PILOTED SIMULATOR EVALUATION OF AUTOMATIC FLIGHT CONTROL MODES FOR HELICOPTER OFFSHORE RESCUE OPERATION IN DEGRADED VISUAL ENVIRONMENT

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ABSTRACT

A piloted simulation experiment was conducted in the Air Vehicle Simulator (AVES) to evaluate and compare the performance of automatic flight control modes for helicopter offshore rescue operations in both good and degraded visual environments. The control systems investigated as part of this study included a ship relative translational rate command (TRC) combined with two different ship relative hold modes based on a model following controller architecture and an attitude command attitude hold (ACAH) which served as the baseline. In addition to the flight control modes, the pilots also had to handle two additional systems namely an in-house range gated sensor and a Head-Mounted Display (HMD) during the evaluation. The task was to locate personnel on the ship and perform rescue operation while performing a stable hover close to the ship. The study included a combination of operational maritime pilots and experimental test pilots who evaluated the flight control modes for offshore rescue operation in different visual conditions. The simulation results and the pilot feedback indicate improved perceived safety for fleet pilots in terms of increased spare capacity, lower workload and improved situational awareness using the automatic flight control modes in Degraded Visual Environment (DVE).

NOTATION

Abbreviations

ACAH	Attitude Command Attitude Hold
ACT/FHS	Active Control Technology/ Flying Helicopter Simulator
ACVH	Attitude Command Velocity Hold
AR	Augmented Reality
AVES	Air Vehicle Simulator
CETI	Control Equivalent Turbulence Input
DH	Direction Hold
DLR	German Aerospace Center
DVE	Degraded Visual Environment
GVE	Good Visual Environment
HDD	Head-Down Display
HEMS	Helicopter Emergency Medical Service
HH	Height Hold
HMD	Head-Mounted Display
HUMAN	HUbschraunbereinsätze im Rahmen der MAritimen Notfallvorsorge (using Helicopters Operations to Support Maritime Emergencies)
NASA TLX	NASA Task Load Index
PH	Position Hold
PFD	Primary Flight Display
RTRC	Relative Translational Rate Command
SAR	Search and Rescue
SART	Situation Awareness Rating Technique
SDK	Software Development Kit
TRAGVIS	Transportable Range-Gated Viewing System
TRC	Translational Rate Command
VH	Velocity Hold

INTRODUCTION

Degraded visibility is one of the most significant challenges faced during helicopter offshore rescue operations, as it severely impairs a pilot's ability to navigate and control the aircraft during Helicopter Emergency Medical Service (HEMS) or Search-and-Rescue (SAR) missions. Typical degraded visual environment (DVE) conditions include night, dense fog, heavy precipitation and brownout caused by rotor downwash. Fog over the sea can be especially persistent and disorienting, often accompanied by low clouds, sea spray and horizon obscuration creating a complex and unstable visual environment during maritime operations. Poor weather, low visibility and environmental factors often create scenarios where pilots must rely heavily on instruments, leading to increased workload, a higher potential for errors

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and loss of situational awareness. In addition to visibility limitations, pilots must contend with turbulent ship air-wake, dynamic sea states, and the need for precise maneuvering in confined spaces, all of which further complicate such operations (Ref. 1).

To mitigate the effects of degraded visibility, past research has focused on the use of visual cues and visual augmentation systems, such as enhanced and synthetic vision or Head Mounted Displays (HMD) (Ref. 2). While these technologies can provide improved situational awareness in low visibility conditions, their effectiveness is often dependent on environmental conditions and pilot experience and they often fall short when external disturbances such as high sea states, deck motion, or wind gusts introduce rapid changes in the aircraft's dynamics (Ref. 3). In these scenarios, the pilot remains responsible for maintaining precise control in an unstable environment, often with limited visual cues. In some cases, excessive reliance on visual augmentation may add to the cognitive burden rather than reduce it, particularly in such high-stress situations. This gap underscores the need for advanced flight control augmentation systems that can directly support the pilot by enhancing aircraft stability and reducing manual control burden (Refs. 4,5). In addition, this has led to growing interest in automation within flight control modes to provide more intuitive and adaptive assistance to pilots (Ref. 6). By reducing manual control effort and compensating for degraded external references, control augmentation and automation has the potential to improve both the overall flight safety and operational efficiency in offshore rescue missions during degraded visibility (Ref. 7).

While pilot assistance systems have made significant progress in terms of reducing pilot workload, improving stability, and enhancing guidance capabilities, there remains a lack of comprehensive evaluation of control augmentation strategies that addresses the specific challenges posed by degraded visibility in maritime helicopter operations (Ref. 8). In particular, the integration of visibility effects into the assessment of control systems is overlooked, despite its critical influence on situational awareness and flight safety. Hence, there is a need for piloted simulation studies that incorporate realistic visibility limitations and maritime disturbances to evaluate how control augmentation systems can contribute to improve pilot performance and enhance safety in such demanding offshore scenarios and to effectively train pilots to use such systems in real-world operations.

The current study evaluates and compares the effectiveness of automatic flight control modes for helicopter offshore rescue operations in degraded and clear visual conditions. A maritime emergency scenario was integrated in the Air Vehicle Simulator (AVES) at DLR Braunschweig, where a piloted simulation experiment was conducted. The pilots performed a rescue operation in Good Visual Environment (GVE) and Degraded Visual Environment (DVE) while managing two additional system operations.

PREVIOUS WORK

Several studies have been performed at DLR Braunschweig, for the implementation and evaluation of pilot assistance systems for maritime helicopter operations including but not limiting to basic and advanced control modes, a range-gated sensor simulation and development of HMD based on Augmented Reality (AR) in the domain of different projects (Refs. 9, 10). As discussed previously, since flight control augmentation offer a more robust means of supporting the pilots during critical phases of flight, their development and evaluation has emerged as a central aspect in the continuation of the current work. As demonstrated in the earlier studies at DLR Braunschweig, an initial evaluation and comparison of the various augmented flight control modes and the implemented automatic flight control modes have been performed for different maneuvers including complete approach, hover over the ship deck and landing operations in clear visual conditions (Refs. 11, 12). In the past studies, the pilots evaluated the suitability of the basic and advanced flight control modes in clear weather conditions for the specific shipboard operations, where they neither had any additional sensors to use nor ancillary tasks to perform in addition to the standard maneuver.

Project HUMAN

The current work is part of the project HUMAN, running from 2022-2024, which stands for HUMAN, Hubschraubereinsätze im Rahmen der maritimen Notfallvorsorge) in German that means using Helicopters Operations to Support Maritime Emergencies. The primary, overarching objectives are to increase safety in maritime infrastructures through the use of helicopters and to secure operation of helicopters in maritime environments. The subordinate objectives of the HUMAN project include increasing situational awareness and reducing the workload of pilots in DVE through the use of sensor and pilot assistance systems. These are derived directly from the operational requirements of the Flight Service of the German Federal Police.

The focus of the HUMAN project is the investigation, development and evaluation of helicopter assistance systems for use in the context of maritime emergency preparedness and maritime surveillance. Therefore, one of the major objectives of the project HUMAN was to integrate multiple pilot assistance systems including the automatic flight control modes and a sensor into a maritime environment to support helicopter pilots in DVE. The current study aims to evaluate the suitability of automated control modes not only in degraded visual conditions but also when the pilots had to operate additional systems and perform rescue operations. These additional systems were perceived as secondary tasks be the pilots. The study provides insights into the challenges of operating in such conditions and assesses how control augmentation can support pilot performance, workload reduction and improve overall safety.

FLIGHT SIMULATION FACILITY

The experiment was conducted in the Air Vehicle Simulator (AVES) at DLR Braunschweig as described in (Ref. 13). AVES represents a replica of the cockpit of DLR's research helicopter Active Control Technology/Flying Helicopter Simulator (ACT/FHS) which is an extensively modified EC135. Evaluations were conducted from the right seat, with the evaluation pilot's position configured with classical longitudinal and lateral cyclic stick, collective stick and pedal pilot control inceptors.

A 3D ship model of a container ship is integrated into the present maritime simulation. Ship movements are calculated in the AVES environment via the in-house developed software called VehicleControl (Ref. 14). For the simulation of the ship dynamics in this project, VehicleControl uses a mass-spring-damper model with adjustable parameters such as amplitudes and phase for the roll, pitch and yaw movement.

In the AVES image generation system, the SunDog Triton software development kit (SDK) is used to generate wave and ocean effects. The wave visualisation assists in the representation of several graphical effects, such as ship airwake and helicopter rotor downwash, which ultimately enhances the situational awareness of the pilots. Weather conditions are simulated using the SunDog Silverlining SDK, which provides realistic cloud rendering, particle-based fog, and precipitation effects such as rain (Ref. 15). In the current study, these features are employed to create realistic degraded visual conditions, to evaluate the pilot performance and the aircraft control under limited visibility.

SYSTEM SETUP

The system comprises the helicopter flight model, flight control modes and two additional visual aids. The technical details for each component of the system is described in the following section.

Helicopter Flight Model

The helicopter dynamics model of ACT/FHS is developed using the in-house real-time nonlinear helicopter modeling program HeliWorX, which is based on the helicopter modeling program SIMH (Ref. 16). The rotor dynamics model uses rigid blade assumptions and blade element theory and the inflow is based on the Pitt/Peters dynamic inflow model (Ref. 17).

The flight dynamics models of the helicopter were extracted using system identification with low-order equivalent models in time domain using flight test data. Several sweeps and multistep inputs were performed at five different operating points from hover to 120 kt in steps of 30 kt in order to cover a broader flight envelope, which were finally stitched together to create a full envelope helicopter simulation. (Refs. 18, 19) provide a detailed description of the system identification and validation process. The Control Equivalent Turbulence Input (CETI) model configured for ACT/FHS was used to provide realistic turbulence for the simulation (Refs. 20, 21).

Flight Control Modes

As part of the broader study objective, the current work aims to evaluate the automated control modes under operationally demanding conditions, specifically, not only in degraded visual conditions but also when the pilots were required to manage additional systems and conduct rescue operations while performing a stable hover close to the ship. In this context, two advanced flight control configurations featuring a ship relative Translational Rate Command (TRC) combined with ship relative Velocity Hold (VH) and Position Hold (PH) were evaluated during the study. Additionally, a conventional response type, with no ship communication, an Attitude Command combined with an attitude hold (ACAH) was used as a baseline for the comparison.

The flight control laws were implemented using a flight tested model-following control system architecture. The control laws feature two different response types combined with specific hold modes namely an attitude command attitude hold as baseline and a ship relative translational rate command combined with ship relative VH and PH. The control system comprises a feedforward and a cascaded feedback controller enabling the helicopter to track the desired command types. Additional information about the development of the control laws is provided in (Refs. 12, 22).

ACAH is a classical mode with no ship communication and the longitudinal and lateral stick deflections are proportional to the aircraft's pitch and roll attitudes. TRC on the other side, is a ship-relative TRC and therefore involves communication with the ship. The stick deflections for TRC are proportional to longitudinal and lateral helicopter velocities relative to the ship, combined with a ship relative VH and PH. In all configurations, the yaw rate and the vertical speed are commanded with pedals and collective stick, and are combined with a Direction Hold (DH) and Height Hold (HH) respectively.

For the ship-relative hold modes, for VH, the helicopter velocity is matched to the current ship speed. When centered, i.e., when the pilot goes complete hands-off, it allows to hold a zero relative velocity with respect to the ship if the pilot did not detrim the stick. Upon activation of the PH mode, the helicopter holds a constant relative position with respect to the ship. As the hold modes are ship relative, the ship position and velocity information are assumed to be available to the controller via a data link. To suppress high-frequency wave-induced motion, ship signals are filtered using a second order filter and delayed by a small time offset before being used by the controller. This delay is necessary because the controller must account for real-world transmission lags to maintain accurate and stable responses.

Once the pilot positions the helicopter, where the relative distance between the helicopter and the ship deck is below the threshold and the pilot can go complete hands-off. Consequently, the PH gets engaged and the pilot now has an option to activate the PH mode and consequently, the longitudinal and lateral positions are maintained over the deck. Please note that the pilots are informed about active modes in each axis on the Primary Flight Display (PFD) as shown in Fig. 1.

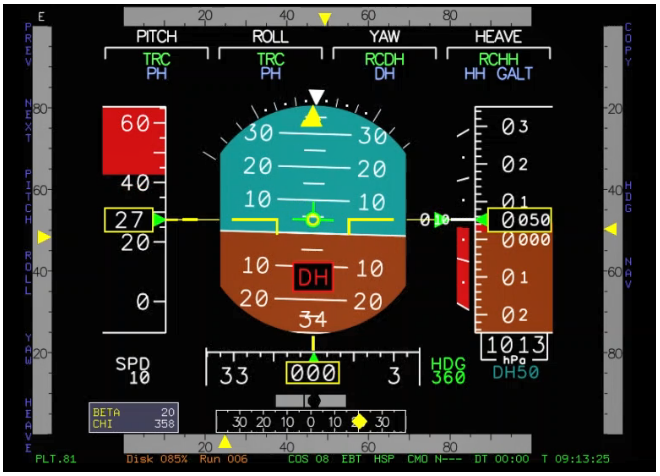

Figure 1. Primary Flight Display (PFD) with active control modes

Additional Systems

In addition to the control augmentation systems, two supplementary systems were integrated into the simulation to further assist the pilots during the trials. First, an in-house range gated viewing sensor named Transportable Range-Gated Viewing System (TRAGVIS) that filters the undesired reflections using an actively pulsed light source and an electronic camera shutter which makes it possible to see through atmospheric particles like fog, water droplets etc. Detailed information about the development of real-time sensor simulation of the sensor can be seen in (Ref. 9). The image generated by the sensor was displayed to the pilots either on a BARCO Head-Down Display (HDD) or on a Head-Mounted Display (HMD) which was also the second system that the pilots were required to operate during the simulator trials. This second system was specifically the Microsoft HoloLens 2 glasses. Figure 2 displays the sensor image of the disabled container ship conformal with the outside view in the HMD. Further details about the integration of the HMD system can be found in (Ref. 23). However, the implementation and evaluation of these additional systems is detailed in (Ref. 24).

The objective to use additional systems was also to understand the influence of the control augmentation when the pilots have additional operations to perform along with the maneuver in challenging conditions. The primary focus of the evaluation was to assess the control augmentation systems, and the other systems were not part of the formal assessment. Although it is challenging to separate the effects, the pilots were instructed to put less emphasis on the performance of the additional systems.

PILOTED SIMULATION TRIAL DETAILS

During the piloted simulation trials, the pilots performed multiple offshore rescue operations during different visual conditions to evaluate the implemented control modes. The complete details about the piloted simulation trials are described in the following section.

Figure 2. 3D conformal TRAGVIS sensor simulation image of a disabled container ship in the HMD (Secondary task)

Test Scenario

In the piloted simulation trials, a maritime emergency scenario was implemented in the research flight simulation facility called Air Vehicle Simulator (AVES) at German Aerospace Center (DLR) Braunschweig. The pilot evaluation campaign was conducted in two phases during the project HUMAN. During the first phase, two pilots from the Flight Service of the German Federal Police flew the configurations in DVE with the focus of the evaluation of all assistance systems including the flight control modes, sensor simulation and HMD, considered as an integrated system. During the second phase of pilot evaluation, the test matrix from Table 1 was flown in GVE and DVE with the focus on the control mode evaluation to compare the pilot workload and task performance. Both GVE and DVE scenarios feature a disabled container ship at sea serving as a recovery target, which was considered to be drifting laterally with 5 kt. Slow sinusoidal oscillating ship motions were considered in pitch and roll axes with amplitudes of 3° and 10° respectively. In the GVE scenario as shown in Fig. 3, environmental visibility was clear, with no oscuration of the horizon or visual references, allowing the pilot full spatial awareness. In contrast, as illustrated in Fig. 4, the DVE scenario was characterised by dense sea fog corresponding to a horizontal visibility of 80 m, severely limiting external visual cues and eliminating the visible horizon, thereby creating a challenging condition for manual control and situational awareness. A fixed turbulence level was used across all simulation trials. This turbulence level was chosen as a trade-off to introduce adequate disturbances that challenge the pilot during task execution in GVE, without imposing excessive workload during more demanding tasks in DVE.

Evaluation Task

Since the primary objective of the project HUMAN was to evaluate new technologies to support helicopter operation during maritime emergency situations, the evaluation task was

Figure 3. Maritime simulation environment in AVES with a disabled cargo ship in good visibility

designed accordingly. During such emergency situations, helicopters play a critical role in rescuing personnel on board the vessel and protecting maritime infrastructure. Accordingly, the task objective for the pilots was to locate and retrieve personnel stationed on the vessel for which they had to approach the ship and perform a stabilised hover for 30 seconds in the close proximity to the ship at the location where they found the personnel and accordingly perform the rescue operation. To facilitate a comprehensive evaluation with different test conditions, the personnel consisting of three humans were placed at four distinct locations on the ship: Bow, Starboard; Stern, Port; Bridge, Port and Amidships, Starboard. During the test campaign, the pilots were required to complete the rescue task under each test configuration as described in Table 1 both in GVE and DVE, providing insights into operational performance in DVE and GVE.

Test Matrix

In total five test points based on two different response types combined with different hold modes were considered for the pilot study. The three flight control augmentation systems were tested with and without two additional systems as described in the system setup in GVE and DVE. Table 1 describes all the test configurations used during the pilot study. During the first phase of the pilot study, there were two additional test points, 6 and 7, that were tested with Pilot 1 and Pilot 2.

In these test points, 6 and 7, the pilots performed the task with the advanced control modes in combination with the sensor simulation image being displayed on the BARCO HDD. However, it was highlighted by the pilots that the additional sensor simulation system displaying the ship image on the BARCO HDD used in these two configurations was not adapted to this procedure and should be further enhanced to optimally support the flight operation; hence due to time constraints, these two test cases were not considered in the final test matrix during the second phase of the pilot study with the rest of the pilots. Additionally, the test configuration 5 was only performed in DVE as it did not bring any additional research value to repeat it in GVE.

Figure 4. Maritime simulation environment in AVES with a disabled cargo ship in degraded visibility

Evaluation Pilots

A total of five evaluation pilots participated in the simulation study in two different phases, where Pilot 1 and 2 participated in the first phase and Pilot 3, 4 and 5 participated in the second phase of the pilot study. Pilot 1 and 2 are helicopter pilots from the Flight Service of the German Federal Police and are familiar with helicopter shipboard operations. Pilot 3, 4 and 5 are helicopter pilots whereas Pilot 4 and 5 are also qualified as experimental test pilots. Even though Pilot 3, 4 and 5 have close to no experience with maritime operations, their experience is considered useful to test the improvements in safety and efficiency of the control modes as they have been constantly participating in the simulation studies involving ship deck landings and other helicopter offshore operations. Pilots 1, 2, 4 and 5 have an IFR rating as well. All of them have operated in DVE including fog and nighttime.

Qualitative Evaluation

Different types of evaluation data was collected during the simulation trials. In addition to the quantitative task performance data, pilots awarded qualitative ratings using different rating scales for the qualitative evaluation data. Furthermore, a pilot questionnaire was also used to record the pilot feedback for different test configurations.

A total of three rating scales namely Bedford Workload Rating Scale, NASA Task Load Index (TLX) and Situational Awareness rating Technique (SART) were used to collect the qualitative data during the simulation trials. The Bedford Workload Rating, inspired by the Cooper-Harper rating scale, is a discrete scale ranging from 1 to 10, where pilots rate their workload by identifying the spare mental capacity while completing the main task (Ref. 25). In contrast, the NASA Task Load Index (NASA-TLX) provides a multidimensional measure of workload by assessing six distinct subscales namely mental demand, physical demand, temporal demand, performance, effort and frustration addressing different aspects of task demand and pilot response (Ref. 26).

The Situational Awareness Rating Technique (SART) is a three or ten dimensional questionnaire using 7-point Likert

Table 1. Overview of Test Configurations

Configuration	Control Mode	Additional Systems
1	ACAH	None
2	TRC/VH	None
3	TRC/PH	None
4	TRC/VH	TRAGVIS on HMD
5	TRC/PH	TRAGVIS on HMD
6*	TRC/VH	TRAGVIS on HDD
7*	TRC/PH	TRAGVIS on HDD

scales to evaluate the pilot's situational awareness in the categories "Demand (D)", "Supply (S)" and "Understanding (U) (Ref. 27). The resulting score is calculated via the formula $SART = U - (D - S)$. For the simulator campaign, the 10D questionnaire was used.

Additionally, a list of questions including but not limited to the following questions were provided to the pilots to collect their feedback about the impact of visual environment, mode specific feedback and overall situational awareness:

- How did degraded visibility affect the task performance?
- Was the augmented mode helpful in degraded or good visibility?
- Did the mode improve the situational awareness?
- What improvements would you suggest for the control modes?
- Were you always aware of the helicopter's position relative to the ship in GVE and DVE?
- Could you predict the helicopter's response to their inputs?
- Were you aware of the ship's motion (pitch/roll/yaw) throughout?
- Did you experience any disorientation or confusion during the task?

SIMULATION RESULTS

The simulation results stem from piloted trials performed in AVES to evaluate the performance and effectiveness of automatic flight control modes in GVE and DVE. A total of five helicopter pilots, with diverse levels of experience and different background performed the evaluation task in two different phases of the simulation trials. All the pilots performed the tests and evaluations of the task and provided the rating independent from each other. The focus of the evaluation was the hover task near to the ship which was performed at different locations depending on the location of the personnel either manually with ACAH or completely hands-off when using the ship relative VH or PH and/or with the additional systems.

Quantitative Results

Figures 5 and 6 show the longitudinal and lateral position deviations during the hover for configuration 1, which was least automated and had no additional systems in GVE and DVE respectively. In configuration 1, the whole approach and maneuver was performed manually by the pilot. As seen in Fig. 5 and 6, the position deviations during the hover phase display that maintaining a stable hover with this configuration is highly challenging for the pilot and they have no spare capacity to operate any additional systems both in GVE and DVE. It can be noticed that the magnitudes of the position deviations for configuration 1 remained comparable across both GVE and DVE, which suggests that improved visual conditions did not provide any benefits to the pilots for improved task execution which is why the pilot performance was relatively unaffected by the visual environment.

Figures 7 and 8 show the position deviations during the hover phase for configuration 2 and 3, which had the increasing levels of automation by Pilot 5 in DVE. However, in configuration 2 and 3 as seen in Fig. 7 and 8, where pilot uses a ship relative TRC and the hover is performed automatically by the VH or PH, the pilot had basically nothing to do in order to maintain the hover and could concentrate on the other tasks. The position deviations using configuration 2 with VH are much smaller when compared to the case when pilot performed the hover manually in configuration 1 and position deviations using the configuration 3 with PH are the least. The pilots commented that completing the task without the assistance of automatic modes in the DVE would have been safety critical due to the extremely high workload and lack of visual references and situational awareness. As the hover was performed in configuration 4 and 5 automatically using VH and PH respectively, the task performance does not have any impact from the use of additional systems. Hence, these results for configuration 4 and 5 are avoided here for brevity.

Moreover, the task performance from the other pilots show similar trends. This can also be confirmed in Fig. 9 which displays the Standard Deviation of the position error of helicopter with respect to the ship during the hover phase for configurations 1, 2 and 3 by Pilot 3, 4 and 5. A clear trend of reduction of position error both in longitudinal and lateral position is visible when using the automatic flight control modes both in GVE and DVE. The results from the first phase of the simulator trials, where Pilot 1 and 2 flew the configurations in

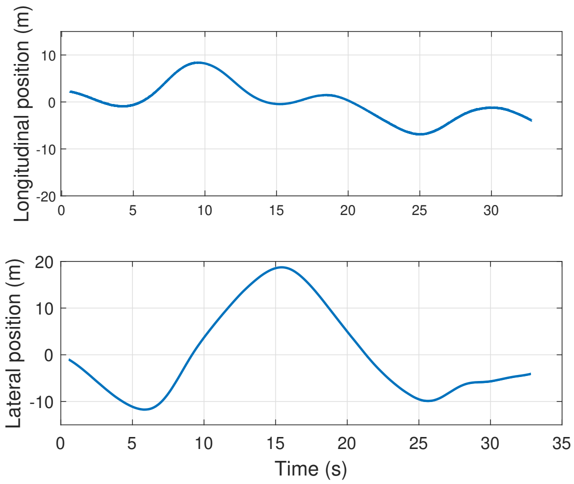

Figure 5. Deviations in helicopter position relative to ship during the hover using configuration 1 by Pilot 5 in GVE

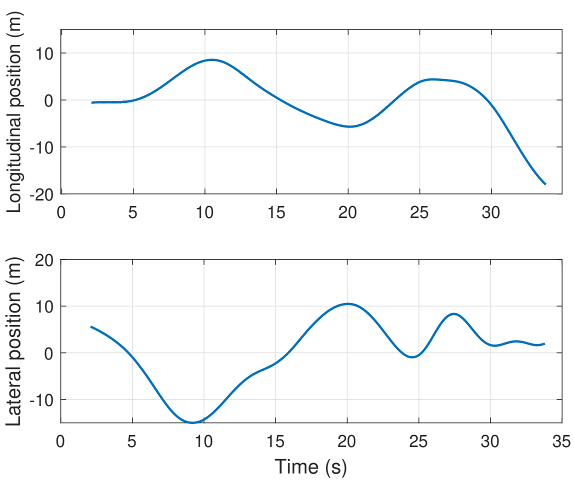

Figure 6. Deviations in helicopter position relative to ship during the hover using configuration 1 by Pilot 5 in DVE

DVE to evaluate the integrated system, showed similar trends but are excluded here to focus on the main comparison between the control modes.

The extent of pilot control input required to perform the maneuver is also an important parameter to be assessed to distinguish the differences in the operation in GVE and DVE. The pilot control inputs with respect to time during the hover phase for configuration 1 are illustrated in Fig. 10 and 11 in GVE and DVE respectively. It can be seen that the pilot had to make more effort in DVE in lateral, yaw and heave axes. However, as seen in Fig. 10 in GVE, there was not a lot of pilot control activity in yaw and heave axes which depicts the overall workload in yaw and heave axis was clearly reduced in GVE. It can be highlighted that although the configuration 1 showed minimal change in position deviations across GVE and DVE, this does not necessarily imply that performance remained unaffected; rather, it highlights that the position accuracy alone may be insufficient to capture effects of degraded visibility.

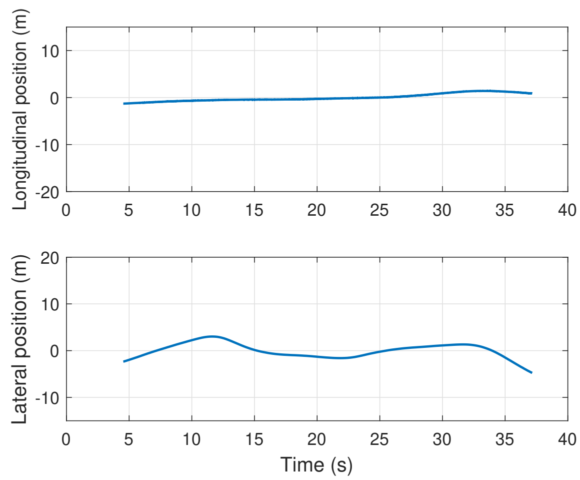

Figure 7. Deviations in helicopter position relative to ship during the hover using configuration 2 by Pilot 5 in DVE

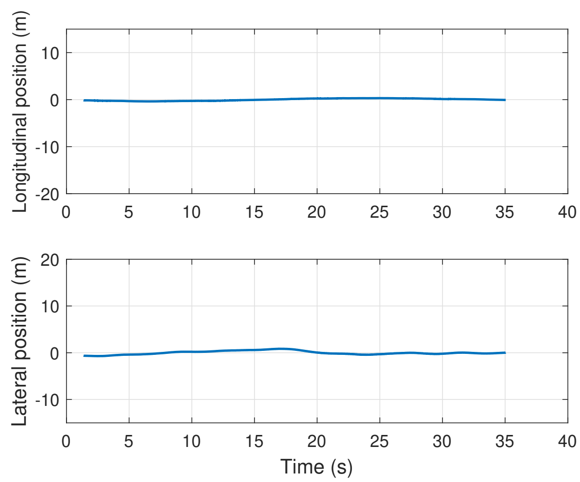

Figure 8. Deviations in helicopter position relative to ship during the hover using configuration 3 by Pilot 5 in DVE

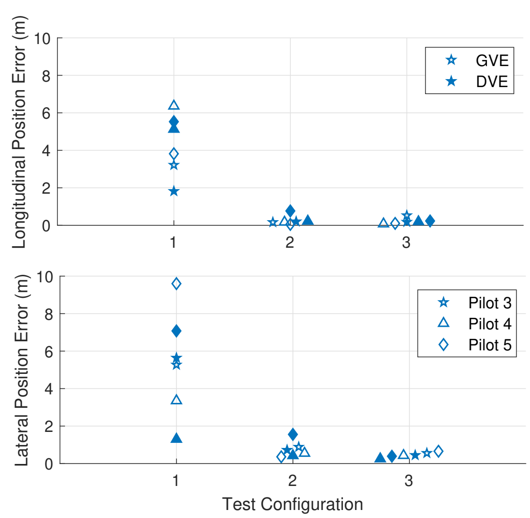

Figure 9. Standard deviation of position error during hover

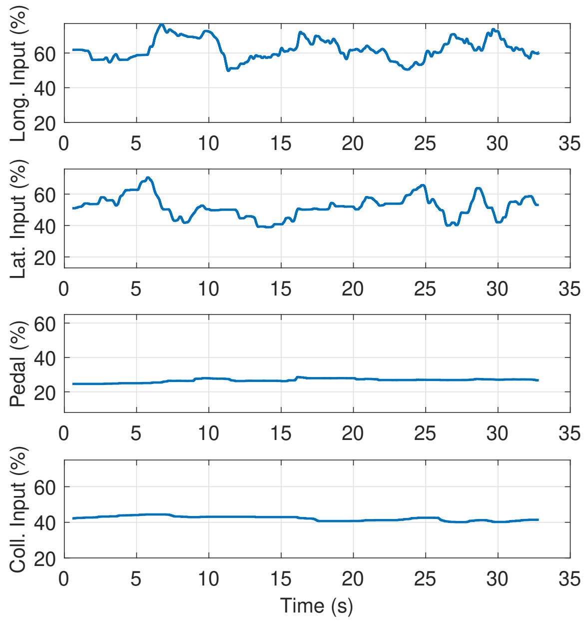

Figure 10. Time histories of pilot control activity during the hover using configuration 1 by Pilot 5 in GVE

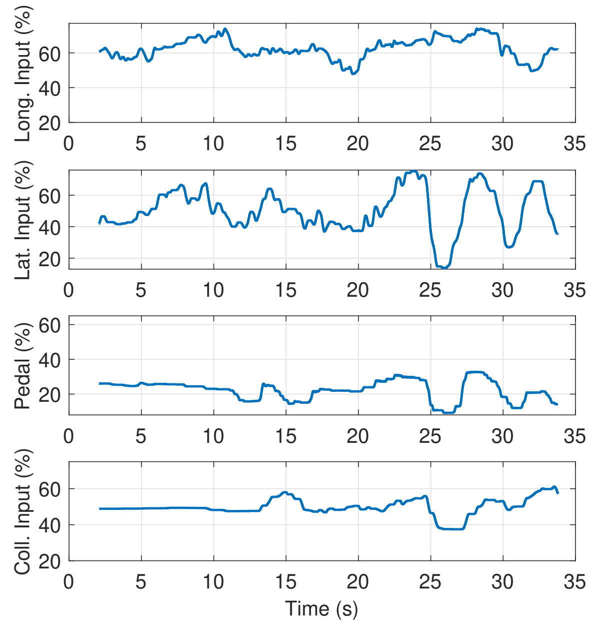

Figure 11. Time histories of pilot control activity during the hover using configuration 1 by Pilot 5 in DVE

Qualitative Results

For the qualitative evaluation of the automatic control modes, the pilots awarded subjective ratings after each experiment based on three different rating scales. It should be noted that due to the limited number of pilots, the pilot ratings are intended to be assessed qualitatively to gain insight into the impact of the control modes in DVE. Figure 12 shows the Bedford Workload Rating for all the test configurations. The Bedford Workload Rating scale assesses the pilot workload by evaluating how much spare capacity they have for additional tasks while performing the primary piloting task. Lower ratings indicate higher spare capacity for handling additional tasks. Accordingly, it can be observed in Fig. 12 that the configuration 2 and 3 with higher levels of automation and no additional systems were rated lower when compared to configuration 1 depicting that the pilots experienced reduced workload and had more spare capacity to handle potential ancillary tasks, had any been present. However, the configuration 4 with VH and TRAGVIS on HMD was rated higher by some of the pilots as the pilots commented that the extra information on the HMD increased the workload and did not really support in the task. Additionally, it is also visible in the figure that the pilots had higher workload in the DVE scenario for individual test configurations when compared to GVE. It was also observed that the Bedford Workload Rating of pilot 3 were generally higher when compared to other pilots. This could possibly be explained by his limited experience with these systems. It should also be noted that the ratings by Pilot 1 and 2 in red in Fig. 12 show the ratings during the first phase of the piloted study, where the pilots flew different configurations with a focus of the evaluation of all the assistance systems. It can be observed that the ratings for the integrated system, where all systems are rated together, also align with the individual control mode focused ratings.

The situational awareness scores for all the test configurations are shown in Fig. 13. It should be noted that in the first phase of the simulation trials, all assistance systems were evaluated together. During this phase, Pilot 1 and 2 flew specific configurations in DVE, and these results are shown in red in Fig. 13. In contrast, Pilots 3, 4 and 5 participated in the second phase of the trials, which focused on evaluating the influence of control modes in different visual environments. Their results are shown in blue in Fig. 13. For most of the test configurations during the second phase of the trials, the pilots experienced higher situational awareness in GVE than in DVE indicating that direct availability of visual references support spatial orientation and improves situational awareness. The results from Pilot 1 and 2 during the first phase of the trials were also consistent with those of the other pilots. However, Pilot 3 has shown reduced situational awareness even in GVE. This was due to the fact that the pilot was unfamiliar to the control modes and the additional assistance systems and the complex test environment which lead to the reduced situational awareness even in GVE. Moreover, the pilots experienced increased situational awareness with configuration 2 and 3 in DVE, both of which featured the automatic control modes. This improvement is attributed to the reduced manual control workload provided by these modes, allowing pilots to concentrate more on external cues, mission progress, and system monitoring despite limited visual references. The situational awareness scores are varying for configurations 4 and 5, as Pilot 4 and 5, who were familiar with the systems, experienced better situational awareness when compared to Pilot 3, who had less experience with those systems.

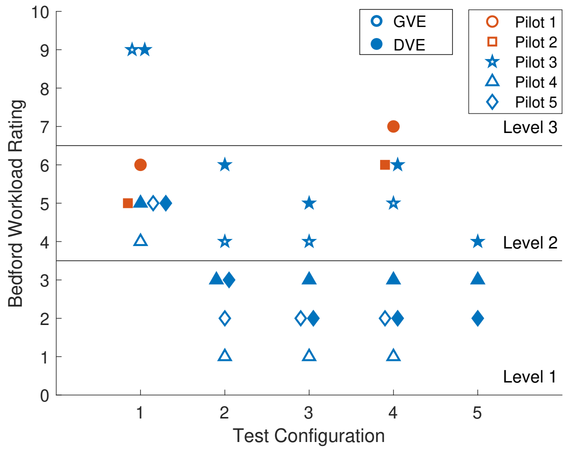

Figure 12. Bedford Workload Rating for the evaluation task using different test configurations in GVE and DVE (red: first phase of pilot study and blue: second phase of pilot study)

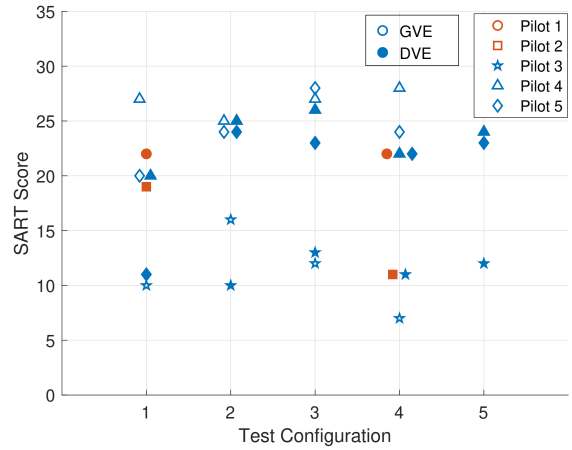

Figure 13. SART Score for the evaluation task using different test configurations in GVE and DVE

The pilot ratings for all the six subscales of NASA TLX score for all the test configurations in both GVE and DVE by Pilot 3, 4 and 5 are shown in Fig. 14. The NASA TLX results include the ratings only from Pilot 3, 4 and 5 in the second phase of the piloted trials. The results from the first phase of the simulator trials, during which Pilot 1 and 2 flew the configurations in DVE to evaluate the integrated system are excluded here to preserve the interpretability of the plots. In most of the six subscales, the NASA TLX score was smaller for the configuration 2 and 3 when compared to configuration 1, which is consistent to the trends observed in the Bedford Workload ratings as shown in Fig. 12. Additionally, it can be observed that the temporal demand for the configuration 2 and 3 and was higher for Pilot 1 in DVE, which was due to the fact that the pilot was not familiar with the advanced control modes and needed more time to perform the task in degraded visibility. Moreover, the temporal demand by Pilot 3 was higher with almost all the configurations when compared to other pilots, which highlights the unfamiliarity with control modes again. It is also interesting to observe that the Pilot 3 rated equal effort for configurations 2, 3, 4 and 5 in DVE as he mentioned it was not much effort once a suitable position was obtained to perform the hover as the positions were automatically maintained. However, the NASA TLX results from the other pilots during the first phase of the simulator trials also demonstrated similar trends.

A sample list of the pilot comments based on the pilot questionnaire for the tested configurations is given below:

- ”PH was very helpful for the hover part, when flying close to the ship.”
- ”One cannot fly safely without the automatic modes at all as there are no references, no horizon, hence the modes are very helpful in DVE.”
- ”One could not see a lot in DVE if one gets far from the ship and if the ship goes out of sight, it would be difficult to find the ship again.”
- ”The visibility of ship motion was substantially reduced in DVE, making it challenging to accurately perceive the vessel movement. It was not clear if the ship has motion or if the helicopter was the one, which was moving, which was not the case in GVE.”
- ”Helicopter’s response was predictable in all other axis mostly. However, roll axis needed a bit more care to operate.”
- ”It was confusing with configuration 4 and 5 in DVE, because with the sensor, the position of helicopter needed to be changed to see properly.”
- ”DVE made the task difficult to find the position as well as to locate the personnel.”
- ”In DVE, the modes were much more helpful for the whole procedure and hover. However, in GVE the modes were helpful for hover mainly.”
- ”Automatic flight control modes improved situational awareness in DVE because while the position was maintained, there was more capacity to do other tasks, especially in DVE.”
- ”The responsiveness in the roll axis can be improved as the roll inputs possibly sluggish, which affected lateral maneuvering, particularly during alignment with the ship.”

Overall, the pilot comments further reinforce the benefits of automatic flight control modes compared to other other additional systems presented in the study especially in DVE that aligns with the findings already identified in the qualitative data from subjective ratings and pilot feedback.

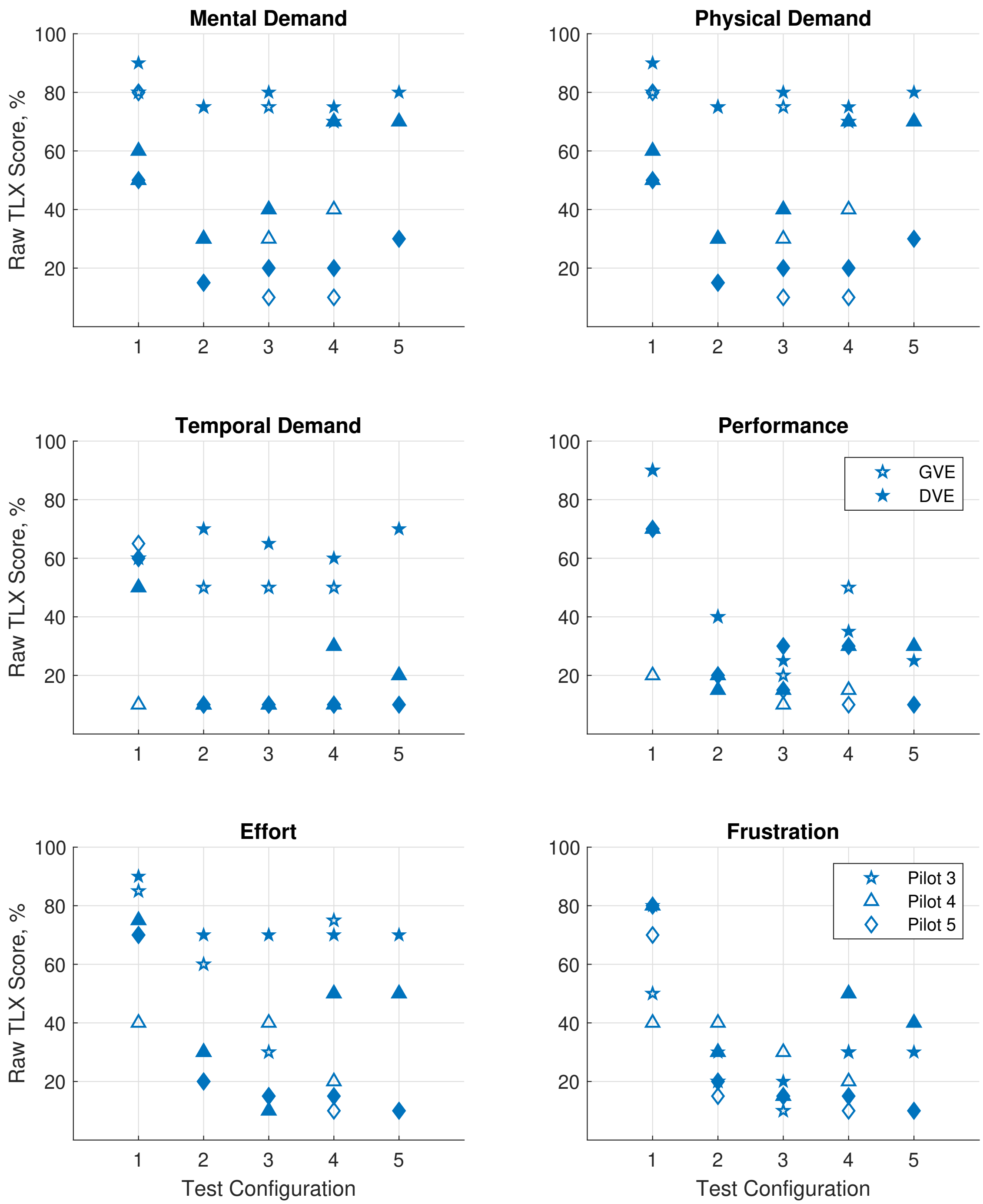

Figure 14. NASA TLX Ratings for the evaluation task using different test configurations in GVE and DVE

CONCLUSIONS

This study presented a piloted simulator evaluation of automatic flight control modes tailored for helicopter offshore rescue operations in good visual environment (GVE) and degraded visual environment (DVE). The automatic flight control modes included the model following controller architecture based ship relative translational rate command (TRC) combined with a ship relative velocity hold (VH) mode or a ship relative position hold (PH) mode. The investigation focused on assessing the effectiveness of various automatic modes in reducing pilot workload, improving situational awareness and enhancing safety in limited visibility conditions. The following key conclusions were made from the simulator evaluation:

1. The implemented automatic flight control modes are capable of performing an automatic ship relative hover with a good position hold/task performance without a need of additional pilot compensation. However, the effectiveness of control modes is environment dependent. In GVE, automatic modes improved task performance and reduced control activity but were not critical for task completion and overall safety. However, in DVE, manual control increased pilot workload significantly and task difficulty and automatic modes were critical for maintaining a stable flight.
2. Results demonstrated that even if the task performance in terms of position accuracy with some configurations showed minimal changes across GVE and DVE, it actually took higher pilot effort and workload to achieve this level of performance. Hence, this metric alone may not adequately reflect the performance degradation under reduced visual conditions.
3. The results from the simulation trials indicate a positive effect of the automatic flight control modes on the task performance, improved situational awareness and pilot's perceived workload in terms of more spare capacities as the pilots were able to trust and comfortably operate the automation. In contrast, limited familiarity with advanced visual aids namely the range-gated optical sensor and the Head-Mounted Display (HMD) reduced pilot reliance on them during high workload phases.

To support future improvements, pilots recommended enhancing the responsiveness in the roll axis for enhanced control during lateral repositioning and fine hover adjustments indicating the need for further controller optimisation. Additionally, pilots also suggested that the field of view of the range-gated optical sensor should be improved and that the overall functionality of the sensor should be further adapted to better support operational needs. Additionally, they emphasized the importance of pilot training in the effective use of such visual aids to ensure safe and reliable integration into shipboard operations.

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