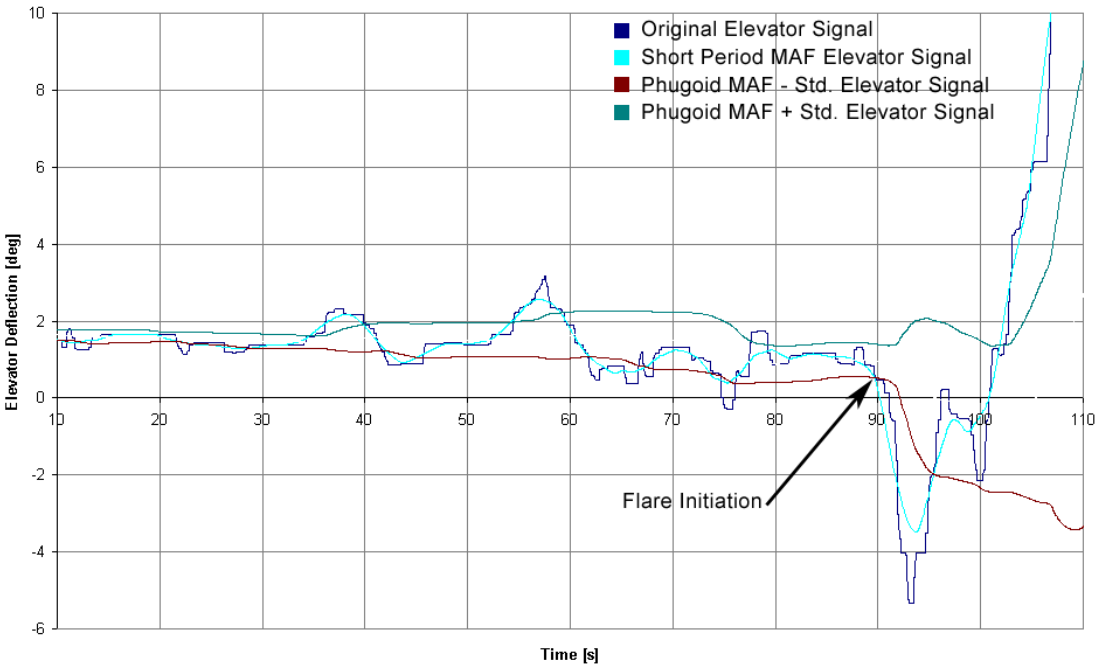

Fig. 20: Using a Moving Average Filter to determine the flare initiation time

In Fig. 20 the signals and the phugoid MAF ± standard deviation range are illustrated. The changed control strategy that initializes the flare is indicated by the arrow. Notice that the short period MAF signal leaves the phugoid MAF ± standard deviation range at approximately 90 seconds which indicates that the flare maneuver is initialized.

This procedure is used to determine the moment of flare initiation for all experiment runs. Visual inspections are used to verify this technique.

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