IMPACT OF CONTROL AUGMENTATION ON PILOT WORKLOAD DURING SHIPBOARD HELICOPTER HOVER OPERATION

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ABSTRACT

The integration of control augmentation techniques into helicopter systems aims to assist pilots during the critical phases of shipboard operations to mitigate the effects of ship motion, wind and other environmental factors that can compromise safety. The control augmentation presented in this paper involves the implementation of model following control laws featuring a combination of advanced response types with hold modes to improve helicopter handling qualities. The paper introduces a translational rate command type, relative to the ship, which incorporates Velocity Hold and Position Hold features to assist pilots and automate various stages of the ship deck landing maneuver. An Attitude Command Attitude Hold has been used as a baseline response type for the comparison. A preliminary pilot evaluation of the proposed control laws during a hover operation is presented to assess the impact of control augmentation on the pilot workload, task performance and operational safety. In addition to quantitative task performance data and qualitative pilot rating scales, eye tracking glasses were used as an additional metric to record pilot gaze data providing insights into attention distribution and cognitive demand across different control strategies. Simulation results demonstrate that the implemented control augmentation techniques enable a stabilised hover relative to ship, while also contributing to reduced workload, improved task performance and increased overall safety perception for the pilots.

NOTATION

Symbols

δ_x	Longitudinal cyclic control input
δ_y	Lateral cyclic control input
δ_p	Pedal control input
δ_0	Collective control input

Abbreviations

ACAH	Attitude Command Attitude Hold
ACP	Airload Computation Point
ACT/FHS	Active Control Technology/ Flying Helicopter Simulator
ACVH	Attitude Command Velocity Hold
ACVsH	Attitude Command Ship Velocity Hold
ADS-33E-PRF	US Army Aeronautical Design Standard Performance Specification
AOI	Area of Interest
AVES	Air Vehicle Simulator
CFD	Computational Fluid Dynamics
CPE	Cockpit Peripheral Environment
DH	Direction Hold
DIPES	Deck Interface Pilot Effort Scale
DLR	German Aerospace Center
DOF	Degrees of Freedom
DRB	Disturbance Rejection Bandwidth
DRP	Disturbance Rejection Peak
EVE	External Visual Environment
GVE	Good Visual Environment
HDD	Head-Down Display
HH	Height Hold
HMD	Head-Mounted Display
HOSTAC	Helicopter Operations from Ships other than Aircraft Carriers
HQ	Handling Qualities
ITC	Inside The Cockpit
ITTC	International Towing Tank Conference
JONSWAP	Joint North Sea Wave Project
MSS	Maritime Systems Simulator
MTE	Mission Task Element
NASA TLX	NASA Task Load Index
OTW	Outside The Window
PH	Position Hold
PFD	Primary Flight Display
RTRC	Relative Translational Rate Command
SDK	Software Development Kit
TRC	Translational Rate Command
VH	Velocity Hold

INTRODUCTION

Shipboard helicopter operations are known for their complexity and high demand on pilot skills. Operating helicopters on ship decks requires precision, skill and awareness of several safety-critical factors. One of the primary challenges is the dynamic and often unpredictable maritime environment that introduces variables such as wind, sea state, and ship motion, which significantly impact the stability and maneuverability of helicopters during takeoff, landing, and hovering (Refs. 1, 2). Furthermore, the limited space available on ship decks poses strict spatial constraints, requiring pilots to execute precise maneuvers amidst potentially crowded conditions. Furthermore, the inherent risks associated with operating in close proximity to maritime structures and equipment necessitate heightened situational awareness and operational vigilance.

The integration of control augmentation techniques into helicopter systems aims to assist pilots during the critical phases of shipboard operations to mitigate the effects of ship motion, wind and other environmental factors that can compromise safety. The standard helicopters in general exhibit complex responses to control inputs that change with airspeed and require constant compensation by the pilot (Ref. 3). Hence, it becomes important to enhance the inherent aircraft dynamics and streamline the helicopter's responses to reduce the pilot workload and effort (Ref. 4). Advancements in pilot assistance systems and visual and control augmentation have played a crucial role in supporting the pilots and mitigating the difficulties associated with helicopter ship deck operations. The use of Head-Down Displays (HDD), Head Mounted Displays (HMD), and advanced flight control architectures can provide pilots with better situational awareness and control during ship deck operations (Ref. 5).

Control augmentation featuring different response types and hold modes not only reduces the overall pilot workload and enhances the situational awareness by augmenting the primary response characteristics of the helicopter, but also enhances the safety levels of the shipboard operations (Ref. 6) (Ref. 7). Such assistance systems enable the pilot to allocate more attention to other ancillary tasks like navigation and mission tasks, thereby improving the safety of the shipboard maneuvers. However, such pilot assistance systems should be evaluated, which requires excessive testing preferably in real flights. Therefore, the simulators with a realistic environment are excellent tools for evaluating the influence of such systems on pilot effort and workload because they provide a safe environment to test different scenarios which might not be possible in real flight.

Despite advancements in the control augmentation for helicopters, not many existing control modes have been specifically evaluated for shipboard helicopter operations (Ref. 8). Even though some of the previous publications already dealt with the development of such ship-deck landing controllers, limited attention has been given to how such control designs affect pilot interaction, cognitive load and task performance. The proposed study assesses the effectiveness of model-following control laws that combine advanced response types such as ship relative Translational Rate Command (TRC) with ship relative hover modes to improve helicopter handling qualities in a realistic shipboard environment, including the integration of an unsteady ship air-wake and realistic ship motions, which was not always the case in previous studies (Ref. 9). Accordingly, the study contributes to the state-of-the-art by aligning control system design more closely with human-centered operational effectiveness which is an increasingly important dimension in the development of advanced rotorcraft for such complex missions.

In the proposed study, a piloted simulation experiment was conducted in the Air Vehicle Simulator (AVES) to assess the influence of different augmented response types and hold modes on pilot workload during a shipboard helicopter hover operation. This paper extends the preliminary results presented in (Ref. 10). Eye tracking glasses were used as an additional metric to record pilot gaze data in order to get insights into attention distribution and cognitive demand across different control strategies. The technology of eye tracking enables to get an insight about a pilot's gaze behavior, points of visual attention and cognitive processes which might indicate towards the pilot effort and workload to perform the task (Refs. 11, 12).

The paper is organised as follows. The paper first describes the implementation of the model following control system based control augmentation for pilot assistance. Control augmentation includes a ship relative translational rate command combined with two different hold modes, firstly a ship relative Velocity (VH) and a ship relative position hold (PH). The paper then describes the details of the experimental setup used for the assessment including the maritime simulation environment, mission task element, test configurations and the quantitative and qualitative evaluation methods. Finally, an evaluation of the advanced control laws featuring ship relative automatic control modes is presented to assess the impact of control augmentation on the pilot workload, situational awareness, task performance and operational safety based on a piloted simulation.

PRIOR WORK

As part of earlier research, various control laws were implemented, evaluated and compared for maritime operations particularly ship deck landing maneuvers (Refs. 13, 14). These research studies presented the development and evaluation of advanced control modes to make the landing task easier for the pilots, from ”basic response types” (Attitude Command Attitude Hold (ACAH), Rate Command Attitude Hold (RCAH), Translational Rate Command (TRC)) to “advanced response types” (Attitude Command Velocity Hold (ACVH), Relative Translational Rate Command (RTRC), Ship-based Attitude Command Velocity Hold (ACVsH)). Previous studies also included the description of maritime simulation environment (flight mechanic code, frigate and air-wake models, frigate dynamics model, visual environment), which are used in the current study.

Additionally, in recent years, DLR has not only begun integrating an eye tracker into the ACT/FHS and the AVES (Ref. 15), but has also conducted several studies to analyse the eye movements of pilots. For example, it was investigated whether differences in gaze behaviour can be detected between real flight and the simulator (Ref. 11). The influence of an optimised simulation environment on the pilot's gaze behaviour was also investigated (Ref. 16). Furthermore, a study was conducted to analyse gaze behaviour during helicopter deck landings in real flight (Ref. 12).

An initial development of the control augmentation systems including the development of the automatic control modes is provided in (Ref. 10), which discusses the preliminary simulation studies using the same models and control laws. The current paper however presents the pilot evaluation to assess the influence of control augmentation on pilot workload using quantitative and qualitative measures and also using the pilot's gaze patterns.

SYSTEM DESCRIPTION

Helicopter Model

The flight dynamics model of ACT/FHS developed using the in-house real-time nonlinear helicopter modeling program HeliWorX has been used. It is based on the helicopter modeling program SIMH (Ref. 17) and each helicopter model consists of a set of modular components (fuselage, stabilizers, main rotor, etc.). Each main rotor blade is divided into 10 blade segments and the Pitt & Peters dynamic inflow model is used (Ref. 18).

HeliWorX features an interface to superimpose additional velocities (one way coupled) from turbulent ship airwakes on 44 Airload Computational Points (ACPs) at the helicopter model. High-fidelity Computational Fluid Dynamics (CFD) have been used to generate 30 seconds of flow field data of the German Navy F-124 class frigate (Ref. 19). The unsteady airwake data is used as a lookup table within the helicopter simulation, which is looped in time to enable continuous simulation above the ship deck. In addition, temporal blending is performed at each time loop for smooth transition. The characteristics of the ship airwake turbulence can be seen in the Power Spectral Density (PSD). Figures 1 and 2 shows the PSD of the airwake turbulence above the ship deck and at a location near to the ship respectively. Analysis reveals that in all three axes, the energy is predominantly concentrated in the low-frequency range, with significant content below approximately $2-3\,$rad/s highlighting the need for controller design with effective disturbance rejection capabilities in this frequency band. Compared to over the deck, PSDs for the turbulences near to deck show slightly higher spectral energy levels at lower frequencies, particularly in the longitudinal and lateral turbulence components. This indicates that the airwake near the ship may carry stronger low frequency disturbances, likely due to direct exposure to upstream turbulent flow. In contrast, PSD of turbulences over the deck exhibit strong vertical component, potentially due to the effects of recirculating or trapped air over the deck structure.

Table 1. Boundaries for disturbance rejection criteria (Ref. 26)

	Pitch	Roll	Yaw
DRB (rad/s) $\geq$	0.5	0.9	0.7
DRP (dB) $\leq$	5.0	5.0	5.0
	Surge	Sway	Heave
DRB (rad/s) $\geq$	0.34	0.54	1.0
DRP (dB) $\leq$	5.0	5.0	5.0
	Axial	Lateral	Vertical
DRB (rad/s) $\geq$	0.17	0.17	0.17
DRP (dB) $\leq$	3.0	3.0	3.0

The model used to design the implemented flight-tested model-following control system is an 11-DOF helicopter dynamic model identified with low-order equivalent models in time domain using flight test data. During the system identification, the most relevant parts of the flight envelope were covered performing sweeps and multistep inputs at five different operating points from hover to 120 kt in steps of 30 kt. These operating points are finally stitched together to create a full envelope helicopter simulation (Ref. 20). The complete details of the system identification and validation process can be found in (Ref. 21).

Flight Control Augmentation

The current research aimed to augment primary responses to advanced response types namely an Attitude Command and a Translational Rate Command combined with Attitude Hold and ship relative Velocity Hold and Position Hold modes respectively. The Attitude Command combined with an attitude hold was used as a baseline for the comparison and to demonstrate the impact of automatic modes on the overall task performance as well as the pilot workload.

The presented augmented response types and the ship relative automatic control modes were embedded in a model-following controller architecture, that imposes the desired commanded dynamics on the controlled helicopter (Ref. 22). An overview of the controller architecture is illustrated in Fig. 3. The main components of the model-following control system are a feedforward and a feedback controller that obligates the controlled helicopter to follow the desired command types. The controller is designed according to the flying qualities specifications provided in ADS-33E-PRF (Ref. 23). A multi-objective optimisation is performed using the systune function in MATLAB to tune the control system components in order to meet the design requirements. The controller design was based on several criteria, including but not limited to the stability margin requirements provided in ADS-33E-PRF and the disturbance rejection requirements as provided in Table 1. Further details of the components of the model following controller can be found in (Refs. 24, 25). The command filters generate reference signals for the desired helicopter motion. For the proposed advanced modes, the command filters were chosen to create a second order reference signal in pitch and roll axes, however first order command fil-

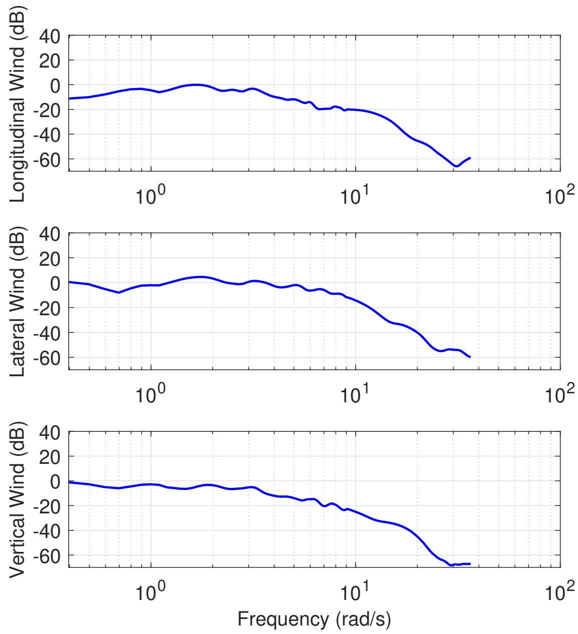

Figure 1. Power spectral densities of airwake turbulence on the ship deck

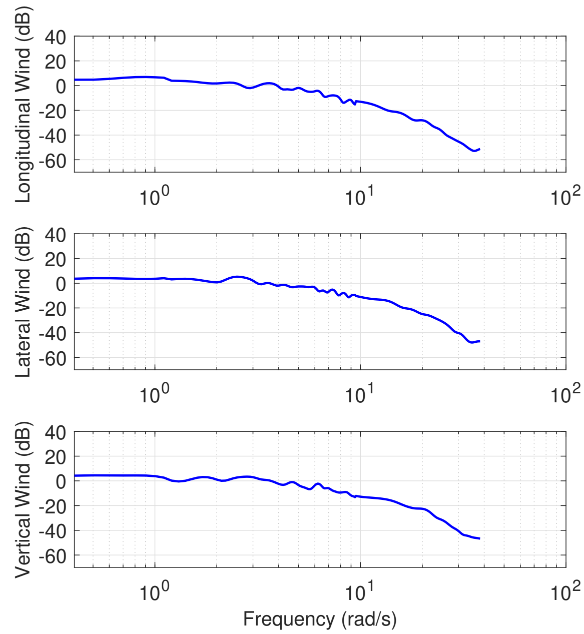

Figure 2. Power spectral densities of airwake turbulence near to ship deck

ters were used for yaw and vertical speed. The parametric values were chosen to fulfill the level 1 HQ criteria defined in ADS-33E-PRF (Ref. 23). In the current implementation, the feedforward controller was chosen to be simple first-order inverses.

The feedback controller is needed to compensate for the resulting command following errors due to feedforward control deficiencies, ensuring stability and performance robustness, in addition. The feedback controller consists of a decoupled cascade structure comprising respective PI-controllers (proportional and integral error feedback). The desired hold functionalities were implemented as outer loops of the feedback controller. The structure used for each axis in the current implementation is described below:

1. Longitudinal cyclic δ_x: the inner loop controls pitch attitude with a PI-controller with additional feedback of pitch rate and its derivative; the outer loop controls longitudinal speed with a PID-controller; the outermost loop controls longitudinal position

2. Lateral cyclic δ_y: the inner loop controls roll attitude with a PI-controller together with additional feedback of roll rate and its derivative; the outer loop controls lateral speed with a PID-controller; the outermost loop controls lateral position

3. Pedal δ_p: the inner loop controls yaw rate with a P-controller; the outer loop controls heading

4. Collective δ_0: the inner loop controls the geodetic vertical velocity with a PID controller; the outer loop controls height

Response Types and Hold Modes

The inner loop of the control architecture allows the system to track a variety of response types. In the current simulation, two response types were used. An Attitude Command combined with an Attitude Hold was used as a baseline command for the comparison. The second response type used for the current study was a ship relative Translational Rate Command (TRC) combined with a ship relative Velocity Hold (VH) or Position Hold (PH). The yaw rate and the vertical speed are commanded in the pedals and collective axis, combined with a Direction Hold (DH) and Height Hold (HH) respectively. These response types are detailed below:

1. ACAH: This is a basic mode with no ship communication. With the ACAH response type, longitudinal and lateral stick deflections are proportional to the aircraft's pitch and roll attitudes. The yaw rate and the vertical speed are commanded with the pedals and collective stick, and are combined with a Direction Hold (DH) and Height Hold (HH) respectively.

2. TRC: In the current study, TRC is a ship-relative TRC and therefore involves communication with ship. With the proposed ship relative TRC, the stick deflections are proportional to longitudinal and lateral helicopter velocities relative to the ship, combined with a ship relative Velocity Hold (VH) or Position Hold (PH). In all configurations, the yaw rate and the vertical speed are commanded with the pedals and collective stick, and are combined with a DH and HH respectively.

In addition to the baseline mode, Attitude Hold which is combined with the Attitude Command, the TRC response type

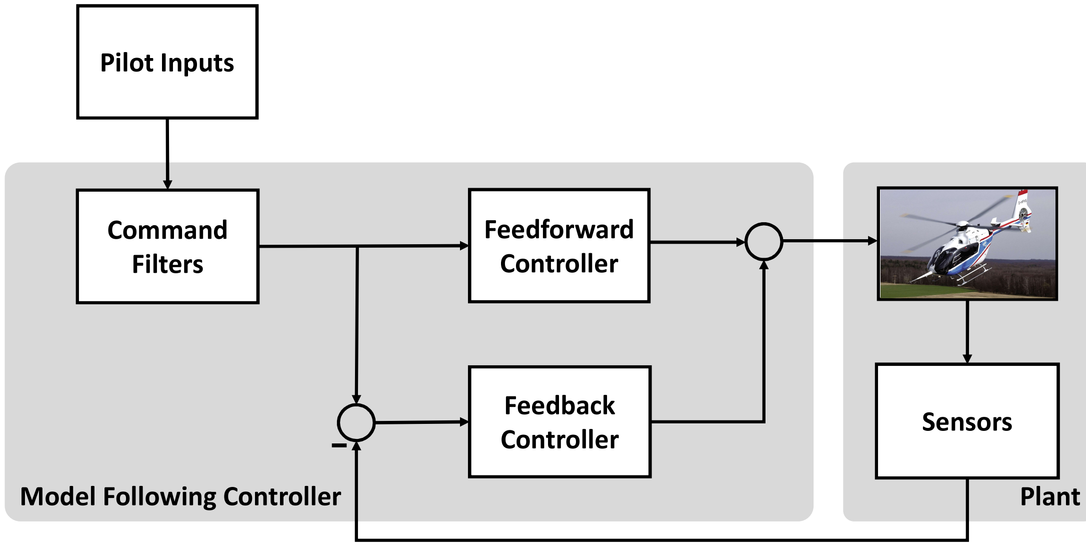

Figure 3. Model-following controller

features two advanced ship relative hold modes:

1. VH: Upon activation of VH mode, the helicopter velocity is matched to the current ship speed and the stick deflections then are proportional to longitudinal and lateral helicopter velocities relative to the ship and if the pilot goes complete hands-off, it allows to hold a zero relative velocity with respect to the ship.
2. PH: Upon activation of PH mode, the helicopter velocity is again matched to the current ship speed and the stick deflections are still proportional to longitudinal and lateral helicopter velocities relative to the ship as in the VH mode. However, if the pilot goes complete hands-off and no command is given, in this case it allows to hold a constant relative position with respect to the ship. This mode is useful to activate once the helicopter in the vicinity of the ship or even more when the helicopter is on top of the deck.

As the presented modes are ship relative modes, it should be highlighted that during the current study, it is assumed that the ship deck's position and velocities are made available to the controller through a data link. However, the ship positions and velocities are filtered using a second order filter in order to avoid high frequency wave induced motion. Additionally, a small delay is considered for the ship velocities when being received by the controller.

The PH mode activates automatically for the current evaluation, when in the vicinity of the ship i.e. when the relative distance between the helicopter and the ship deck is less than the threshold. Once the pilot is able to position the helicopter, where the relative distance between the helicopter and the ship deck is below the threshold or the helicopter is already on the top of the ship deck and the pilot goes complete hands-off.

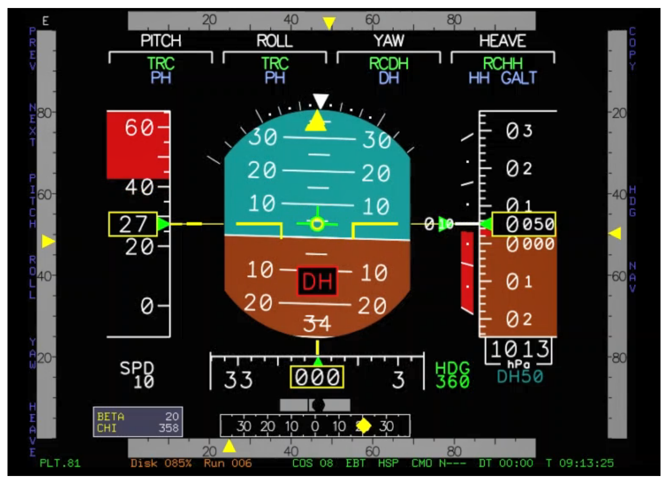

Figure 4. Primary Flight Display (PFD)

When the relative velocity of the helicopter with respect to ship deck is also below the threshold, then the outermost loop gets closed for pitch and roll axes which controls the position. Consequently, the PH gets engaged and the longitudinal and lateral positions are maintained over the deck. Please note the pilots could access the information about active modes in each axis on the Primary Flight Display (PFD) as shown in Fig. 4. It is very important for the pilot to be aware about which mode is active in which axis in order to act accordingly. In Fig. 4, it can be seen that TRC command type is selected for longitudinal and lateral axes and Rate Command is selected in yaw and heave axes. Additionally, PH is active in longitudinal (pitch) and lateral (roll) axis, Direction Hold (DH) in yaw axis and Height Hold (HH) is active in heave axis.

One of the difficulties during the control design was to ensure smooth transitions during the activation and switching of control modes. This is important specially for the automatic engagement and disengagement of the Position Hold mode. To achieve this, the integrators in each feedback loop were carefully initialized, and the trim velocity of the inner velocity loop was adjusted during PH mode activation or deactivation to avoid transients.

SIMULATION ENVIRONMENT FRAMEWORK

Simulation Facility

The simulation setup in the current research study consisted of the research flight facility, Air Vehicle Simulator (AVES) at DLR Braunschweig. AVES represents a replica of the cockpit of DLR's research helicopter Active Control Technology/Flying Helicopter Simulator (ACT/FHS; a highly modified EC135), that can be operated on a full-sized six degrees of freedom (DOF) hexapod motion-based platform or a fixed-based platform. Complete details of the components of AVES can be accessed in (Ref. 27).

The maritime simulation environment integrates a 3D ship model similar to a German Navy F124 "Sachsen class" frigate that has a deck landing spot located at the stern. The ship's dynamic motion was simulated using an in-house traffic server software called VehicleControl. The software is capable of modelling the dynamics of vehicles using simple motion equations, trajectory following algorithms or by using complex MATLAB/Simulink models. A MATLAB/Simulink model created by Maritime Systems Simulator (MSS) library was used for the current study (Ref. 28). Additionally, the dynamics of a S175 ship model calculated with the International Towing Tank Conference (ITTC) wave spectrum was used. The ship motion is calculated for the defined model synchronously to other simulation models such as the helicopter model (Ref. 29). However, as the model uses a separate wave generation engine, the ship motion is not synchronized with the wave visualisation in the current implementation. The motion of the modeled vehicles (here e.g. the ship) can be defined in the software to follow specific paths like a straight path defined by height, speed, and heading, or a predefined path from a KML file.

Sea waves and water representations are implemented using the Sundog Triton Software Development Kit (SDK) in the AVES RTIG software. The wave visualisation enhances the situational awareness of the pilots by assisting in the representation of several effects like ship airwake and helicopter down wash on water. The wave effects were generated using the Joint North Sea Wave Project (JONSWAP) wave spectrum (Ref. 30). The weather visualisation is done through the Sundog Silverlining SDK featuring several weather conditions like fog, clouds, and precipitation (Ref. 31). Such conditions could be used to represent a scenario with degraded visual environment. However, for the current study, a good visual environment as seen in Fig. 5 with sea state 4 was used.

Figure 5. DLR's simulator's cockpit point of view during maritime simulation

Mission Task Element

The pilot evaluation was based on the standard port lateral approach which is based on the for-aft procedure as defined in the Helicopter Operations from Ships other than Aircraft Carriers (HOSTAC) as shown in Fig. 6 (Ref. 32). For the current study, the approach was performed from the starboard side, even when it is into the turbulent airwake. The task was intentionally made challenging to demonstrate the impact of automatic flight control modes on the pilots. The pilot task begins at a height 65 ft and approximately 600 ft behind the ship. The pilot approaches the ship and establishes a ship hover alongside the deck, followed by a lateral transition maintaining the same barometric altitude over the deck and then finally performs a vertical descent and performs a hover over the deck (Ref. 33). The whole task is defined by the following elements:

1. Hover alongside the ship deck: Decelerate from translating flight to a stabilized hover alongside the ship deck; then, hold relative position, altitude, and heading alongside the ship deck.

2. Lateral Transition over the deck: Translate laterally to the center of the ship deck and attain stabilized hover.

3. Precision hover over the deck: Decrease altitude to 45 ft hold relative position, altitude, and heading above the deck for 30 s.

The evaluations were also performed with a straight in approach, but that is out of the scope for this study. For the evaluation, the pilot performed only a 30-second hover over the ship deck and no actual landings were performed. The limits for task performance were based on the "Hover" Mission Task Element (MTE) of ADS-33E-PRF (Ref. 23). The precision of the hover over the ship deck can have a significant impact on the pilot workload not only due to the spatial variation of the ship's turbulent airwake but also the ship motion. Therefore,

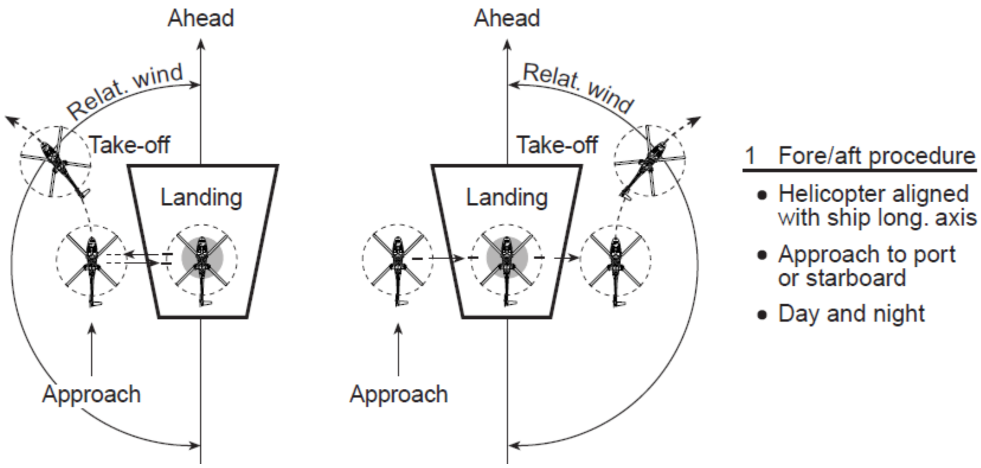

Figure 6. Mission Task Element (MTE) based on port lateral approach

the selected task is considered suitable to evaluate the automatic modes and to assess how they influence pilot workload.

Selected Scenario and Test Configurations

As mentioned before, a scenario with a Good Visual Environment (GVE) was considered for the current study. The scenario involved a F124 'Sachsen class' like ship proceeding with 10 kt in sea state 4 with a wind over deck of 20 kt at G30° to the bow. The currently used ship dynamic model also included a simulation of turbulent ship airwake attached to it (Ref. 29). The ship motions were mainly considered in pitch and roll axes to illustrate peaks and quiescent periods in the angular motion. The atmospheric parameters were chosen to provide a scenario which challenges the pilots due to the strong winds and ship motion.

As the goal of the piloted simulation trials was to assess the impact of the augmented control modes, the test points were based on automatic control modes with advanced ship relative features namely ship relative Velocity Hold and Position Hold. An Attitude Command Attitude Hold was used as a baseline for comparing and assessing the impact of the automatic modes on the pilot workload for the defined task. The other two test configurations involved a Translational Rate Command response type which commands longitudinal and lateral velocities relative to ship velocities combined with VH and PH respectively. A standard Rate Command combined with Direction Hold (DH) was used in the yaw axis and with a Height Hold (HH) was used in the heave axis. The information about the active modes is available to the pilots on the Primary Flight Display (PFD) as shown in Fig. 4.

Pilot Demographics

A pilot-in-the-loop simulation experiment was conducted in the Air Vehicle Simulator (AVES) at DLR Braunschweig to investigate and quantify the impact of control system augmentation on handling qualities and pilot task performance. Three of the DLR helicopter pilots participated in the evaluation study, two of which are qualified experimental test pilots. All the pilots have extensive rotorcraft experience in light utility single main rotor helicopters like Eurocopter EC135 and in other helicopter sizes and configurations. All the pilots are experienced with scientific flight testing for research and with subjective pilot rating methods. Unfortunately, they do not have much experience with helicopter ship deck operations but as they have been participating in various pilot studies in the simulator, their feedback is highly valued in the context of this study. Furthermore, automatic flight control modes can be incredibly effective to reduce the pilot workload and provide them spare capacity to perform additional tasks. They are effective even if the pilot does not have experience with ship deck landing. This can greatly improve the safety and efficiency of the landing process. Therefore, pilot feedback is highly valuable to test the improvements in situational awareness, safety and performance of the control modes.

Data Collection Methods

Quantitative and Qualitative Evaluation For a quantitative evaluation, the task performance is evaluated during the hover task for different flight control modes using an overall evaluation toolchain that provides a quantitative as well as qualitative assessment. The limits for task performance limits were based on the "Hover" Mission Task Element (MTE) of ADS-33E-PRF (Ref. 23). The main focus of the task was to maintain a stabilised hover over the ship deck. For the qualitative evaluation, pilot workload is measured in terms of subjective pilot ratings and comments of the pilots during the simulation study. Pilots used Bedford scale, DIPES and NASA TLX for the evaluation during the simulation trials.

Bedford Workload Rating scale, which is a modification of the Cooper-Harper rating scale was used to quantify pilot workload. This 10-point rating scale is designed to measure the workload by identifying the spare mental capacity of the pilot while completing the main task (Ref. 34). A rating of 1 indicates low workload whereas 10 indicates that the task must be

Figure 7. Pro Glasses 3 by Tobii

abandoned. During the current study, the Bedford scale was used to evaluate the impact of the proposed control augmentation on pilot workload generated by the primary piloting task; the lower the workload, the greater spare capacity the pilot would have to perform ancillary tasks.

Even though, no actual landings were performed, pilots were asked to award DIPES ratings in order to get an insight of how difficult would it have been for them to land in such conditions. DIPES is used to quantify the workload of an average fleet pilot for the landings on ship decks. Therefore, the evaluating pilot should be experienced in this maneuver and be able to empathize with an average fleet pilot (Ref. 35). Using this 5-point scale, pilots can rate the landing maneuver based on workload, performance, accuracy and consistency. Ratings between DIPES-1 to DIPES-3 are considered as acceptable indicating a precise and safe landing whereas the higher ratings are considered as unacceptable. The pilots could indicate the cause of the growing workload with letter suffixes (e.g. ”T”-Turbulence). Furthermore, NASA TLX rating scale was also used to record subjective pilot assessment to assess the impact of automatic modes on pilot workload. NASA TLX quantifies the overall workload based on a weighted average of ratings on six subscales namely, mental demands, physical demands, temporal demands, own performance, effort and frustration (Ref. 36).

Physiological Data: Eye Tracking During the simulator trials, the pilot's eye movements were also recorded. The head-mounted eye tracking system, Tobii Pro Glasses 3 was used for this purpose. The system has 16 infrared illuminators and 4 infrared cameras that record the eye movements in a stereo geometry, dark pupil tracking process with a sampling rate of $50 Hz$. The field of view is 106° diagonal and 95° horizontal, with an accuracy of 0.6° according to the general information provided by the manufacturer. The recorded pilot gaze data was then further processed using the Tobii Pro Lab software on the recorded video of the scene camera to identify fixations and saccades. A fixation is a localised stationary gaze that typically represents a place of operator's visual attention and the phases of movements between two fixations are called saccades. The assisted mapping function of the Tobii Pro lab

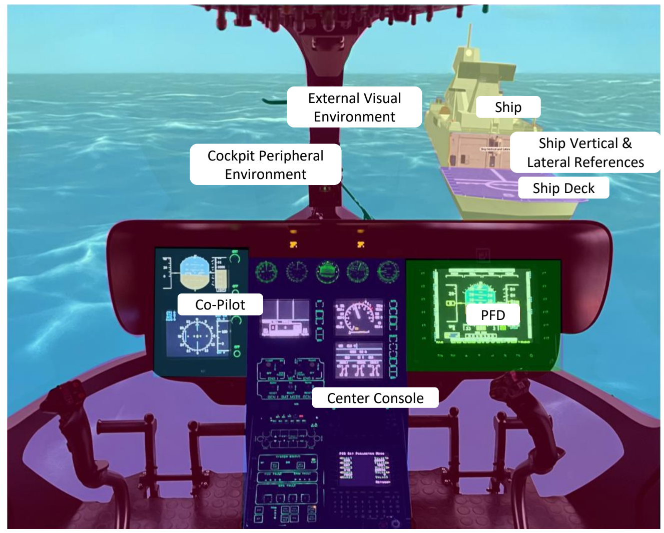

Figure 8. Definition of AOI within the maritime scenario

Software was used to map the fixations automatically on the snapshot to predefined Areas of Interest (AOI) which were then checked manually and corrected if necessary. AOIs are designated regions or areas within the visual environment (e.g cockpit instruments, horizon, ship deck) that are used to categorize and analyze where and how long the pilot directs their gaze during a task. They can be manually created by the user as desired. During fight operations, they often include regions Inside The Cockpit (ITC) involving the areas inside the cockpit and Outside The Window (OTW) involving the elements in the outside view. The definition of AOIs for the current evaluation within the maritime scenario are shown in Fig. 8. The selected ITC AOIs for the current evaluation were PFD, Co-Pilot, Center-Console and Cockpit Peripheral Environment (CPE) and the OTW AOIs included ship deck, ship, ship vertical and lateral references and the External Visual Environment (EVE).

SIMULATOR TRIAL RESULTS

Task Performance

The augmented control modes have been evaluated in a pilot study in AVES with a total of three helicopter pilots. Each pilot performed the approach using ACAH or TRC towards the ship to a stabilized hover alongside the ship, performed the lateral transition over the ship deck and then went hands-off when using the ship relative VH or PH once they achieved a stablised hover over the deck.

For a quantitative evaluation, the focus remained on the 30 s hover phase over the ship deck with a wind of 20 kt from G30°. Figure 9 shows the trajectories of the helicopter relative to the ship deck center during the hover operation using different control configurations by Pilot 2. It should be noted that the pilot was in control throughout the entire maneuver using ACAH. However, with VH and PH, only the approach was piloted; once a suitable hover position was achieved, the pilot switched to hands-off, allowing the hover to be maintained

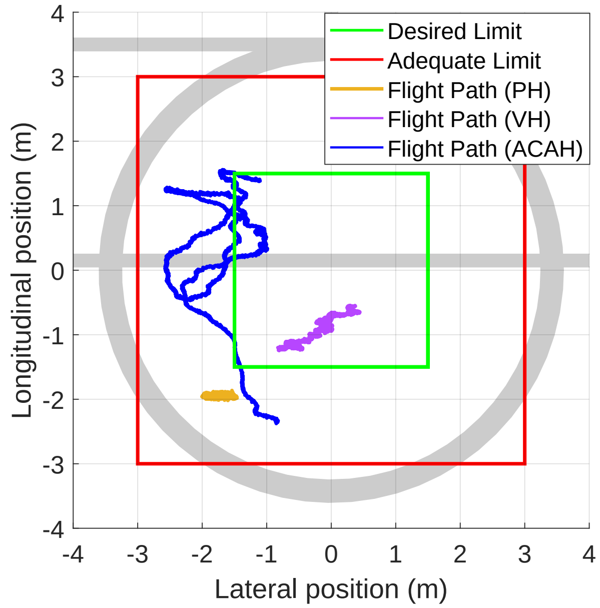

Figure 9. Helicopter position relative to deck center during the hover using ACAH (blue), VH (violet) and PH (yellow) by Pilot 2

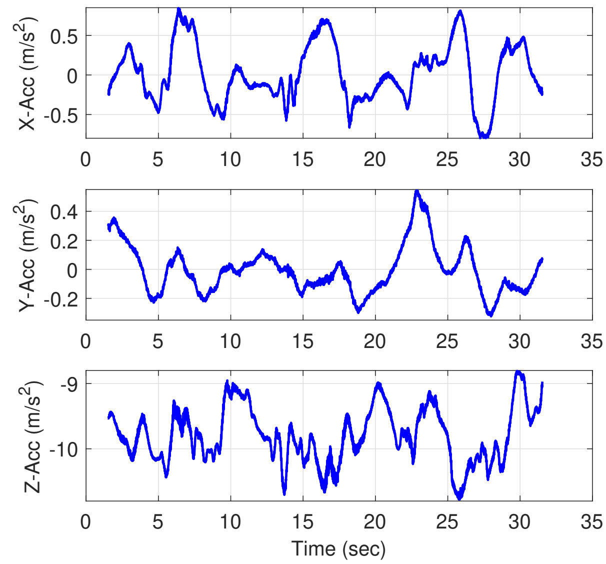

Figure 10. Helicopter accelerations during the hover using ACAH by Pilot 2

automatically by the controller. In Fig. 9, the blue curve indicates the hover trajectory manually performed by the Pilot 2 using ACAH, the violet and the yellow curves indicate the trajectories using the VH and the PH modes respectively. The position deviations display that it is extremely difficult for the pilot to maintain a stable hover using ACAH, however, the hover with VH and PH are more stable when compared to ACAH. Furthermore, the figure also illustrates that the hover with PH is more stable than the hover with VH as it has lower position deviations. It should be noted that the pilots were informed about the desired and adequate limits before conducting the experiment. However, there were no objective displays to judge the parameters, they had to achieve the position or velocity based on observation and subjective assessment using the optical references on the ship and relevant flight instrument data. Even though the position over the deck during the hover was in adequate limits with PH, the overall position deviations during the presence of airwake were highly reduced when compared to the deviations in the hover position with VH or ACAH. It should be noted that the reason that with PH only adequate limits were acheived was also that in the current implementation the pilot flew to the hover position manually and then the VH/PH mode was activated and that position was held and the controller did not actively try to reach the deck center.

In addition to position deviations, acceleration can also be a critical variable when assessing the performance. Figures 10, 11 and 12 show the helicopter accelerations during the hover phase using ACAH, VH and PH. As using VH, translational velocity is maintained, the accelerations are very small and varying indicating minor corrections due to the velocity deviations because of turbulences. For all the modes, the accelerations are small indicating no controls were saturated. It is clearly visible in Fig. 10 that with ACAH, where the pilot manually maintains the hover, that the accelerations are slightly larger indicating more pilot input required by the pilot commands. It is also visible in Fig. 12 that the longitudinal and lateral accelerations are slightly larger when compared to VH because these variations are needed to counteract drift and disturbances in order to hold position against turbulent winds.

Pilot Subjective Ratings

This section presents subjective ratings provided by the pilots after each experiment. Please note that due to the limited number of pilots, the subjective ratings are assessed only qualitatively to assess the impact of proposed control augmentation on pilot workload. Bedford Workload ratings awarded by the pilots in Fig. 13 show a clear trend of reduction in workload with the automatic flight control modes namely ship-relative VH and PH. The Bedford Workload ratings scale requires the pilot to rate the level of workload associated with the primary piloting task, based on the amount of spare capacity they have to perform additional tasks. Lower ratings indicate higher spare capacity to perform additional tasks. The pilots commented that even though there was no additional task, but they still had enough capacity to perform one if required. However, the outcomes must be considered with care due to the limited number of pilots.

Even though no actual landings were performed, DIPES ratings were awarded by the pilots for the current evaluation in order to get an insight of how difficult would it have been for them, in case they had to land in such conditions. Figure 14 illustrates the DIPES ratings by all the pilots. As shown in Fig. 14, the DIPES ratings were acceptable indicating a safe operation is achievable by a fleet pilot using all the control configurations. There was improvement in the ratings from

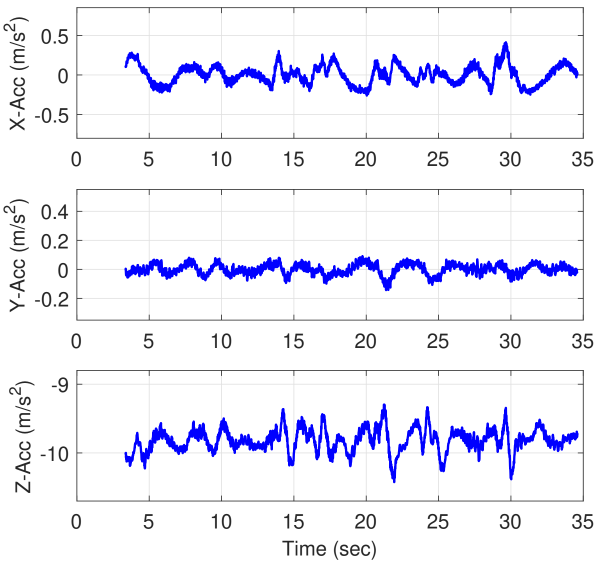

Figure 11. Helicopter accelerations during the hover using VH by Pilot 2

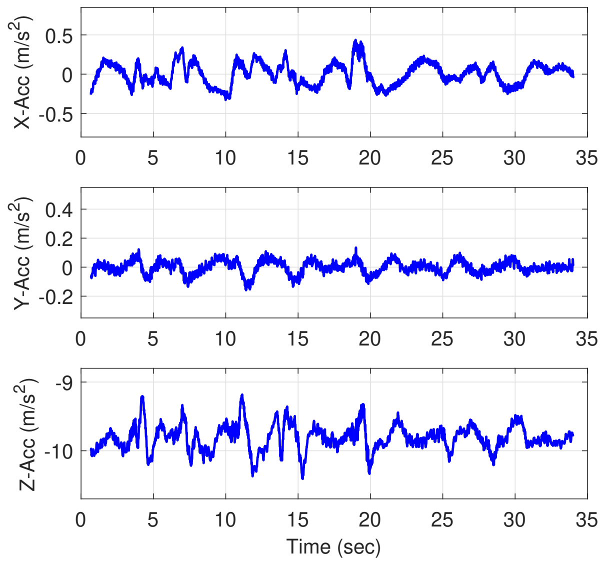

Figure 12. Helicopter accelerations during the hover using PH by Pilot 2

DIPES-3/2 to DIPES-2/1 with the automatic control modes. All the pilots awarded DIPES-1 for the TRC/PH, depicting only reasonable compensation was required and tracking and positioning accuracy was consistently maintained throughout the hover phase and the fleet pilots will have enough spare capacity to conduct if there are any ancillary tasks. It should be noted that DIPES considers that the pilots award the ratings based on their perceived ability of an average fleet pilot to accomplish the mission task. Pilots remarked that once a suitable hover position was achieved, there was basically no additional pilot compensation needed when using PH depicting extensive reduction in the workload, which was not the case with ACAH. However, one of the pilots also mentioned that he had the urge to do minor corrections during hover using TRC/VH as the helicopter drifted on the ship deck due to the airwake turbulence, however due to the design of the task, they were asked not to do any corrections. DIPES ratings also provides a possibility for the pilots to indicate the cause of the increased workload using one or more suffixes. For all the test points, the cause of the workload varied from pilot to pilot. For Pilot 1, "Y-Yaw control", "H-Height Control" to "F-Fore/Aft positioning" were the main factors that made the task difficult whereas for Pilot 2 "L- Lateral positioning" was challenging to achieve the accurate hover position.

Figure 15 shows the raw NASA TLX workload ratings for all the six subscales. It can be seen in Fig. 15 that Pilot 2 and Pilot 3 had overall less workload in most of the subscales when compared to Pilot 1. The higher workload by Pilot 1 could be dependent on the level and type of experience of the evaluation pilot. Figure 15 also illustrates higher physical demand for Pilot 1 with the TRC response type. As the pilot mentioned, the cause for that was the pilot required higher stick deflections with TRC in order to achieve a stable hover over the deck as TRC is a slow response type in contrast to Attitude Command which is known to be agile. Furthermore, Pilot 1 also commented that relatively higher effort was needed to find a suitable hovering position over the ship deck in order to engage PH when compared to VH, which was not a case for Pilot 2 and Pilot 3. The pilots also commented that the ship relative VH and PH modes were able to perform the automatic hover and no additional pilot compensation was required which reduced the pilot workload extensively. Besides the previously described exceptions, all the subscale ratings extensively improved with the augmented control types indicating lower workload during the hover task as the task was performed completely hands off. This also aligns to the pilot comments during the experiments. It can also be concluded looking at all the six subscales that the overall workload was reduced with the augmented control modes. Additionally, this was also confirmed by the pilot remarks that the Velocity Hold and Position Hold features are easier and more intuitive when the reference point is non-stationary, which is the case for the ship deck.

Eye Tracking

This section details the pilot's gaze patterns and visual engagement as captured by eye tracking. It should be noted that due to physiological constraints, it was not possible to collect eye tracking data with Pilot 3. Consequently, only the results from Pilot 1 and 2 form the basis of the subsequent analysis. Figures 16 & 17 show the hitmaps of Pilots 1 and 2 during the hover phase for the different control configurations. Both pilots used the PFD and the references on the ship's deck to gather sufficient visual information to perform the flight task successfully. In the sequence diagrams in Fig. 18 - 20, the AOI hits for Pilot 1 are plotted over time for the different control configurations. For the test case with ACAH and TRC/VH, an increasing focus from the ship in general to the ship references

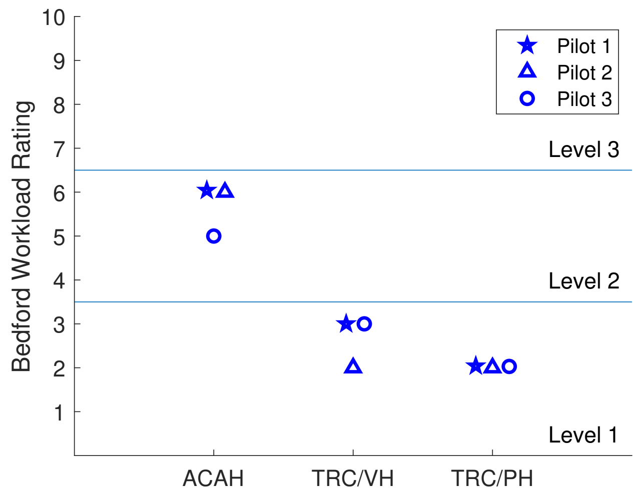

Figure 13. Bedford Workload Rating for the hover task using different control modes

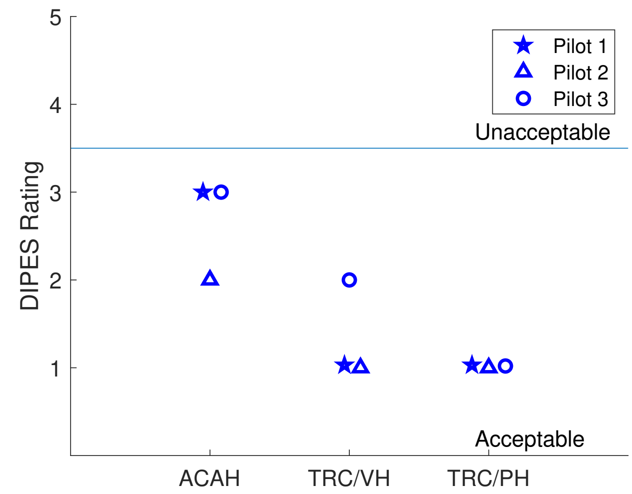

Figure 14. DIPES results for the hover task using different control modes

as well as the markings on the ship's deck can be seen during the approach with decreasing distance to the ship. However, during the hover phase, they observe mostly the ship references. Information from the PFD was continuously retrieved by Pilot 1 for the entire duration of the recording, independent of the selected control configuration. It can be seen in Fig. 18, that the pilot frequently switches gaze between the PFD and OTW. This indicates on one side, active situational awareness as the pilot is relying on both visual cues and instruments, and on the other side, higher cognitive demand, as the pilot is mentally integrating multiple information sources and due to the manual control compensation. In Fig. 19 with TRC/VH, the pilot gaze is mostly concentrated on the PFD, with fewer shifts to the OTW, which indicates that the pilot tends to rely more on the flight instruments proabably due to more stable control behaviour but is less visually engaged with the environment. In comparison to the other control configurations, a change in the distribution of attention from OTW to ITC can be recognised for TRC/PH. During the hover, Pilot 1 was almost exclusively focused on the PFD. Even though time was not considered as a metric for the evaluation task, it was observed that compared to ACAH, Pilot 1 was able to achieve a stable hover position and complete the approach approximately 30 seconds faster with TRC/VH.

Figure 21 shows the convex hull area of Pilot 1 and 2 for the different control configurations for the individual flight phases. From ACAH to TRC/VH, the change in the convex hull area of both pilots is comparable, whereby it increases from ACAH to TRC/VH regardless of the flight phase. Accordingly, the gaze points of both pilots occupy a larger area indicating a more spread out gaze and better situational awareness. From TRC/VH to TRC/PH, the pilots show different behaviour. While the convex hull area of Pilot 1 decreases again and corresponds approximately to the convex hull area of ACAH, the convex hull area of Pilot 2 remains similar.

Analysis and Discussion

The overall results of the study clearly demonstrate that increasing levels of control augmentation provide benefits to support the pilots during the hover task. Quantitative evaluation of position deviations confirms that both VH and PH modes enable better position-keeping performance compared to ACAH, with PH showing the most consistent ability to precisely maintain the hover. However, the PH performance remained within adequate limits but not desired limits, primarily due to current limitations in the implementation design rather the control logic itself. While these quantitative metrics provide objective insights into task performance, they alone are not sufficient to fully evaluate the effectiveness and pilot acceptance of the control modes. Therefore, subjective pilot ratings were also collected to capture perceived workload and operational safety. Subjective pilot ratings aligned with these findings, highlighting reduced workload and improved controllability in TRC modes. Nonetheless, NASA-TLX scores revealed that one pilot experienced high mental, physical, and temporal demands, especially in TRC/PH, emphasizing the role of prior experience and system familiarity.

Pilot gaze data further shed light on pilot behaviour: while ACAH showed active gaze switching between OTW and ITC suggesting high manual engagement, the automatic modes induced a shift toward heavier reliance on the PFD. In TRC/PH, this was most pronounced, with minimal attention directed outside the cockpit. Although this may reflect increased trust in automation and reduced need for visual corrections, it also raises potential concerns about reduced situational awareness in visually dynamic maritime environments. It should be noted that due to limited number of pilots, it is not the intention of this study to generalise conclusions. Instead, the pilot gaze analysis is assessed qualitatively providing only preliminary insights into the effects of control modes on gaze behaviour.

The increase in the convex hull area from ACAH to TRC/VH

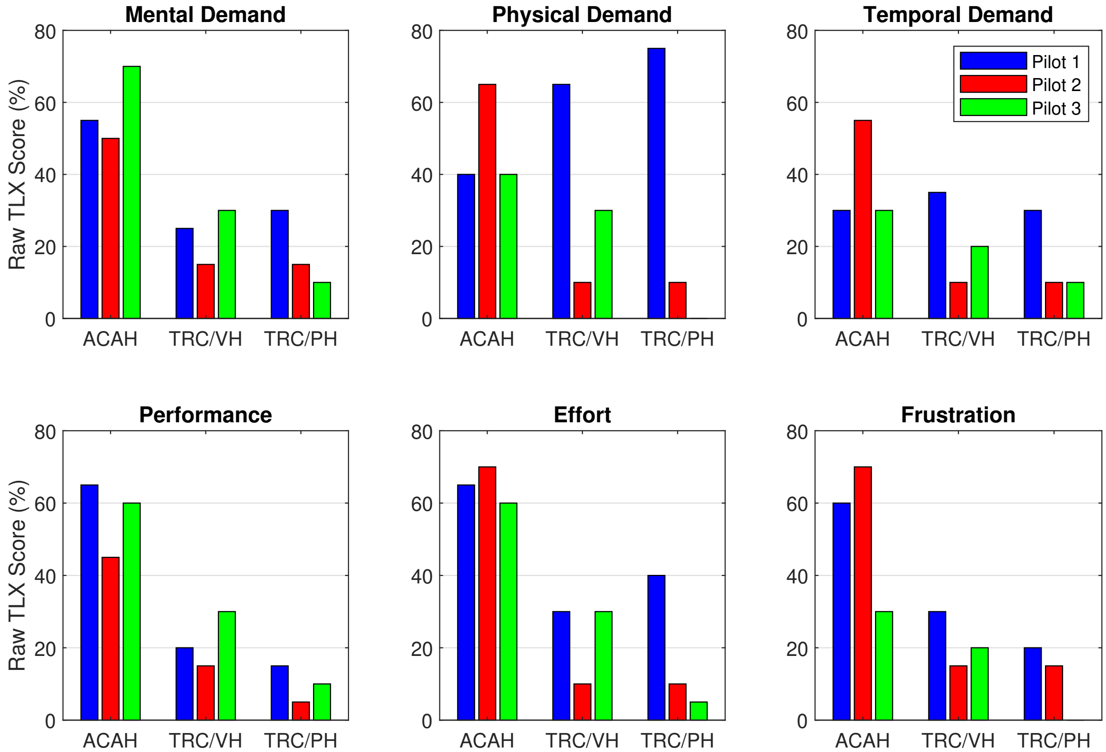

Figure 15. NASA TLX results for the hover task using different control augmentation systems

Figure 16. Hitmap of Pilot 1 during hover for different control laws

Figure 17. Hitmap of Pilot 2 during hover for different control laws

by both pilots may be seen as a positive trend, as a larger convex hull area can be associated with better situational awareness, although this interpretation cannot be further confirmed due to the lack of supporting subjective pilot ratings. However, it can be interpreted that if the gaze points cover a larger area, not only more but also different visual information was perceived by the pilot. This is particularly important when operating in the vicinity of objects such as ship superstructures. The opposite behaviour of Pilot 1 from TRC/VH to TRC/PH must therefore be evaluated critically. These observations are also supported by the sequence diagrams. The desired pilot behaviour here would be a regular change between the AOIs or at least between ITC and OTW, because it can be assumed that the pilot has all the relevant information about both the flight status of the helicopter and the environment in order to ensure a stable and safe flight status at all times. However, it was not the case while using TRC/PH during the entire hover phase, as the Pilot 1 looked exclusively at the PFD, although he was in direct proximity to the ship's superstructure. This also indicates higher trust in automation and reduced need for continuous visual corrections. Whether this is beneficial depends on the task demands. It might be acceptable during hover but might be critical while perform a deck landing. Overall, the findings highlight the dual importance of

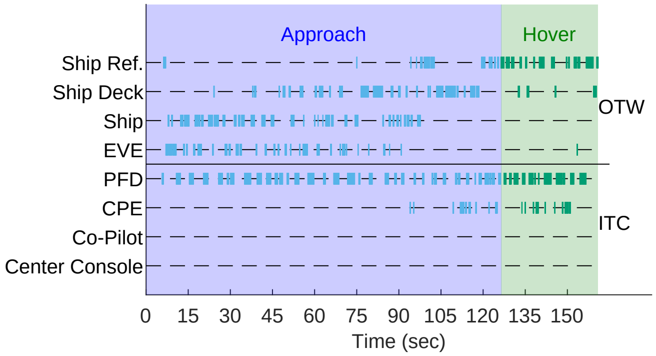

Figure 18. Sequence diagram of Pilot 1 during ACAH

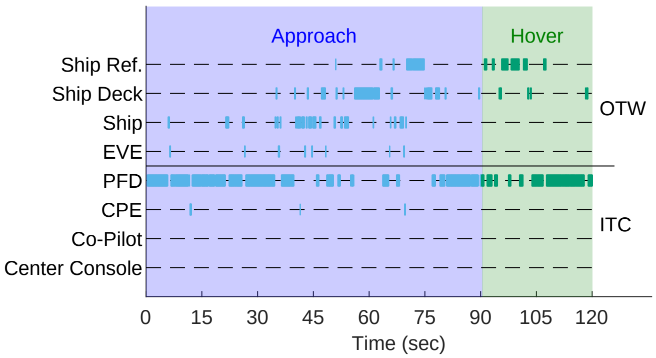

Figure 19. Sequence diagram of Pilot 1 during TRC/VH

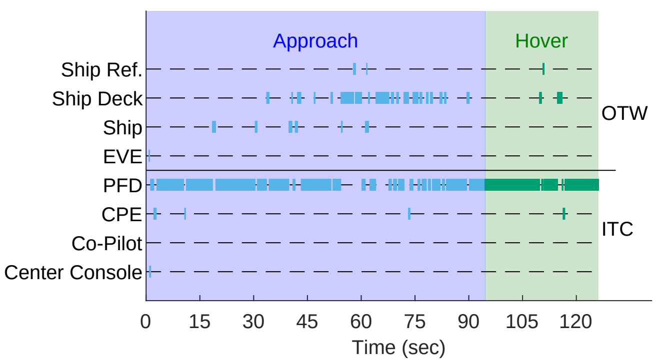

Figure 20. Sequence diagram of Pilot 1 during TRC/PH

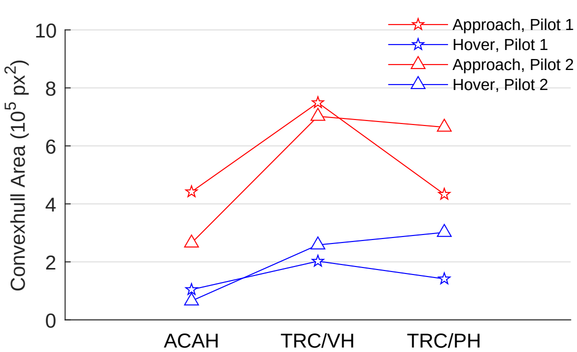

Figure 21. Comparison of the convexhull area of Pilot 1 and 2 for approach and hover for different control laws

effective control augmentation and appropriate pilot training to ensure that reduced workload does not come at the expense of environmental awareness.

CONCLUSIONS

A piloted simulation study was conducted in Air Vehicle Simulator to assess the influence of flight control augmentation on pilot workload and task performance during a shipboard helicopter hover operation. Additionally, eye tracking glasses were used as an additional metric to record pilot gaze data providing insights into attention distribution and cognitive demand across different control augmentation techniques. The simulation trials highlighted the following key conclusions:

1. Results demonstrated that when compared to ACAH, TRC combined with VH and PH illustrated better capabilities to perform an autonomous hover over the ship deck, without a need of additional pilot compensation. This allows the pilots to retain sufficient spare capacity to conduct if there are any ancillary tasks.

2. The position deviations indicate that PH is more efficient to maintain a hover over the deck when compared to ACAH and VH, providing the pilot with a high-precision maneuvering over the ship deck while reducing pilot's workload extensively.

3. The subjective pilot ratings and feedback indicated that the pilot workload was extensively reduced with the ship relative VH and PH modes even in the presence of turbulent airwake. However, the effectiveness of these systems is dependent on pilot familiarity and trust. Proper pilot training is essential to ensure safe and effective use of these modes and to avoid increased cognitive workload during such demanding operations.

4. Eye-tracking analysis depicts a shift in visual attention across control modes, with broader gaze dispersion with TRC/VH, suggesting more active visual monitoring and potentially enhanced situational awareness compared to ACAH.

5. With TRC/PH, pilots showed more focused attention on cockpit instruments, which may indicate increased trust in the automation but also highlights the need to ensure maintaining external awareness, especially in dynamic maritime environments.

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