Evaluation of a Ranged-Gated Viewing Sensor with a Head-Mounted Display and Advanced Flight Control Modes for Helicopter Offshore Rescue Operation

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ABSTRACT

During offshore and maritime emergency missions, helicopter pilots are often confronted with challenging weather conditions. Strong winds, precipitation and visual degradation through sea fog can lead to dangerous situations such as a controlled flight into terrain due to an inadvertent entry into instrument meteorological conditions. Modern offshore helicopters are already equipped with vision sensors to support pilots, but yet without features to see through particle clouds such as fog. One solution to this problem is to combine range-gated visual sensors, as already used on sea rescue boats, with a sensor video visualization conformal to the outside world in a Head-Mounted Display (HMD) as well as task-optimized control modes. In this work a system setup has been built up consisting of DLR's TRAGVIS ranged-gated sensor, a Microsoft HoloLens 2 HMD and a ship-relative translational rate command mode. The system was integrated into the simulation environment of DLR's Air Vehicle Simulator and evaluated in a campaign by two pilots from the Flight Service of the German Federal Police. Results from the campaign show a potential benefit in flight safety from the system setup and revealed problems through the limited field-of-view of the sensor and the tinted glasses from the HMD.

ABBREVIATIONS

ACT/FHS	Active Control Technology / Flying Helicopter Simulator
AVES	Air Vehicle Simulator
BPOLFLD	Flight Service of the German Federal Police
DVE	Degraded Visual Environment
F3S	Flexible Sensor Simulation Suite
FCS	Flight Control System
HDD	Head-Down Display
HEMS	Helicopter Emergency Medical Service
HMD	Head-Mounted Display
IFR	Instrument Flight Rules
PH	Position Hold
SA	Situational Awareness
SAR	Search-and-Rescue
TRAGVIS	Transportable Range-Gated Viewing System
VFR	Visual Flight Rules
VH	Velocity Hold

INTRODUCTION

During Helicopter Emergency Medical Service (HEMS), Search-and-Rescue (SAR) or military and police surveillance missions in the offshore or mountainous area, helicopter pilots are often confronted with unexpected weather changes, which can lead to low visibility and a resulting loss of Situational Awareness (SA). The visual degradation, which can deteriorate within few minutes, is often caused by fog as a result of advection effects on sea or by orographic lifting, radiation and valley fog in the mountains.

For a helicopter pilot it is particularly important to have sufficient visibility and visual references to be able to operate under Visual Flight Rules (VFR) in ground vicinity. Since a typical HEMS and police surveillance mission includes the operation close to the ground under VFR during hover, take-off and landing, the mission success and the flight safety is highly depended on the visibility and the SA.

Two different consequences of the effects of low visibility due to fog have to be considered separately; firstly, the compromising of the flight safety and secondly, the inability to accomplish the mission.

The main threat to flight safety during helicopter operation due to bad visibility is Controlled Flight into Terrain (CFIT) or Collision with Obstacle(s) during Take-Off and Landing (CTOL) due to Inadvertent Entry into IMC (IIMC) in VFR operation. According to the EASA Safety Review 2024 those two categories rank 6th and 10th for CS-27 and CS-29 helicopters. For CAT helicopters the CTOL is ranked 3rd among the most incidents and accidents over the past five years [1].

Figure 1. Prototype of the portable range-gating instrument TRAGVIS, originally developed for ship-based applications. The laser illumination module is on the right, the camera/receiver on the left. Both components can be mounted on a motor (middle) enabling pointing the instrument in any direction.

When the pilot decides that the transition from Instrument Flight Rules (IFR) to VFR is not be possible to not compromise flight safety, the consequences is, that the mission can't be fulfilled. For HEMS or SAR missions this might result in the fact, that one or multiple lives cannot be saved.

Most helicopters in professional rescue operation are equipped with advanced vision sensors which allow limited operations in Degraded Visual Environment (DVE). Common multi-sensor systems, such as the Hensoldt ARGOS II or similar products combine optical, thermal imaging and infrared cameras [2]. Those systems are not able to see through atmospheric interferences caused by particles such as water droplets (fog), sand or ice. A promising solution to enhance the visibility in these conditions is the range-gated technology, as described in the next chapter. Current sensors based on the range-gated technology, such as the OptoPrecision MODAR, which are used in the naval environment for maritime SAR or sea-surveillance, are too bulky and too heavy to be used with helicopters [3].

In addition to vision-enhancing systems, flight control augmentation systems are commonly used to support pilots by improving handling of ship based rotorcraft and reducing workload during demanding operations [4, 5]. However, conventional control modes lack sufficient integration with ship-relative dynamics in a realistic environment, limiting their effectiveness in offshore environments and highlighting the need for advanced, task-tailored control systems.

This work addresses the following research questions:

1. Can a modified sensor based on the range-gated technology with a Head-Mounted Display (HMD) or Head-Down Display (HDD) visualization be benefitial for helicopter operation in DVE?
2. Can pilots be supported during helicopter offshore ship operation by such a sensor system in combination with advanced, ship-relative, flight control modes?

The work described in this paper consisted of the following steps. A sensor simulation has been developed for the range-gated viewing sensor TRAGVIS, as shown in Fig. 1, and the parameters were adjusted to meet realistic characteristic. The sensor image is transferred and shown either on a HDD or a HMD using the Microsoft HoloLens 2 glasses and presented conformal with the outside view. Two advanced flight control modes based on a ship-relative Translational Rate Command (TRC) were integrated to support pilots during operations close to moving obstacles. Two pilots from the Flight Service of the German Federal Police evaluated the sensor setup in a realistic simulator scenario in a piloted simulator campaign in December 2024 in the Air Vehicle Simulator (AVES).

This paper is structured as follows. In Sec. "Previous Work" the development of the HMD, TRAGVIS sensor and the Flight Control System (FCS) modes during previous projects is described. Sec. "System Setup" contains a detailed description of the system setup as it was integrated into DLR's Air Vehicle Simulator (AVES). A piloted simulator campaign to evaluate the developed system setup including the results from the campaign is described in Sec. "Piloted Simulator Campaign". A conclusion and an outlook is given in Sec. "Discussion" and "Outlook".

PREVIOUS WORK

In past research works, various sensors were tested with helicopters or simulators in combination with head-down or head-up displays to increase pilots SA during DVE. During the project ALLFlight in 2015, the Active Control Technology / Flying Helicopter Simulator (ACT/FHS) was equipped with a laser, radar and infrared sensor. The data from the sensors was fused to create an environmental model, which could be visualized head-down or using the JedEye HMD. With the system setup a landing in a confined and unknown area with the ACT/FHS helicopter was achieved and it was concluded that the HMD might increase SA [6]. A group of researchers from Airbus Helicopters, Hensoldt and Airbus tested a DVE system in 2019 in a certified Airbus H145 consisting of a Light Detection and Ranging (LiDAR) and an Enhanced Vision System (EVS) sensor. The data from the sensor was fused into a map which could be visualized on a Helionix display and the SkyVis HMD. Their evaluation of flight test data and subjective feedback from pilots suggest an improvement of SA [7]. The US Army conducted the DVE Mitigation (DVE-M) program, where complementary sensor technologies as well as visual and auditive cueing methods were integrated into the helicopter environment to increase pilots SA. In a latest paper from 2021, flight trails with an EVS supported by a radar and a HDD as well as the SA-Photonics HMD were conducted in an obstacle environment.

While the overall system was assessed beneficial by the pilots, they felt distracted by the HMD due to alignment and depth issues of the fused Forward Looking Infrared (FLIR) image [8].

In the three past projects Helicopter Flight Safety in Maritime Environments (HELMA), Helicopter Deck Landing Assistance (HEDELA) and Using Helicopters to Support Maritime Emergencies (HUMAN), various research has been performed on assistance systems for maritime helicopter operation at the DLR Institute of Flight Systems.

HELMA

Starting with the project HELMA, a HMD has been developed and integrated into the AVES environment [9]. As military and civil aviation certified HMD are very expensive, it was decided to perform research on the use of modern commercial off-the-shelf (COTS) Augmented Reality (AR) glasses in helicopter cockpits. The AR glasses were initially based on the Microsoft HoloLens 1, but were quickly upgraded to the Microsoft HoloLens 2. During the project, a color coded symbology concept with typical helicopter-fixed indicators as well as world fixed objects, such as wind turbines, and a maritime simulator environment were developed. As one of the project objectives was to evaluate a potential improvement of flight safety through cost-effective HMD, a piloted campaign was conducted with pilots from the Flight Service of the German Federal Police (BPOLFLD) in the AVES. The evaluation task consisted of an IFR cloud breaking maneuver, a navigation task in a wind farm in DVE with low visibility and a hover task close to a wind turbine. Results from the campaign demonstrated a reduction of workload and an increase in SA across all tasks [10].

HEDELA

Based on the results from project HELMA, it was decided to transfer the system setup with the Microsoft HoloLens 2 to a real helicopter. As DLR's research helicopters offers a safe research and development platform for the integration of new control systems as well as experimental avionic hard- and software, the relevant systems for the HMD were tested for airworthiness during experimental flights and integrated into the research helicopter. The main challenge, which was the measurement of the pilot's head orientation, was solved through a simple, gaming-proven head tracker. Furthermore, the maritime simulation was enhanced by maritime objects and models to be able to perform research on helicopter ship deck landings. During a piloted campaign in the AVES, the HMD as well as various advanced flight control modes were evaluated during ship deck landings. The results demonstrated challenges with the visibility through the HMD during operations close to objects and differences in the acceptance of the system between novice and experienced pilots [11, 12]. The task performance of the ship deck landings was found to improve with the use of advanced flight control modes [13].

HUMAN

As the projects HELMA and HEDELA focused on wind farm and ship deck operation, the research in the successor project HUMAN focused on helicopter offshore operation during maritime emergencies. The main project objective was to improve helicopter flight safety and increase the availability of helicopters for maritime emergency operations and airborne sea surveillance, especially in DVE conditions. The project was conducted from 2022 - 2024 by the DLR Institutes of Flight Systems, Flight Guidance and the Protection of Maritime Infrastructures as well as the BPOLFLD as associated partner. As research goals, the development and evaluation of the three helicopter assistance systems presented in this paper were addressed, aiming to reduce pilots' workload and increase the SA in DVE. In addition to the work described in this paper, in the project the HMD system setup was optimized through improved head tracking, which was achieved by fusing data from an optical tracker operating in the infrared range with data from inertial sensors. This setup offers a better and faster tracking fidelity especially in challenging environmental conditions such as direct sunlight. Multiple flight tests with DLR's research helicopter ACT/FHS were conducted to evaluate and improve the integrated systems [14].

Range-Gated Sensors

Range-gated or gated-viewing is a well-known vision enhancement technique in both underwater as well as above the water applications [15, 16]. The measurement principle and the used instrument is described in detail in Sec. "System Setup". Although some portable (goggle) devices exist [17], the majority of instruments is often rather heavy, bulky, power-consuming and expensive as being based on scientific-grade components. Therefore, a downscaled range-gated sensor called TRAGVIS was developed by DLR for small vessels and dedicated needs in maritime search and rescue applications [18]. Two further main goals were to reduce costs and to ensure eye-safety during operation. More recently, a digital twin of the sensor and a simulation of its measurement method was developed to investigate the potential for supporting helicopter ship deck landing and air-borne surveillance activities when mounting the (simulated) instrument beneath a helicopter [19]. This simulation enabled to easily change sensor specifications (e.g., field of view, emitted optical power) and to study the influence of the measurements, allowing a goal-oriented improvement of the hardware. In terms of the range-gated sensor TRAGVIS, the present study is a more sophisticated and comprehensive continuation of the previous work.

Sensor Simulation

Over the years there have been numerous approaches for sensor simulation in the areas of flight simulation and computer games. Radar simulation has attracted some interests recently due to the development of autonomous driving [20] and flight [21, 22].

The use of photo-realistic game engines that are capable of simulating high-fidelity scenes [23, 24] has shown great potential, with Carla [25] and AirSim [26] being the most popular examples. Other than sensors like camera or Lidar, that are extensively implemented and used in the existing graphics technology such as ray tracing, radar sensor simulation is not yet widely used.

The idea of using a computer's graphics capabilities to simulate non-optical sensors dates back to 1997 [27]. Later, this approach was implemented in different simulators using both, shared CPU and GPU and GPU-only techniques [28–33].

The simulation in this experiments is accomplished using DLR's *Flexible Sensor Simulation Suite (F3S)*. F3S is a real-time sensor simulation solution developed by the DLR-Institute of Flight Guidance [31,34]. Essentially, it is a "Game Engine" for sensor simulation based on OpenGL and OpenSceneGraph. It allows a simple import of, e.g., terrain elevation databases, 3D models, buildings, streets etc. from publicly available GIS sources and model repositories. Utilizing OpenGL's shader code F3S is able to simulate different sensors, e.g., cameras (visible and infrared), LIDAR, and RADAR systems. In particular, F3S is used at DLR for simulating sensors attached to helicopters in the flight simulator AVES.

SYSTEM SETUP

The developed system structure, which was integrated into the AVES environment during the HUMAN project is shown in Fig. 2. The sensor simulation of the TRAGVIS is done via the software Flexible Sensor Simulation Suite (F3S). Ship movements as input for the sensor simulation are calculated within the AVES environment via the software VehicleControl (VehCTRL) and forwarded via the Interface Computer (IC) and the Data Management Computer (DMC) in the ACT/FHS Experimental System (ExpSys). The resulting sensor image is sent from the DMC, a firewall and an WiFi access point (AP) either to the HMD or the HDD in the EC135 cockpit. The advanced FCS modes are enabled via the Experimental Computer (EC) in the ExpSys.

Flight Control Modes

To support the pilots during the offshore rescue operation, advanced flight control modes were implemented. Two ship-relative advanced flight control modes were implemented in an established and flight-tested model-following control system [35]. The different components of the model-following control system, namely the command filters, feedforward controller, a cascaded feedback controller and the helicopter flight model are described in detail in [36]. The control laws provide a ship relative TRC response type combined with ship relative hold modes for velocity and position. A classical attitude command response type combined with attitude hold (ACAH) mode with minimal augmentation was included as a reference standard, providing a baseline for comparison with the more advanced control modes.

The primary pilot control inputs are augmented with two different response types namely, a ship relative TRC and a conventional attitude command. The stick deflections in TRC correspond to longitudinal and lateral velocities relative to the ship velocities and stick detent holds the relative velocity to the ship when combined with the Velocity Hold (VH) and the stick detent holds the relative position to the ship when combined with the Position Hold (PH). The longitudinal and lateral stick deflections in ACAH correspond to the helicopter pitch and roll attitudes and this mode does not involve any communication with ship. For all the flight control modes, yaw rate is commanded with the pedals and vertical speed is commanded in the collective axis. As the used hold modes are ship-relative, it is assumed in the current study that the exact ship position and velocity are available for use within the controller.

The whole approach was performed manually by the pilots, whereas the ship-relative hold modes were used during the final positioning phase during the hover. Hence, while using PH, once the pilot had located the personnel on the ship and had maneuvered the helicopter such that the relative distance to the ship deck is within a predefined threshold, the PH mode was automatically activated in the current study, maintaining longitudinal and lateral position without further pilot input. In a similar manner, when the pilot goes hands-off, the VH mode was also automatically activated and the helicopter longitudinal and lateral velocity was held with respect to the ship without further pilot input. Both VH and PH modes remained activated until the pilot takes over the control using the stick. During the whole maneuver, the pilots could see the active modes in each axis on the Primary Flight Display (PFD).

Range-Gated Sensor

The TRAGVIS sensor, as shown in Fig. 1, uses the range-gating or gated-viewing technology. Using an actively pulsed light source and an electronic camera shutter this technology enables the filtering of unwanted reflections and backscattering from atmospheric particles. As the shutter is closed for a defined period of time after a light pulse is emitted, backscatter from water droplets (fog), sand or ice particles does not contribute to the resulting sensor image. This avoids sensor saturation or offsets from backscattering and thus enhances the contrast when imaging through fog or dust. The shutter delay and its opening time determine the distance and the length of the so-called gate.

The real hardware sensor, which was used to create a digital twin in the project, provides short laser pulses of $< 100\,\text{ns}$ at a repetition rate of 342 kHz. The resulting average optical power is $\sim$2.5 W, which also meets the standards for an eye-safe class 1M laser module. The camera's Field-of-View (FoV) is approx. $7°\text{x}6°$. However, as mentioned above, these specifications could be changed in the simulation to study their effect on the measurements and the benefit for the simulated scenarios, allowing a goal-oriented hardware improvement.

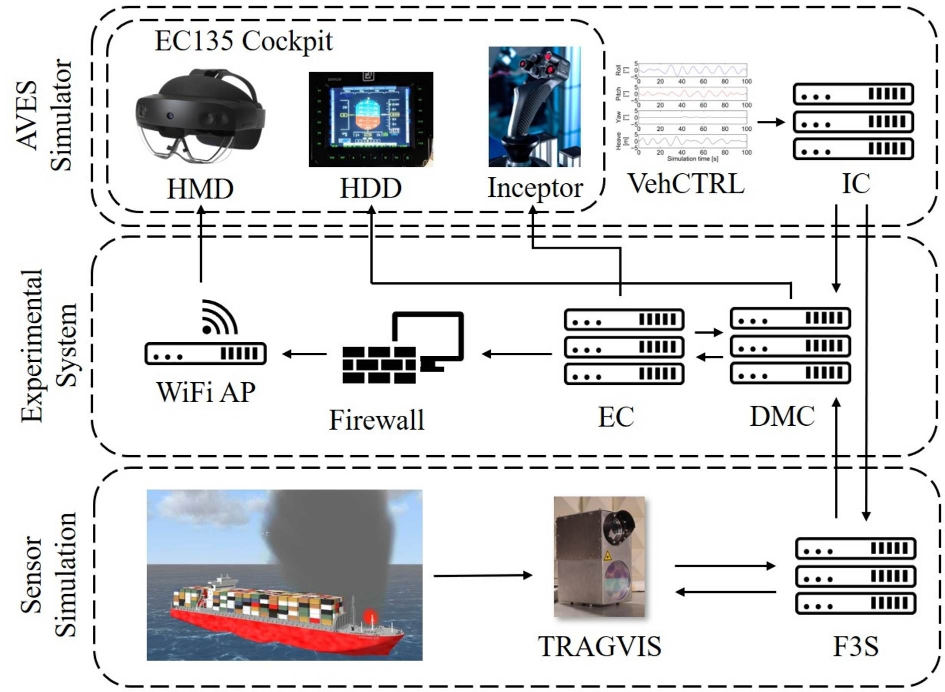

Figure 2. System setup for the TRAGVIS sensor simulation in the AVES environment

Sensor Simulation

During the project HUMAN, the display of the sensor image either on the HDD or the HMD was enabled using DLR's F3S simulation suite, as described in chapter "Previous Work" and in [19]. To archive a realistic sensor simulation, a shader equation was developed and validated using real-world measurements. The simulation offers the possibility to replace the physical sensor parameters with virtual values, such as optical dissipation factors, FoV, optical power and reflection properties. The resulting simulation picture is shown in Fig. 4 and Fig. 5. While the HDD only shows the raw sensor image, it is possible to show the sensor image conformal with the outside view in the HMD. In both configurations the sensor orientation and gate distance could be controlled via a space mouse in the cockpit. Such space or 3D mouses are typically used in computer-aided design and enable easy navigation and interaction with complex models through multiple axes.

Figure 3. 3D mouse for TRAGVIS sensor orientation and gate distance control

Head-Mounted Display

The Microsoft HoloLens 2, utilized in this project as a HMD, renders holograms to support research on reducing pilot workload and enhancing situational awareness. While it has been tested in various real-world vehicles, this paper focuses specifically only on the application in a helicopter simulator. Developed within the Unity3D game engine, the HoloLens displays high-contrast holographic lines, such as horizon indicators, Primary Flight Display (PFD) information, or flight path vectors, which minimize visual obstruction while providing intuitive guidance. Calibration, achieved by manually aligning a grid displayed in both the holographic and the simulator outside view, ensures precise hologram positioning. Head-tracking, enabled by the HoloLens 2's Inertial Measurement Unit (IMU) and four environment-facing cameras using Simultaneous Localization and Mapping (SLAM), functions effectively in a static environment with minor limitations due to the 52-degree FoV constraint of the environment-facing cameras. Vehicle-tracking utilizes the helicopter's onboard sensors to determine its position, governing hologram positional accuracy. A key challenge is the simulator's external world, projected with warping onto a spherical dome using projectors, which is mirrored in the holographic world to maintain alignment. The integration process is detailed in [37].

Figure 4. TRAGVIS sensor simulation image of lost containers floating on the sea surface in the HDD

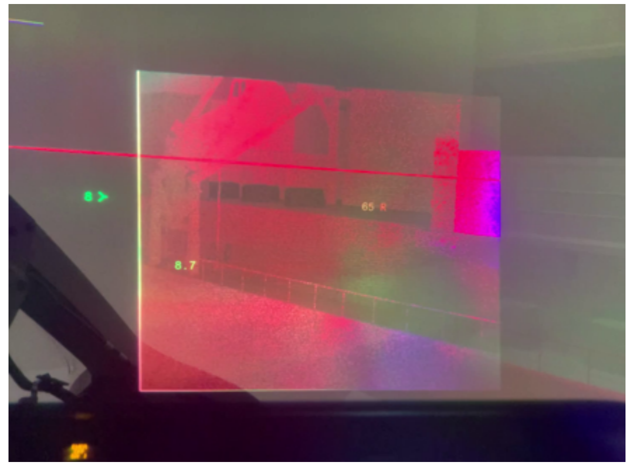

Figure 5. 3D conformal TRAGVIS sensor simulation image of a disabled container ship in the HMD

Holographic Display of the TRAGVIS Sensor

The TRAGVIS sensor, analogous to a standard camera, provides a video stream that is holographically overlaid at its precise position in the real-world environment using the HMD, enabling enhanced visibility through fog for improved pilot operation. In the AVES helicopter simulator, the F3S sensor simulation generates this stream as grayscale JPEG images, transmitted via UDP to the HMD along with sensor parameters such as FoV, position, and orientation. The HMD decodes these images into a texture, mapped onto a spherical segment surface that matches the simulator's dome curvature to align with the projected external world. This surface dynamically adjusts to the sensor's FoV, position, and orientation, ensuring the holographic video appears at the sensor's line of sight over the simulator's world (see Fig. 5). A 3D mouse, which is shown in Fig. 3 is worn on the operator's knee. It controls the sensor's direction and the depth of the range-gated image. This implementation supports holographic display of various video feeds, including optical and infrared cameras. Performance limitations of the HMD restrict the video stream to approximately 800x600 pixels at 60 Hz.

PILOTED SIMULATOR CAMPAIGN

As one of the objectives of the project HUMAN was to evaluate new technologies to support helicopter operation in DVE during maritime emergency situations, a piloted simulator study was conducted to evaluate the developed system. For the study, a realistic scenario was created, considering knowledge and input from the BPOLFLD and the German Central Command for Maritime Emergencies.

Scenario and Test Matrix

The scenario, a disabled container ship drifting towards a wind farm, is a typical threat scenario for maritime infrastructure. Examples for similar past maritime emergency events include the disaster of the Pallas cargo ship in 1998 with a huge environmental impact and the near-miss collision of the disabled Santorini cargo ship with a wind farm in the northern sea in 2020 [38, 39]. To encounter such events and organize the rescue of personnel onboard the ship and to protect maritime infrastructure, the German Central Command for Maritime Emergencies is responsible to coordinate emergency forces such as firefighters, maritime SAR organizations, police and, if necessary, military forces. Helicopters are typically essential for the success of a maritime emergency mission as they allow to quickly transport personnel from the damaged ship but also to deploy rescue, firefighting and towing teams on the ship. Furthermore, they allow for an intensive search for persons in the water and they can operate even at high waves. The limiting factor for the operation of helicopters typically is the visibility, as it can lead to a reduced SA with the risk of a Controlled Flight into Terrain (CFIT). As the developed system setup shall support pilots during such events, the scenario is defined as follows: a disabled, rolling and pitching container ship drifting towards the wind farm Alpha Ventus in the German Bight with low visibility. The environmental and helicopter trim conditions are shown in Tab. 1. In the emergency scenario of a disabled ship, a Towing Assistance Team (TAT) would be brought by a helicopter from the BPOLFLD to the ship to mount lines for towing the ship to a safe environment. In the created scenario, the TAT is finished with their work and needs to be picked back up by the BPOLFLD helicopter.

Due to time constraints, the number of configurations in the test matrix was limited. Therefore, four configurations were chosen for the campaign with increasing FCS, sensor and visualization pilot assistance support level.

To be able to conduct the study in the four different test conditions, as shown in the test matrix in Tab. 2, the TAT group, consisting of three humans, was positioned on four different positions onboard the ship: Bow, Starboard; Stern, Port; Bridge, Port; Amidships, Starboard. The exact position of the TAT group on the ship at each of the four configurations is shown in Fig. 7.

Figure 6. Cargo ship in the AVES maritime emergency scenario with TAT on the ship's bridge

An example with the TAT positioned on the ship's bridge is show in Fig. 6. The scenario was considered as partly realistic by the pilots from the BPOLFLD. The pilots remarked, that in reality they would instruct the persons onboard to gather on an accessible and possibly obstacle-free hoisting spot on the ship. This was only the case for the persons position in configuration 3 on the ship's bridge.

Figure 7. Container ship with TAT group position in the four configurations

Table 1. Scenario settings

Obscuration	Advection Fog
Precipitation	none
Visibility	80 m
Wind	030°/20 kt
Helicopter distance to ship	250 m
Helicopter height	100 ft HASL
Helicopter airspeed	0 kts
Ship direction	0°
Ship speed	5 kt

Figure 8. Piloted simulator campaign scenario in the AVES simulator with a disabled cargo ship in DVE

Table 2. Configurations for the simulator campaign

No.	FCS	Sensor, View Mode	Crew Position
1	ACAH	n/a	Bow, Starboard
2	TRC+VH	TRAGVIS, HDD	Stern, Port
3	TRC+PH	TRAGVIS, HDD	Bridge, Port
4	TRC+VH	TRAGVIS, HMD	Amidships, Starboard

Test Environment

The piloted campaign was conducted in the AVES facility, DLR's research simulation center, as shown in Fig. 9. It includes multiple aircraft modules: an Airbus Helicopters EC135, Airbus A320, Deutsche Aircraft D328, Dassault Falcon 2000X cockpit modules as well as a single aisle passenger aircraft cabin, all of which can be interchanged between a motion-based and two fixed-based platforms. Both platforms feature a visual system with 9 projectors providing a FoV of 240° x 95° and multiple realtime-capable computers for various in-house developed simulator software modules, e.g. the communication framework, flight models, image generation and motion simulation. This enables a fast and flexible adaptation of the simulator infrastructure on the given research evaluation task. For this evaluation, the EC135 cockpit, a replica of DLR's research helicopter ACT/FHS, was used.

For the described piloted campaign, a maritime environment located in the German Bight consisting of multiple high-fidelity 3D models, particle simulations and the ship motion software VehicleControl was developed [40]. The ship motion is driven by a mass-spring-damper-model with the parameters adjusted to the ship motion of a large cargo vessel.

Figure 9. The AVES simulator research facility at DLR Braunschweig

This resulted in a slow sinusoidal oscillation with a roll amplitude of 3° and a period of 20 s.

For the helicopter flight dynamics, the in-house developed realtime rotorcraft flight model HeliWorX was used [40]. It is based on a nonlinear helicopter model with rigid body dynamics using a Pitt-Peters dynamic rotor inflow model with a discretization of 10 elements per blade using a 2.5° azimuthal resolution and second-order flap and lead/lag dynamics [41]. For the piloted campaign, a four-bladed EC135 T2+ model based on DLR's ACT/FHS and verified with flight test data was used.

Methodology

For a qualified analysis of the results and pilots' opinion from the simulator campaign, subjective and objective methods were used. As subjective measures, the NASA Task Load Index (NASA TLX) workload assessment scale, the Situational Awareness Rating Technique (SART) questionnaire to assess SA and the System Usability Scale (SUS) questionnaire for a usability analysis was used. To analyze coherences between objective and subjective data such as the control activity shown in Sec. "Results", the record capability of the research helicopter experimental system, as available in the helicopter and in the AVES simulator, was used.

The NASA TLX method uses a six dimensional, 21-point scale questionnaire to asses the pilots' "Mental Demand (MD)", "Physical Demand (PD)", "Temporal Demand (TD)", "Performance (PE)", "Effort (EF)" and "Frustration (FR)" during a task [42]. An advantage of this questionnaire is the possibility of identifying categories, where the pilots' remaining capacities are limited. The additional weighting questionnaire from the NASA TLX method is not used in this research as multiple pilots reported confusion with the weighting task during prior experiments.

The SART by Taylor is a questionnaire to evaluate pilots' situational awareness [43]. The ten dimensional questionnaire consists of 10 questions on a 7-point Lickert scale in the subcategories "Demand (D)", "Supply (S)" and "Understanding (U)". The final SART score calculates via the formula $SART = U - (D - S)$.

To evaluate the usability of the TRAGVIS system with the 3D mouse as control input and the HDD and HMD display options, the SUS method by Brooke was used [44]. It consists of ten questions with a 5-point Lickert scale and is an established tool to evaluate usability in a wide range of technologies. A later-added adjective rating scale associates a SUS score above 68 with a good usability [45]. As the adjective rating scale was verified with user interfaces within software and web pages as well as various hardware devices, it can be used to categorize the usability of the discussed TRAGVIS system.

Participating Pilots

Two pilots from the BPOLFLD with an experience of > 17 years and > 3500 flight hours, of which both reported > 1500 flight hours being offshore, participated in the study. Both pilots had an IFR rating and were experienced with Ship Deck Landing (SDL), winching and using Night Vision Goggles (NVG), FLIR and LiDAR systems. Pilot 1 reported experience with consumer AR glasses while pilot 2 did not. None of the pilots had any experience with military aviation-approved HMD.

RESULTS

This chapter shows the results of the objective and subjective evaluation of the complete system setup in the above described scenario. A detailed analysis of the ship-relative control modes with data from an additional campaign with pilots from DLR is described in [46].

Usability

The pilots feedback on the usability of the TRAGVIS sensor is shown in Fig. 10. It includes the sensor, visualization with both the HDD and HMD, the control via the space mouse and was given after test configuration 4. Additionally to the participating pilots from BPOLFLD the feedback from three additional pilots from DLR was included here.

All pilots agreed that the system usability in terms of control and display options needs to be improved for use as an assistance system, but it is "promising". A detailed look on the individual questions showed that all pilots could "imagine that most people would learn to use this system very quickly" and they all "felt distracted by the system". One pilot commented, that an automated alignment of the sensor image with the head direction could improve the control of the sensor orientation. Two pilots mentioned that with additional training they would feel more comfortable in the use of the system.

As the questions in the SUS are very generalized, an individual evaluation questionnaire would have to be designed to assess the usability in more detail.

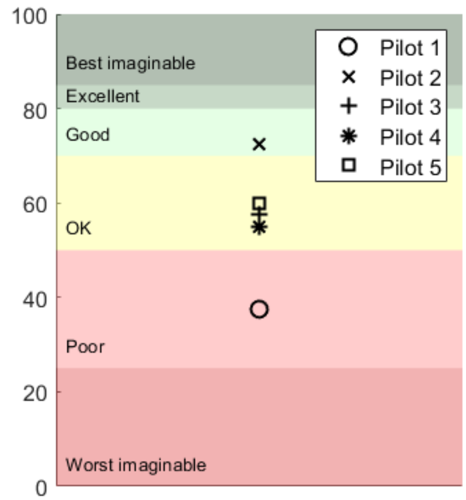

Figure 10. Results for the SUS questionnaire including ratings from three additional pilots

Situational Awareness

As results from previous campaigns with the HMD and additional control modes for pilot assistance showed earlier, novel system can both increase but also decrease pilots' SA, depending on the task, the environment and the implementation of the assistance system [10, 12]. The individual analysis of the SART scores of both pilots for the evaluation of the system setup described above is shown in Fig. 11.

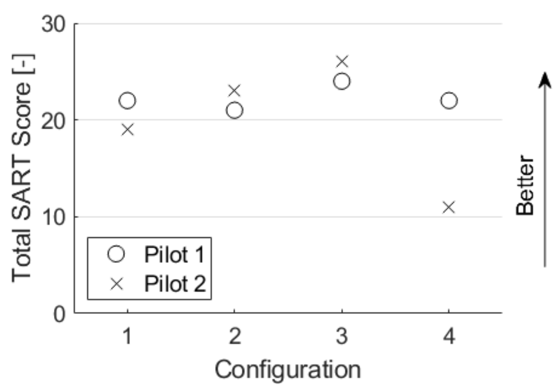

Figure 11. SART Score

With one exception, all total SART scores were in the interval [19, 26], indicating only minor effects of the system on the pilots' SA. The ratings of pilot 1 range between 21 and 24, showing an almost insignificant effect of the assistance systems on this pilots' SA. Pilot 2 experiences a constant minor increase in SA for the higher augmented configurations with a noticeable decrease for configuration 4 (TRC-VH/TRAGVIS/HMD). The pilot reasoned this with visual restriction through TRAGVIS sensor video in the direct FoV in the HMD. Both pilots remarked that the sensor's FoV and the maximum gate distance are not enough to fully rely on the sensor during a flight in DVE with a visibility of $< 100\,\mathrm{m}$.

Both pilots rated the highest SA in configuration 3 (TRC-PH/TRAGVIS/HDD). They both commented that the slight tinting of the HoloLens 2 glasses used in configuration 4 reduced the available light in the DVE scenario even more and, as mentioned above, the TRAGVIS sensor stream overlay distracted them in some situations. They both mentioned that they felt the urge to remove the glasses while operating close to the ship. This corresponds to pilots comments in a previous evaluation campaign with a ship deck landing scenario and the HMD [12].

As in configurations 2 and 3 only the flight controllers hold mode was changed from Velocity-Hold (VH) to Position-Hold (PH), the shown slight increase in the SART scores might suggest an influence of the hold mode on pilots' overall SA. A follow-up study with more pilots is needed to conduct further research on this effect.

Workload

The assessment of the NASA TLX questionnaire is shown individually for both pilots in Fig. 12. Both pilots experienced the lowest workload while flying with the task-specific control hold modes compared to the configurations with Attitude-Command, Attitude-Hold (ACAH) control mode (configuration 1) and the HMD (configuration 4).

Pilot 1 experiences a lower overall workload for the higher augmented configurations 2-4 (TRC control mode, task-specific hold modes, TRAGVIS sensor, HDD/HMD) in comparison with the basic configuration 1 (ACAH,no sensor/visualization). This trend is valid for all NASA TLX dimension except for "frustration" and "performance", where the pilot rated a decrease for configuration 2 (TRC-VH, TRAGVIS, HDD) compared to configuration 1 and then an increase of workload for configuration 3 (TRC-PH, TRAGVIS, HDD) and configuration 4 (TRC-VH, TRAGVIS, HMD). The increased performance can be explained with a training effect. The frustration, as defined in the NASA TLX questionnaire in [42] with an "insecurity, discouragement, irritation, stress, annoyment" leads to the pilots comment about the disturbance through the sensor image in the HMD described above. Furthermore, the pilot mentioned a missing awareness of the currently active control hold mode during the hoisting maneuver in the debriefing.

Pilot 2 experienced a similar total workload in configuration 1 (ACAH,no sensor/visualization) and 4 (TRC-VH, TRAGVIS, HMD). He rated the lowest score in all dimensions except for the "performance" in configuration 3 (TRC-PH, TRAGVIS, HDD). This high performance rating, as defined as the "success in accomplishing what you were asked to do" can be explained with this pilot experiencing a severe pilot induced oscillation in the roll axis during the ship approach phase in TRC control mode, which lead to a repetition of the test point.

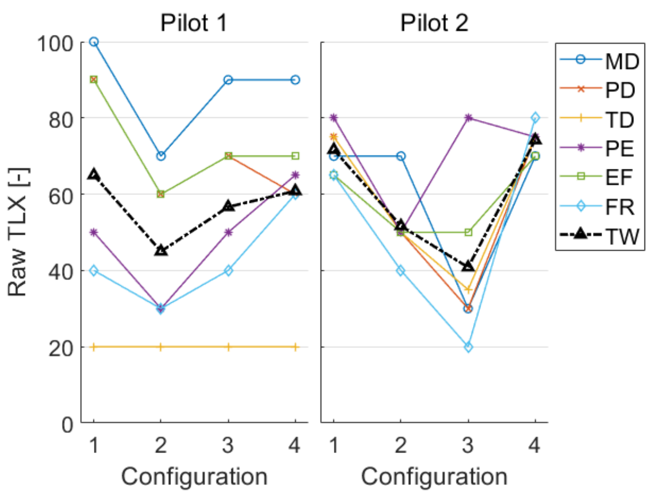

Figure 12. Workload Rating (NASA TLX raw) for pilots 1 (left) and 2 (right)

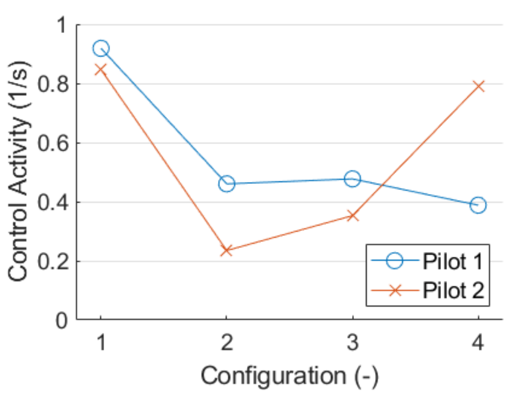

Figure 13. Control Activity for pilots 1 and 2

The high ratings in all dimensions in configuration 4 (TRC-VH, TRAGVIS, HMD) were reasoned by the pilot through the disturbance of the HMD's slight tinting and the sensor image in the direct FoV which lead an increased workload and, as described above, a decrease in SA.

A more detailed analysis focusing specifically on the performance of the individual control modes during the campaign is provided in [46]. As mentioned earlier, the analysis of the study results in the publication indicate an increased task performance accompanied by a decreased workload especially in DVE.

A similar trend as in the NASA TLX workload ratings can be seen in the control activity, as shown in Fig. 13. Pilot 1 with previous AR experience shows the minimum control activity in configuration 4 (TRC-VH, TRAGVIS, HMD) while pilot 2 has almost a similar control activity as in configuration 1 (ACAH,no sensor/visualization). This could be explained with a positive training effect for pilot 1 and negative impacts for pilot 2 using the HMD in configuration 4 (TRC-VH, TRAGVIS, HMD). This supports the NASA TLX analysis results described above.

The shown total control activity is calculated as a the average control activity between all control axis (cycle lateral and longitudinal, collective, pedals). The control activity per axis was calculated as the ratio between the total count of discrete control movements on that axis and the task duration. The definition for the control movements, as defined in [47], is a control deflection from a zero velocity control movement to the next zero velocity movement. To reduce noise, only control movements with deflections above or below 0.5% (depending on the deflection direction) of the last zero velocity control deflection are considered in the calculation. In [47] the control activity method was successfully used for the comparison between ACAH and rate command control modes and a correlation to the NASA TLX was shown for various mission task elements. As no clear mission elements were defined in this study and only one NASA TLX questionnaire per run was requested from the pilots, only one control activity score without differentiation between the mission elements was calculated per run.

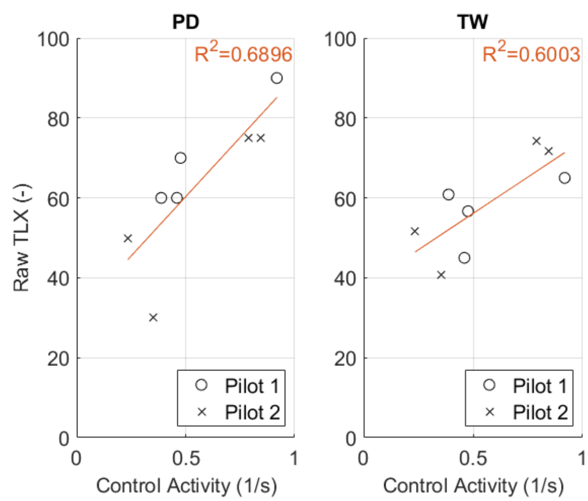

Figure 14. NASA TLX raw Physical Demand (PD) and Total Workload (TW) versus Control Activity

A comparison of the raw NASA TLX workload against the control activity is shown in Fig. 14. Two categories from the NASA TLX show a high correlation with the control activity, as concluded from the coefficient of determination R^2. The high correlation in the Physical Demand (PD) shown in the left plot shows the effectiveness of the NASA TLX questionnaire for the PD dimension for evaluating the perceived workload as physical compensation. As other NASA TLX dimension also show minor connections to the control activity, the Total Workload (TW) in the right plot, which is calculated as the average from all NASA TLX dimensions, also shows a good correlation. Overall it can be seen, that the pilots prefer the configurations with a high assistance level, as the low control activity and the correlating low workload ratings show. For this specific mission the results indicate that a low control activity might lead to a lower perceived (physical) workload which supports the results from [47].

CONCLUSION AND OUTLOOK

During the project HUMAN, a system to assist pilots during offshore and maritime emergency missions was developed. The system consisting of a range-gated optical sensor, task-optimized control modes and a HMD was integrated into DLR's research simulator environment AVES. A sensor simulation was created for the range-gated sensor, which was verified with data from real measurements. The task-specific control modes consisted of two ship-relative hold modes added to a TRC. For the HMD, the AR glasses Microsoft HoloLens 2 with flight indicators, world fixed elements and a sensor visualization was used. During a piloted campaign the system was evaluated by two pilots from the BPOLFLD in a maritime emergency mission consisting of a disabled container ship in DVE. For the evaluation, questionnaires for the analysis of pilots' workload, their situational awareness and for system usability were used. Four configurations with progressively increasing levels of assistance in the control mode domain, sensor availability and sensor visualization were tested during the piloted campaign.

From the developments during the project and the analysis of the results from the piloted campaign, the following conclusions could be drawn:

- The created system setup within the AVES simulation environment could be used for evaluating the fidelity of the separate components (sensor, control modes, visualization) with the possibility of changing the components parameters for different configurations. A transfer of the system setup to the real environment, e. g. in DLR's research helicopter ACT/FHS would be possible.
- The maritime emergency scenario, consisting of a disable container ship with a hoisting task, was considered partly realistic by the pilots. As remarked by the pilots, in reality the helicopter crew would instruct personnel onboard to gather on a convenient hoisting spot on the ship.
- The sensor simulation of the TRAGVIS sensor, which was validated using real measurements, offered the possibility to investigate sensor parameters beyond the current physical capabilities of the sensor. This enabled a testing of different sensor parameters for various helicopter missions and an application of the sensor as a pilot assistance system or third-crew-member operated surveillance system.
- The general ability of the TRAGVIS sensor to filter reflections from particles such as water, ice or sand was labelled by both pilots as the "missing piece of the sensor puzzle for all-weather-ops".
- The current specifications of the physical sensor, reproduced in the sensor simulation, was considered by both pilots as not sufficient for helicopter operations in DVE as in the evaluated scenario. This refers to the sensor's field of view and the maximal distance of the gate.
- The system usability was evaluated as "OK". The pilots commented that a coupling of the sensors orientation with the head movements would a strong improvement.
- The analysis of the SART questionnaire showed only minor effects of the tested configurations on SA with the exception of configuration 4 (TRC-VH,TRAGVIS,HMD), where one pilot felt seriously disturbed by the HMD.
- Both pilots mentioned the temporarily urge to remove the HMD glasses in configuration 4 (TRC-VH,TRAGVIS,HMD), as the tinted glasses reduced the available light and the sensor visualization directly in the FoV was disturbing.
- The analysis of the workload evaluation using the NASA TLX indicates a positive effect of the task-specific ship-relative hold modes on the pilots workload.
- Both pilots commented on the task-specific ship-relative hold modes as generally useful, but reported an initial missing trust and a missing awareness on the active control mode's status. Furthermore, they mentioned that due to the necessity of quick responses on the controls during hoist operations near obstacles in turbulent wind conditions, most pilots (in their fleet) currently don't use upper modes but stick to basic and direct control modes.

Resulting from the analysis results and pilot comments, various improvements for the system setup are planned for future projects. As the improvement of the TRAGVIS sensor parameters are limited by physical parameters, such as shutter efficiency, optical power and FoV, an optimization and enhancement of the resulting sensor image via artificial intelligence algorithms is planned. Furthermore, a coupling between the sensors and the pilot's head orientation will be implemented to simplify the operation of the sensor. For the visualization with the HoloLens 2 HMD, various improvements are planned during the follow-up project Helicopter Crew Supporting Holographic Technologies (HECHT), including the appearance and location of the sensor image, optimizations for transparency and low light environments

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ETHICS STATEMENT

This study involving human participants was reviewed and approved by the Ethics Committee of the German Aerospace Center (DLR). The participating pilots were informed prior about all recorded data and gave their written consent to participate in the study.

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