EVALUATION OF A HEAD-MOUNTED DISPLAY AND ADVANCED FLIGHT CONTROL LAWS FOR HELICOPTER SHIP DECK LANDING

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Abstract

Within the maritime environment, helicopters can be used for a wide variety of missions including rescue missions, transport of personnel and material as well as for surveillance and reconnaissance. To perform such tasks on open sea and to expand the onshore refueling range, ship deck landings are necessary. Adverse weather conditions, such as high winds, fog and precipitation lead to strong ship movements and create a turbulent environment on the ship's landing deck. Combined with few visual cues, ship deck operations put a high workload on pilots which can compromise flight safety. To support pilots during ship deck operations a symbology concept was integrated into the previously developed head-mounted display (HMD) based on a Microsoft HoloLens 2. Three advanced flight control modes were developed for the approach phase. Results from a simulator campaign with pilots in a realistic scenario indicate that the handling qualities can degrade with the HMD and only the relative translational rate command (RTRC) is suited as advanced control mode for ship deck operation.

ABBREVIATIONS

ACAH	Attitude Command Attitude Hold
ACT/FHS	Active Control Technology/ Flying Helicopter Simulator
ACVH	Attitude Command Velocity Hold
ACVsH	Ship-Based Attitude Command Velocity Hold
AVES	Air Vehicle Simulator
DLR	German Aerospace Center
DoF	Degree of Freedom
DVE	Degraded Visual Environment
FOV	Field of view
HEDELA	Helicopter Deck Landing Assistance
HELMA	Helicopter Flight Safety in Maritime Operations
HMD	Head-Mounted Display
ITC	Inside-the-Cockpit
TLX	NASA Task Load Index
OTW	Out-the-Window
OW	Overall Workload
RTRC	Relative Translational Rate Command
SART	Situation Awareness Rating Technique
SDL	Ship Deck Landing
TRC	Translational Rate Command

1. INTRODUCTION

Helicopters are used in the maritime environment in a wide field of military and civil applications. Military missions cover search-and-rescue (SAR), surveillance, reconnaissance and defence while civil applications mainly cover rescue and transport missions to maritime infrastructures. In many missions the mission range and time is very limited by the amount of fuel which the helicopter can carry as refueling must be performed onshore. The refueling problem and further offshore mission challenges can be resolved by performing ship deck landings (SDL). In the past, the SDL manoeuvre has been mainly performed by military operators while in recent years civil police operators have also started to acquire the capabilities for SDL to support their tasks such as maritime border control.

This enables operators to quickly transport personnel and material to and from ships and to use the helicopter outside the onshore refueling range for reconnaissance and rescue missions.

Figure 1 Final approach during a ship deck landing on the F-124 frigate in the AVES simulator with eye gaze (red circle)

In comparison to helicopter onshore operation, flying offshore is often challenging for pilots. Maritime weather is frequently dominated by low cloud bases, perception and fog, which lead to poor visibility. High wind speeds and turbulence put high demands on performance and maneuverability of helicopters. A ship deck landing on open sea puts multiple challenges on pilot and the helicopters performance. Particularly during adverse weather conditions the landing deck is moving around the rotational and translational axis, mainly in roll, pitch and heave. The ships superstructure, the hangar, masts and rotating antennas create a turbulent and constantly changing air wake above the landing deck. Spray from breaking waves disturb the direct sight and the horizon as a visual reference might not be visible due to fog and perception.

Those conditions, turbulence and poor visibility combined with few visual cues in the maritime environment and challenging manoeuvres during the ship deck landing can lead to a low situational awareness and can create a high workload on pilots. To find the limits of acceptable weather conditions for SDL a helicopter ship qualification testing is conducted for every relevant combination of vessel and helicopter types. The result is a ship helicopter operation limit (SHOL) chart for each deck approach pattern, as defined in flight procedure instructions, e.g. the Helicopter Operations From Ships Other Than Aircraft Carriers (HOSTAC) [1]. It shows the maximum allowable wind speed for each wind direction combined with the ship's maximum roll and pitch angle at which test pilots considered the workload for the fleet pilot still as acceptable [2].

Previous research has shown that the helicopter's handling qualities as well as pilots workload and situational awareness can be reduced by using visual assistance systems [3, 4]. A recent study investigated the potential benefits of helmet-mounted displays (HMD) in in the offshore environment [5, 6, 7, 8]. Previous research activities at DLR show the benefit of HMDs for obstacle avoidance and guidance for helicopter missions in degraded visual environments (DVE) [9, 10]. Further improvements in the overall performance of ship deck landings can be achieved by utilizing advanced control laws. There exist designs based on nonlinear dynamic inversion which feature augmented response types that regulate acceleration, velocity and position relative to the landing deck [11]. It was found that a combination of visual cues with control augmentation can also improve the helicopter handling qualities and increase the operational capabilities in DVE [12].

One research area of the Department of Rotorcraft of the Institute of Flight Systems at the German Aerospace Center (DLR) in Braunschweig is the use of assistance systems to improve the helicopters handling qualities and to increase the pilots situational awareness and to reduce their workload for land but also for offshore operations.

In this research a symbology concept for a visual assistance system based on the commercial-off-the-shelf augmented reality (AR) glasses Microsoft HoloLens and three advanced flight control modes were developed to support pilots during the ship deck landing manoeuvre. A maritime environment was implemented into the research simulator AVES (Air Vehicle Simulator) consisting of elements in the visualization and a ship simulation. The assistance systems were evaluated in a simulator campaign by three pilots from the Flight Service of the German Federal Police. During the campaign, the pilots flew two ship deck landing tasks derived from the SHOL chart with and without the developed HMD and in different control mode configurations.

The paper proceeds as follows. In Sec. 2 the work on the visual assistance system during former projects and results from previous campaigns is described. In Sec. 3 and 4 a detailed description of the implemented symbology in the HMD and the advanced control modes is given. Sec. 5 and 6 cover the preparation, simulator configuration, evaluation methods and test missions for the evaluation campaign. In Sec. 7 and 8 the results from the evaluation campaigns are presented and a conclusion, discussion of the results and outlook for further research is given.

2. PREVIOUS WORK

The research on helicopter assistance systems for the maritime environment was performed within the projects HELMA (Helicopter Flight Safety in Maritime Environments) and HEDELA (Helicopter Deck Landing Assistance). Both projects were conducted together with the Flight Service of the German Federal Police.

2.1. Project HELMA

The goals of the project HELMA (2016 - 2018) were to increase helicopter flight safety in offshore wind farms by use of assistance systems. To conduct research on the possibilities of modern visual assistance systems for helicopter operation, the commercial-off-the-shelf (COTS) augmented reality (AR) glasses Microsoft HoloLens 1 were selected. The main selection criteria for the COTS system was the low price, a quick and versatile development toolchain and state-of-the-art color displays and connectivity technologies. A development environment using the recent graphics programming engine has been built up and the glasses were integrated into the AVES at DLR Braunschweig [13, 14]. The first symbology concept for assisting pilots during their missions in offshore wind farms, which was integrated into the Head-Mounted Display (HMD) is shown in Fig. 2. The symbology is described in detail in Ref. [6].

To evaluate the benefit of the developed HMD two piloted campaigns were conducted in the AVES simulator. A maritime environment consisting of 3D models and a wave and weather simulation was integrated into the AVES visualization engine. A total of ten pilots participated in the studies and flew two tasks in the first campaign (a SAR mission and a navigation task) and one task in the second campaign (a hover task at a wind turbine) under DVE conditions in the offshore wind farm Alpha Ventus. The Situation Awareness Rating Technique (SART) was used to evaluate situational awareness and the NASA Task Load Index (TLX) and the Bedford Workload Rating were used to evaluate pilots workload.

The analysis of the subjective SART data shows that with one exception all pilots during all missions experienced an increased situational awareness by using the HMD. As for the NASA TLX ratings most pilots experienced a decreased overall workload while using the HMD. In three cases pilots experienced a higher workload mainly due to the complexity of the symbology and unfamiliarity with the HMD.

As a conclusion, all pilots stated that such a HMD could support their daily work during commercial and police operations in offshore wind farms and could increase flight safety. For notable benefits, most pilots stated that more training is necessary and the symbology colours and shapes should adapt the pilots helicopter avionics concept.

2.2. Project HEDELA

The goal of project HEDELA (2019 - 2021) was to increase helicopter flight safety during helicopter ship deck landing. During the project, the HMD was upgraded to a Microsoft HoloLens 2 [15] and the symbology concept was enhanced with elements to support the ship deck landing task. This is further described in chapter 3. Advanced 3D ship models and a ship movement simulation were added to the maritime environment, which is further described in chapter 5.1.

A major achievement during the project was the integration of the COTS AR glasses as a HMD into DLR's research helicopter ACT/FHS (Active Control Technology/Flying Helicopter Simulator), a highly modified EC135. An algorithm for stabilizing the internal head tracking with an external head tracker was developed and the helicopter was equipped with a COTS head tracker and a WIFI interface to the build-in experimental system. Designed as a proof-of-concept demonstration the first test flights showed the qualification of COTS AR glasses as HMD in a civil helicopter and revealed further technological challenges [16].

3. SYMBOLOGY IN THE HMD

With the HoloLens 2 as HMD it is possible to place three-dimensional holograms anywhere in the world. The holograms themselves are only limited by the capabilities of current game engines. However, due to the general requirements for visual pilot assistance, such as low clutter, simplicity and intuitiveness, the holograms usually only consist of lines. The basic set of holograms, independent of ship deck landings, are shown in Fig. 2.

Various visual cues were developed for the HMD to support pilots when they approach and land on ship decks. It is not intended that all holograms are always active, but rather that the pilots evaluate a variety of indications.

For navigating to the ship, a purple marker is first displayed. It consists of an icon with a label and a direction indication, see Fig. 3.

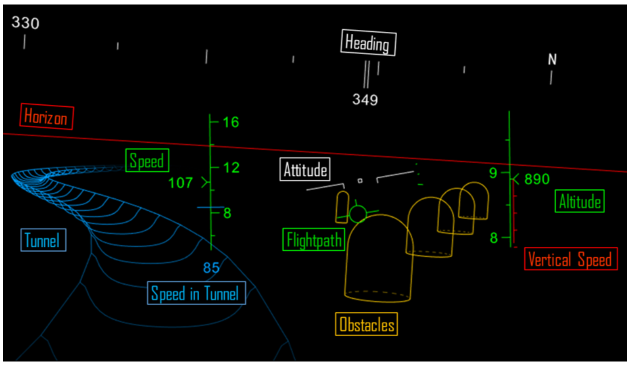

Figure 2 Basic HMD symbology

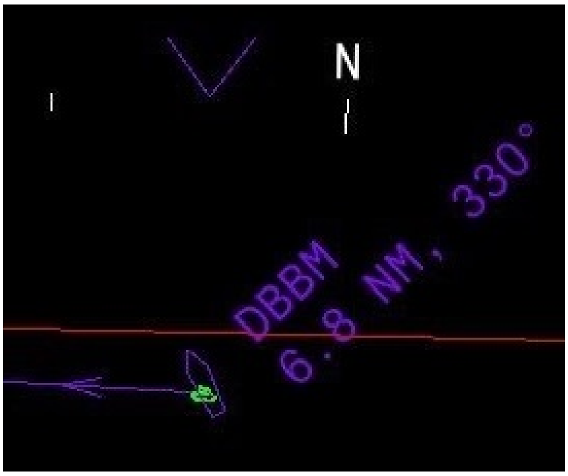

Figure 3 Detailed view of the visual cues to assist navigating to the ship (purple)

The icon symbolizes the top-down view of the ship. This tells the pilot (a) which object the icon represents and (b) which direction the ship is heading. The label next to the icon shows the ship's identification. The detailed information, distance and heading, in the label text are only displayed if the pilot looks at it, representing an automatic head tracking based decluttering. In addition, a "V" icon is displayed in the heading tape, which indicates the direction from the helicopter to the ship. The direction in which the ship is moving is shown with a conformal arrowed line.

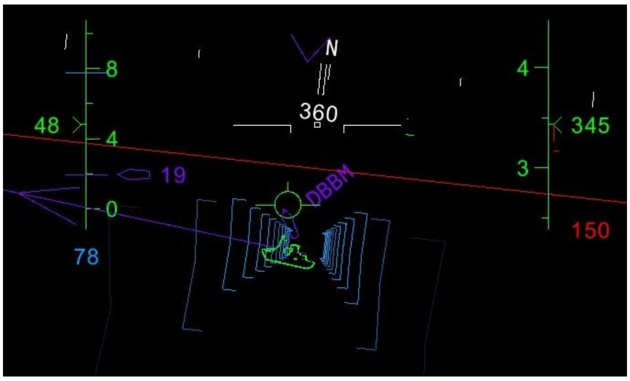

Figure 4 TACAN approach for ship deck landing visualised with a Tunnel-in-the-Sky

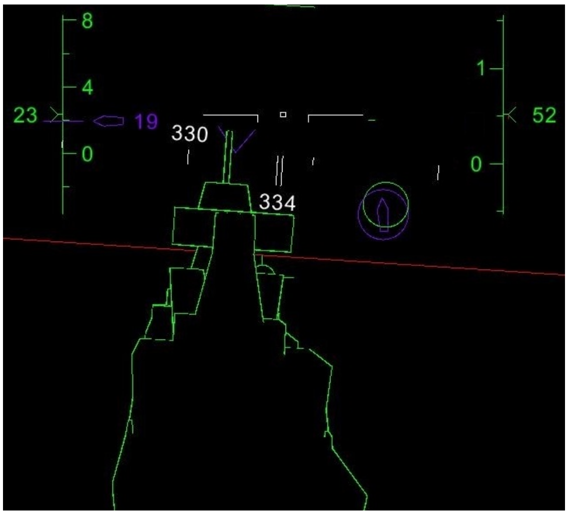

Figure 5 Detailed view of the ship's outline. A drift indicator shows the relative speed to the ship (green circle = helicopter and purple = ship)

If the helicopter gets closer to the ship, a tunnel-in-the-sky is shown, which corresponds to the TACAN (Tactical Air Navigation) approach from the HOSTAC [1], see Fig. 4. The tunnel is virtually attached at the ship so that it moves with it, except for pitch and roll. Such a tunnel can guide the pilot during manual flight or it can be used to monitor the autopilot. Normally, the pilot can customize the shape of the tunnel gates, but the square brackets were predefined for this experiments because other gate design can obscure the view of the ship.

Especially for the final approach, the ship's speed and the relative drift speed are additionally displayed, see Fig. 5. The ship's speed is shown as a marker in the speed band. To show the drift relative to the ship, the existing drift display for fixed objects was modified accordingly. The circle representing the ship is marked by the ship icon. The icon rotates so that heading deviations from the ship are also displayed here. The example in Fig. 5 shows that the helicopter drifts slightly forward relative to the ship.

4. FLIGHT CONTROL MODES

To support pilots during the final approach and landing phase, augmented flight control laws were implemented. Two basic and three advanced control modes were developed focusing the ship deck landing task and were implemented in an established and flight-tested model-following control system [17]. This is a model-following control system which imposes the desired command model dynamics on the controlled helicopter [18]. The control system consists of the command model, a feedforward controller and a decoupled cascaded feedback controller (as shown in Fig. 6). The command model generates reference signals for the desired helicopter motion. Different command types combined with various hold functions are implemented in the command model. These control modes are supposed to reduce pilot's workload and to optimize the vehicles handling qualities especially in situations with high turbulences above the ship deck or degraded visibility.

The feedforward controller is based on a 11-DoF helicopter dynamic model. This model was derived by system identification in time domain [19]. The feedforward controller improves the response quickness and provides basic response decoupling. The feedback controller compensates differences between commanded and measured values due to disturbances and modeling deficiencies. The feedback controller additionally includes the control mode hold function, e.g. the attitude hold mode.

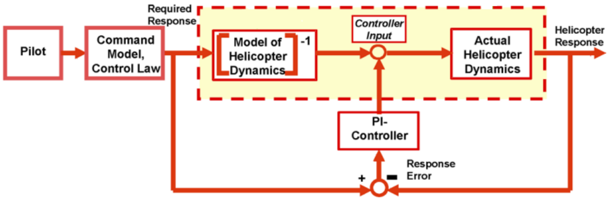

Figure 6 Model-following flight control architecture [20]

4.1. Classical control modes

Two classical command types, namely Attitude Command Attitude Hold (ACAH) and Translational Rate Command (TRC) were implemented in the AVES simulator. With the ACAH command type, the longitudinal and lateral stick deflections are proportional to aircraft pitch and roll attitudes. With the Translational Rate Command (TRC) mode, the stick deflections are proportional to longitudinal and lateral aircraft velocities. In the two command types, yaw rate is commanded with the pedals and is combined with a Direction Hold (DH) and vertical speed is commanded using the collective stick and is combined with a Height Hold (HH).

4.2. Advanced control modes

Three advanced command types, Attitude Command Velocity Hold (ACVH) (with no ship communication), Relative Translational Rate Command (RTRC) (with ship communication) and a ship-based Attitude Command Velocity Hold (ACVsH) (with ship communication) are described in the following section.

The ACVH mode holds the flight path of the helicopter (ground speed and course) when the cyclic is released and acts as a classical attitude command mode when the stick is moved by the pilot. Additionally, the speed and course can also be adjusted using the 4-way stick button. The forward speed and course of the helicopter at activation are stored as reference for the controller. The lateral reference ground speed is set to zero to prevent the drift caused due to the wind. The helicopter returns to its reference speed and course on release of the control stick. The most significant feature of this mode is that no communication between the ship and the helicopter is required. This mode can be useful for EMCON (Emission Control) missions where no communication with the ship is permitted to avoid hostile detection. The mode is designed for pitch, roll and yaw axis and the vertical axis has a classical rate command/height hold.

During the RTRC control mode the speed of the helicopter is matched to the ship speed. In this mode, inputs in the cyclic stick are proportional to a velocity output in the longitudinal and lateral helicopter axis like in a classical TRC mode. The vertical axis has a classical rate command/height hold.

In the ACVsH mode the helicopter initially adapts the heading and speed of the ship. Using the 4-way stick button on the cyclic stick the heading and speed of the helicopter can be adjusted. Inputs at the cyclic stick are proportional to a pitch or roll output angle and by releasing the stick, the ACVsH control mode is reactivated at the new position. The difference of this mode to ACVH is that it involves a communication with the ship and hence can match the ship speed whereas in ACVH the pilot holds manually the current speed and heading of the helicopter and adjusts later.

5. TEST ENVIRONMENT

A piloted campaign was conducted in DLR's AVES facility [21]. The research flight simulator center features three air vehicle modules, which can be exchanged between a fixed based and a motion based platform. To perform basic and advanced research on helicopter systems and in preparation for real test flights, a replica of the cockpit of the research helicopter ACT/FHS is available as a cockpit module. While the motion platform is enabled by a 13 t electropneumatic hexapod system, the recently revised visualisation on both platforms is based on 9 state-of-the-art LED projectors in cross-fire configuration driven by image generators with the latest gaming graphics cards.

The in-house developed nonlinear rotorcraft flight model HeliWorX is used to simulate the helicopter dynamics. It runs in real time at 1 kHz and is based on DLR's former flight model SIMH [22].

The study was conducted in two parts, a control mode evaluation phase and a HMD evaluation phase. As flight control mode during the approaches in the HMD evaluation phase, an ACAH in the roll and pitch axis is used. This control mode corresponds to the Attitude Hold (ATT) mode on the Airbus Automatic Flight Control System (AFCS) used in the standard EC135.

5.1. Maritime Simulator Environment

The maritime environment, as also presented in [23], consists of elements in the visual simulation and the flight model. Various high fidelity 3D models were integrated into DLR's in-house developed image generation software for the outside view projection system. Relevant for the conducted simulation campaign is the F-124 "Sachsen" class military frigate ship model.

As described in Tab. 2, a turbulent wind field based on CFD (computational fluid dynamics) calculation with the F-124 was used during the campaign. The integration and validation of the wind field into the rotorcraft flight model HeliWorX is described in Ref. [24, 25].

The motion of the ship model is driven by the in-house developed software VehicleControl. This software is integrated into the AVES simulator architecture via the real time simulation framework 2simulate. It can execute vehicle dynamic models in MATLAB/Simulink, C++ or replay recorded data. At the current state, a MATLAB/Simulink model based on the Maritime Systems Simulator (MSS, [26]), a C++ hydrodynamic mass-spring-damper model or a replay using data from the SCONE (Systematic Characterization Of the Naval Environment, [27]) project of the US Navy Office of Naval Research can be used to simulate ship movements. An example of the output of the models is shown in Fig. 7. A direct comparison of the output data is not possible at the current state since the models use different hydrodynamic ship data and different wave spectra. Eventually the models shall be used to analyze the required model complexity and fidelity for a helicopter ship deck landing simulation.

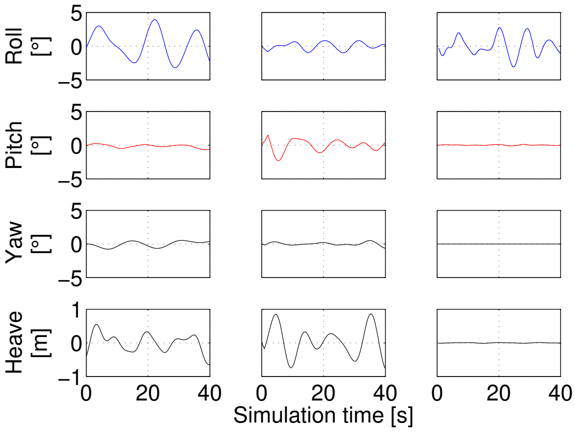

Figure 7 Ship movements from the SCONE model (left), MSS model (middle) and mass-spring-damper model (right)

While the MATLAB/Simulink model uses a separate wave generation algorithm and the SCONE recordings use prerecorded waves, the hydrodynamic mass-spring damper model uses the same wave model and heights as shown in the visualization. The wave calculation and visualization in the image generator is performed by the Sundog Triton Software Development Kit (SDK) which is currently configured to use the JONSWAP (Joint North Sea Wave Project) spectrum [28]. During the simulator campaign, the MSS model with 2 - 3 m significant wave heights corresponding to a wind speed at 20 kt from 30° was used. Considering the constraints of the realtime simulation this model was at that time the best compromise between simplicity and realism.

6. SIMULATOR CAMPAIGN

The developed HMD symbology and the flight control modes were evaluated in a piloted simulator campaign.

Three pilots with different experience from the Flight Service of the German Federal Police participated in the study. The overall experience as well as HMD and offshore experience of the pilots is shown in Tab. 1.

Table 1 Pilots experience

Pilot	Total Flight Hours [h]	Offshore Experience	HMD Experience	Test Pilot
A	2800	Yes	Yes	No
B	750	No	No	No
C	23000	Yes	Yes	No

The average age of the pilots was 45.3 (SD 11.9) years. As the overall flight experience shows, one pilot with only little flight experience, one with a medium level of experience and one very experienced pilot participated in the study. The experienced pilots were familiar with HMD, Night Vision Goggles (NVG) and were in possession of an Instrument Flight Rules (IFR) rating. These pilots also regularly flew offshore missions with varying helicopters while the novice pilot only had experience on onshore missions as pilot-in-command with an Airbus EC135.

6.1. Test Missions

During the simulator campaign, two ship deck landing tasks were flown. The weather conditions and the ships configuration are shown in Tab. 2.

Table 2 Tasks flown in the simulator campaign

Task	1	2
Visibility	1300 m	CAVOK
Wind	20 kt, 30° Airwakes behind the ship	20-40 kt, 30°
Distance to ship	3 NM	1 NM
Height	300 ft HASL	
Airspeed	100kts (IAS)	80kts (IAS)
Ships direction	0°	
Ships speed	10 kt	
HMD	with/without	without
Flight Control Mode	ACAH	ACAH,TRC, ACVH,RTRC, ACVsH

Task 1 was designed as a typical offshore DVE scenario. The helicopter was positioned randomly 1000 m right or left of the extended ships longitudinal axis at a diagonal distance of 3 NM behind the ship. The mission was to recognise the ship and to land. This task was flown with and without the HMD. Since the purpose of the different control modes was to improve the handling qualities during the final approach and landing, the helicopter was positioned in task 2 directly behind the ship in a Good Visual Environment (GVE) scenario with Ceiling and Visibility OK (CAVOK) and a smaller Indicated Airspeed (IAS). This task was flown in two classical control modes (ACAH, TRC) and three advanced control modes (ACVH, RTRC, ACVsH).

The pilots received a briefing prior the simulator campaign where all control modes and the indications in the HMD were explained in detail. Before the evaluation flights, the pilots had 30 min to get familiar with the helicopter control, the HMD and the control modes in the simulator.

6.2. Evaluation Methods

For the subjective evaluation of workload the NASA TLX, as described in [29], was used. It consists, as shown in Fig. 17, of a questionnaire in the six dimensions mental, physical and temporal demand as well as performance, effort and frustration. In a first step those are rated by the pilot on a 21-level Likert scale ranging from very low to very high. In a second step the pilot is asked to weight the dimensions with a comparison questionnaire. The results of the questionnaire can be shown either as raw TLX value or with the second questionnaire as weighted TLX results. However, due to many complaints in previous campaigns on the weighting questionnaire and resulting unmotivated answering, only the raw TLX results were used in this campaign.

To evaluate the situational awareness the Situation Awareness Rating Technique (SART) by Taylor [30] as 10D questionnaire was used (Fig. 18). The pilot is asked to rate ten questions from the subcategories demand (D), supply (S) and understanding (U) of the situation on a seven-point scale. The final SART score is calculated by Eq. 1.

$$(1) \quad SART = U - (D - S)$$

For the analysis of the pilots eye movements the Tobii Pro Glasses 3 were used. The binocular head-worn glasses use eight integrated IR LEDs and two cameras per side to track the movement of the eyes. The cameras work at a sampling rate of up to 100 Hz with an accuracy of 0.6°, according to the manufacturers data [31]. The glasses are equipped with a gyroscope, accelerometer, magnetometer, a microphone and a 95° horizontal FOV and 63° vertical FOV scene camera recording at 25 frames per second.

A screenshot from the scene camera during a ship deck approach is shown in Fig. 1.

For the data analysis the software Tobii Pro Lab in combination with a MATLAB script was used. Within the Tobii Pro Lab software multiple areas of interest (AOI) were defined; an Inside-the-Cockpit (ITC) area covering all cockpit instruments and one area each for the airspeed indicator (ASI), altitude indicator (ALT), heading (HDG) and attitude indicator (ATT). The Out-the-Window (OTW) area was defined as all valid tracking points which were not ITC. The mapping of each valid eye tracking recording frame to one or multiple AOI was done by the Tobii Pro Lab software using an image recognition algorithm. Using the results of the mapping, the in-house developed MATLAB script calculated the number of AOI hits and the ITC/OTW percentage. The eye tracking was only used without the HMD at this point.

7. RESULTS

In this section the results of the subjective and objective analysis are presented. The first subsection covers task 1 with situational awareness and workload for the evaluation flights with and without the HMD and eyetracking results for the case without HMD. The second subsection covers task 2 with the objective results from the deck landing evaluation toolchain and the subjective workload rating for the evaluation flight with different control modes.

7.1. Task 1: HMD Evaluation

The situational awareness scores as shown in Fig. 8 are varying for all three pilots during task 1. While the novice pilot B experiences a relatively high situational awareness with the HMD, the medium-experienced pilot A only rates a slight increase and the expert pilot C even experiences a decrease of situational awareness with the HMD.

The results of the workload analysis show a similar picture. Here both expert pilots A and C experience a slightly higher overall workload (OW) with the HMD while the novice pilot B experiences a decrease in OW, as Fig. 9 shows. Especially in the domain of effort (EF) as shown in the complete NASA TLX analysis in Fig. 10 both expert pilots see an increasing workload while using the HMD. Opposite to results from previous campaigns, where some pilots experienced a higher mental demand (MD) when getting used to new symbology concepts in the HMD (see [6]), both expert pilots didn't experience a higher MD in this campaign.

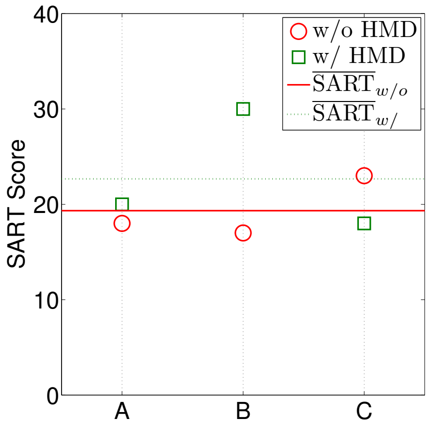

Figure 8 SART Score for Task 1

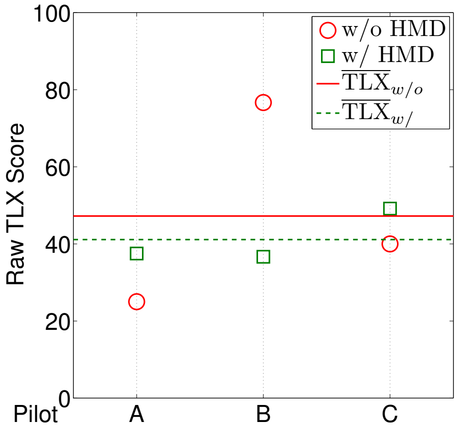

Figure 9 Raw TLX Overall Workload (OW) Score for Task 1

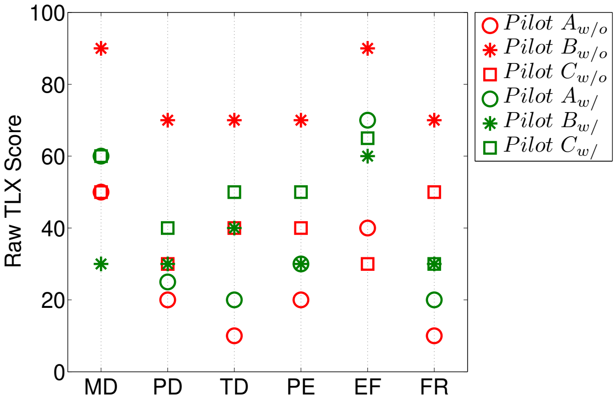

Figure 10 Complete Raw TLX Scores for Task 1 (MD=Mental Demand, PD=Physical Demand, TD=Temporal Demand, PE=Performance, EF=Effort, FR=Frustration)

7.2. Eyetracking analysis

While it was initially planned to compare the results from the internal eyetracking of the HMD with the results from the external eyetracking glasses, only the data from the external eyetracking was used for this analysis. This can be explained by difficulties in mapping the 2D recordings from the Tobii glasses with the 3D recordings from the Microsoft HoloLens 2 and different origins of the used coordinate systems.

The analysis of the eye tracking ITC/OTW percentage in Fig. 11 shows that all pilots spend most of the approach looking out-the-window. The differences between the two experienced pilots A,C and novice pilot B can be interpreted as an effect of training and flight experience.

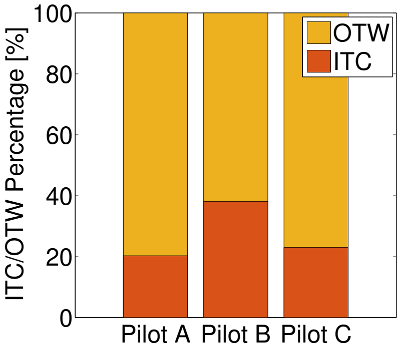

Figure 11 Percentage of ITC/OTW in Task 1 without HMD

The results from the AOI analysis in Fig. 12 show the relevance of the main cockpit indicators during the approach. All pilots have the most number of hits on the attitude indicator followed by the altitude indicator. It can be assumed from the results of this analysis that there is only a minor dependence on the flight experience.

7.3. Task 2: Control Mode Evaluation

A recently developed evaluation toolchain in DLR was used for assessing helicopter ship deck landings and to compare the effects of advanced control modes on selected metrics in comparison to classic control modes [32]. For an objective evaluation, touchdown conditions like position, velocity and attitude errors between the ship deck and the helicopter are evaluated. In addition, supplementary evaluation parameters for the entire approach such as levels of control activity (amplitude and frequency) and position and track error (x and y) during the whole flight trajectory were also investigated.

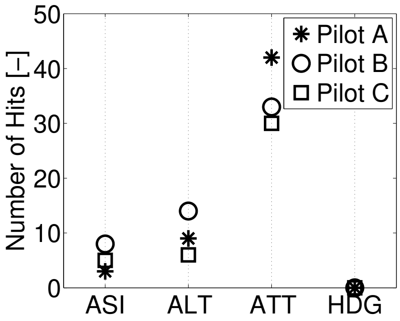

Figure 12 Number of hits on main cockpit indicators in Task 1 without HMD (ASI: Airspeed indicator, ALT: Altimeter, ATT: Attitude indicator, HDG: Heading indicator)

Fig. 13 and Fig. 15 illustrate the position of the helicopter relative to the deck center throughout the whole approach including the landing phase using the basic mode ACAH and the advanced ACVH control configuration by pilot A (other test points are avoided here for brevity). The touchdown positions in the two figures depict that the pilot was able to achieve landing position inside the desired limits with both the command types. Moreover, the pilots were able to achieve a desired or at least adequate performance for landing positions with almost all the command types. The trajectories also depict that it was much simpler to perform the landing in the ship air wake using ACVH command type than the classical ACAH approach. In addition, the results clearly show the improvement in accuracy of landings achievable using the advanced command type.

The power spectral densities (PSD) for the pilot control inputs by pilot A for all the five control configurations are presented in Fig. 16. It should be noted that the results by other pilots are not presented here due to brevity. However, the control inputs by other pilots also demonstrated similar trends. The figures illustrate that the advanced command types resulted in moderate reductions in the pilot control activity. An increase in the pilot control activity indicates a higher workload and moreover, a larger control deflection demands a larger control stick deflection force [33].

The analysis of the subjective data for pilot A for the five flight control modes is shown in Fig. 14. Judged by the overall workload the control modes TRC and RTRC support the pilot best to reduce his workload during the approach. Especially the low TLX rating in the dimension of the mental demand

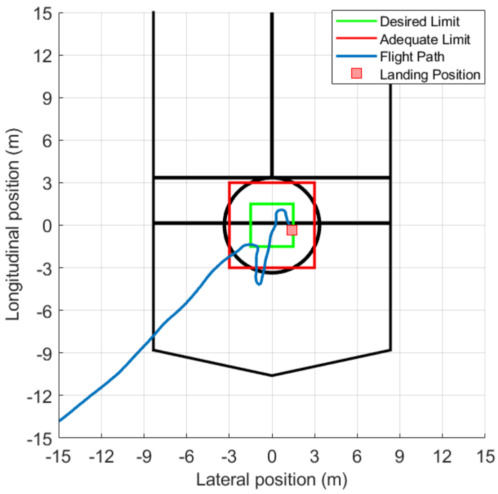

Figure 13 Helicopter position relative to landing position throughout ACAH Approach (by pilot A)

shows that those control modes are very intuitive and do not require much training. Since the other pilots did not finish the evaluation flights with all control modes, only the results from pilot A were presented. The opinion of those pilots regarding the advanced control modes coincides with pilot A. Following this campaign, a dedicated simulator campaign with two additional pilots to evaluate only the control modes also indicated the RTRC as preferred control mode [17].

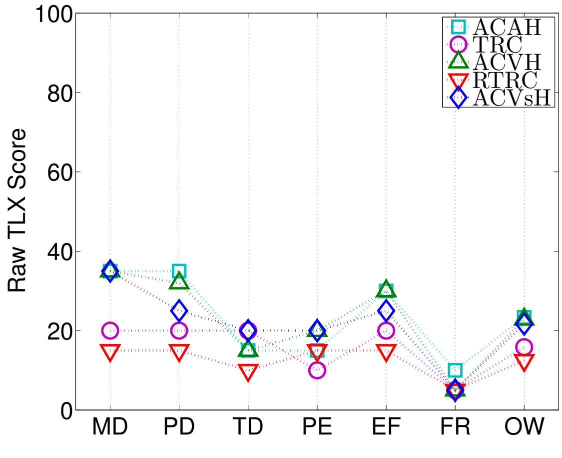

Figure 14 Complete Raw TLX Scores for pilot A in Task 2 (MD=Mental Demand, PD=Physical Demand, TD=Temporal Demand, PE=Performance, EF=Effort, FR=Frustration, OW=Overall Workload)

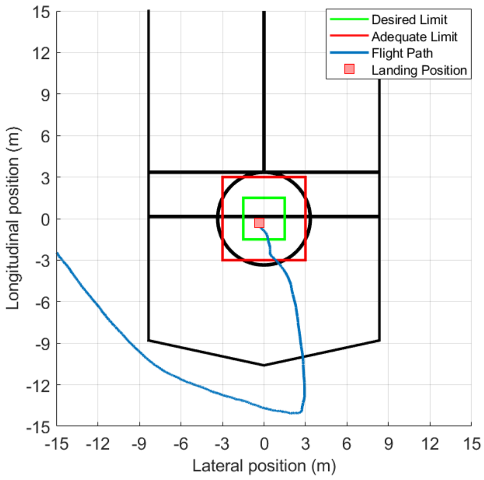

Figure 15 Helicopter position relative to landing position throughout ACVH Approach (by pilot A)

7.4. Discussion

All pilots participating in the campaign complained about the reduced visibility of the HMD as an effect of the limited FOV and the slight darkening of the Microsoft HoloLens 2 glasses. The view is obscured by the multiple edges of the optics of the lenses. The darkening caused by the HoloLens is a simulator problem that occurs due to the low brightness of the outside view.

While the additional cueing in the HMD still created a benefit for the novice pilot, the expert pilots felt primarily disturbed during the final ship deck approach. The reduced visibility is a disadvantage of the COTS AR glasses compared to aviation approved HMD. In a previous simulator study with evaluation tasks in an offshore wind farm (as described in Ref. [6]) none of the pilots felt disturbed by the reduced visibility. Further research is necessary to investigate at which weather conditions and missions the use of COTS AR glasses is still acceptable.

Three pilots with very different flight experience participated in the study. This can be seen in all results from the subjective analysis in perceived workload, situational awareness and results from the eye tracking analysis. While it is very interesting to see the opinions from pilots with different skill levels, it might be difficult to compare the results. In the case of large differences in pilots flight experience it is more useful to compare individual scores and to keep the flight experience in mind rather than focusing on statistical methods. Further research is necessary to investigate the effects of flight experience on subjective metrics and objective performance.

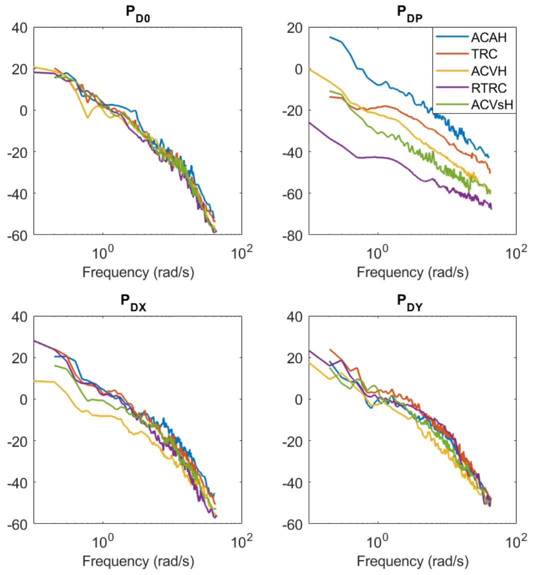

Figure 16 Power Spectral Densities of pilot control inputs throughout different approaches (pilot A)

One factor that is important but could not be considered is the training time required to become familiar with such an HMD system. Even if the indicators are intuitively understood, it takes hundreds of hours to fully re-learn a behavior that was trained thousand of hours. Therefore, the results obtained here refer to pilots who had very little training time with the display method.

In this research only the eye tracking results of the Tobii Pro glasses without the HMD were presented. It has to be investigated in the future, how this data can be compared with eye tracking data from the HoloLens 2. A challenge here is the accuracy of the eye tracking in the HoloLens 2 which might not be sufficient to distinguish between the head-down indicators [15]. Furthermore both systems need to be calibrated in order to use the same coordinate system for the data recording. This can be realized for example with an external head tracker.

8. CONCLUSIONS

The focus of the investigations during the project HEDELA was to evaluate a potential benefit of advanced assistance systems during ship deck landings regarding helicopter handling qualities. A symbology concept was developed and implemented into the Microsoft HoloLens 2 HMD and five flight control modes as well as a maritime test environment were integrated into the AVES research simulator. The assistance systems were evaluated in a simulator campaign with three pilots. Objective data and subjective assessments using NASA TLX, SART and eye tracking analysis was recording during the evaluation.

The following conclusions can be drawn from the analysis of the results of the evaluation campaign:

1. Both expert pilots experienced an increase in overall workload with the HMD during the SDL.
2. Two pilots experienced a (slight) increase in situational awareness with the HMD.
3. The most experienced pilot evaluated the HMD as not useful for close ship deck operation due to reduced FOV and overloaded indications in the HMD.
4. The less experienced pilot evaluated the HMD as very useful and experienced a decrease in workload and an increase in situational awareness.
5. All pilots named the artificial horizon in the HMD as the most useful indication.
6. The analysis of the eyetracking data shows that all pilots spend most of the time during the landing looking OTW. The main focus during gazes inside the cockpit was on the attitude indicator follow by the altimeter.
7. The pilot ratings and feedback indicated that the pilot workload was extensively reduced with the advanced control modes.
8. The classical flight control mode TRC and the advanced flight control mode RTRC was rated as most useful for ship/helicopter operation by pilot A.

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9. ACKNOWLEDGMENTS

The work in this paper was funded through the projects HELMA and HEDELA of the Program Coordination Defence and Security Research (PK-S) within the German Aerospace Center (DLR). A special thanks go to the supporting pilots from the Flight Service of the German Federal Police and DLR.

10. APPENDIX

The appendix contains the questionnaires and scales used in the piloted simulator study. Fig. 17 shows the NASA TLX Scale and Fig. 18 shows the Situation Awareness Rating Technique (SART) scale.

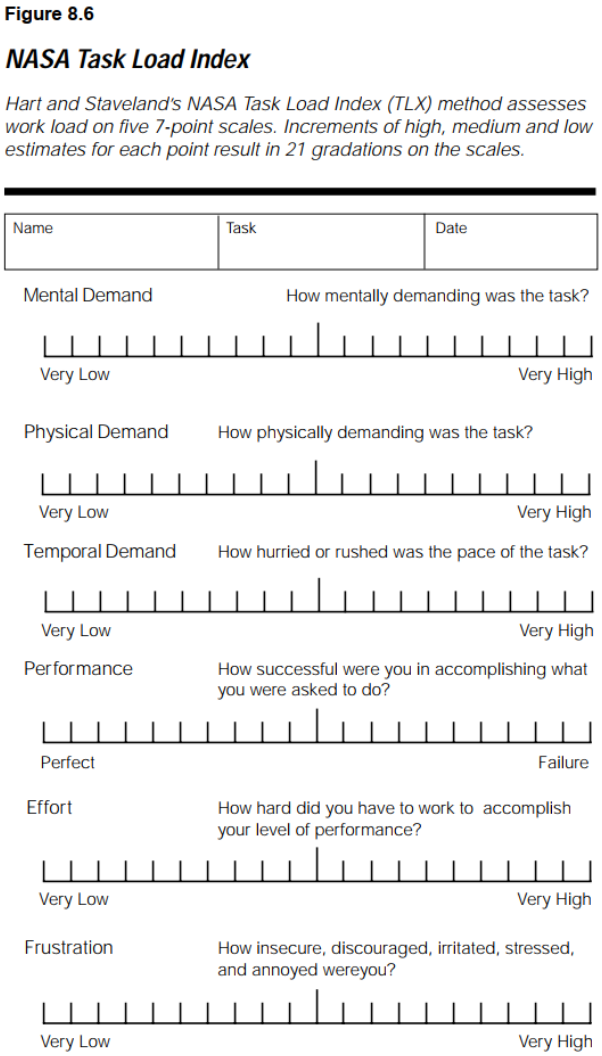


Figure 8.6

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

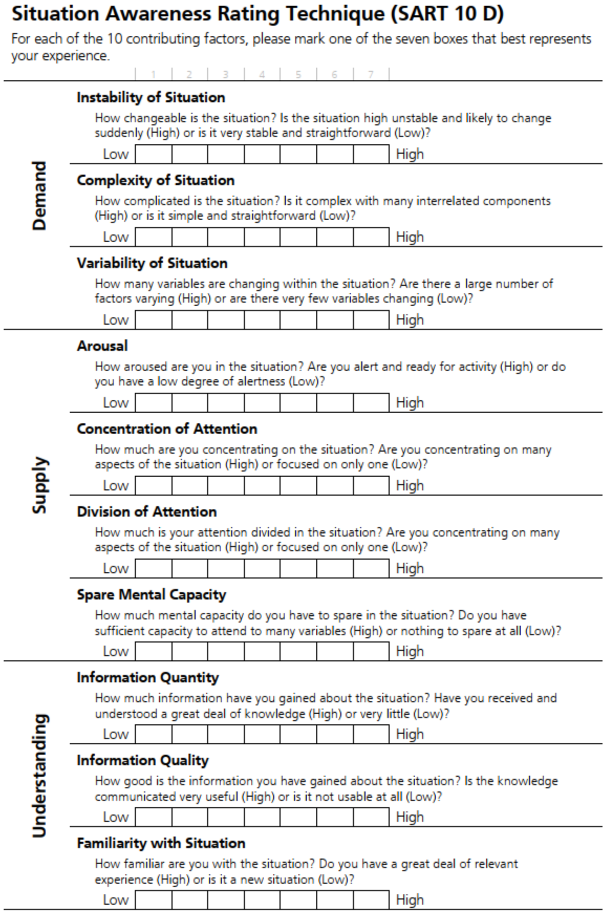
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure 17 NASA TLX Paper/Pencil Version [34]



Situation Awareness Rating Technique (SART 10 D)

For each of the 10 contributing factors, please mark one of the seven boxes that best represents your experience.

1 2 3 4 5 6 7

Demand

Instability of Situation

How changeable is the situation? Is the situation high unstable and likely to change suddenly (High) or is it very stable and straightforward (Low)?

Low ☐☐☐☐☐☐☐ High

Complexity of Situation

How complicated is the situation? Is it complex with many interrelated components (High) or is it simple and straightforward (Low)?

Low ☐☐☐☐☐☐☐ High

Variability of Situation

How many variables are changing within the situation? Are there a large number of factors varying (High) or are there very few variables changing (Low)?

Low ☐☐☐☐☐☐☐ High

Supply

Arousal

How aroused are you in the situation? Are you alert and ready for activity (High) or do you have a low degree of alertness (Low)?

Low ☐☐☐☐☐☐☐ High

Concentration of Attention

How much are you concentrating on the situation? Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?

Low ☐☐☐☐☐☐☐ High

Division of Attention

How much is your attention divided in the situation? Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?

Low ☐☐☐☐☐☐☐ High

Spare Mental Capacity

How much mental capacity do you have to spare in the situation? Do you have sufficient capacity to attend to many variables (High) or nothing to spare at all (Low)?

Low ☐☐☐☐☐☐☐ High

Understanding

Information Quantity

How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)?

Low ☐☐☐☐☐☐☐ High

Information Quality

How good is the information you have gained about the situation? Is the knowledge communicated very useful (High) or is it not usable at all (Low)?

Low ☐☐☐☐☐☐☐ High

Familiarity with Situation

How familiar are you with the situation? Do you have a great deal of relevant experience (High) or is it a new situation (Low)?

Low ☐☐☐☐☐☐☐ High

Figure 18 Situation Awareness Rating Technique (SART) 10D Scale [30]