Manned-Unmanned Teaming Cooperative Formation Flight - A Project Review

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ABSTRACT

Manned-unmanned teaming is a key aspect for improving the efficiency of civil and military operations. This paper provides an overview of a four-year project to develop and evaluate methods for manned-unmanned teaming formation flight. The formation flight scenarios are tailored towards manned and unmanned rotorcraft performing a close formation flight. This paper explains use cases as well as the test methodology. Two formation flight algorithms were developed and evaluated against a preprogrammed waypoint-based baseline. The evaluation was done in a simulator campaign with different pilots and in a flight test campaign with one evaluation pilot. During the final flight test campaign the first coupled close formation flight between a manned and an unmanned helicopter was achieved. Finally, this paper contains the results of both the flight test and simulator campaign.

INTRODUCTION

Manned-unmanned teaming (MUM-T) is a key aspect in improving mission efficiency, adding new capabilities, and reducing operational risks for manned assets. However these improvements generally come at the price of increased technical complexity, increased workload for the crew, and increased training effort. The scope of this paper is manned-unmanned teaming of two helicopters: a typical manned helicopter represented by the Flying Helicopter Simulator FHS (a modified EC135 introduced in Ref. [1]) and the superARTIS, an unmanned intermeshing helicopter introduced in Ref. [2] and [3] with parts of the current instrumentation. The general concept is to replace a manned helicopter with an unmanned helicopter in order to perform mission tasks better suited for an unmanned aerial vehicle (UAV). A main drawback of close formation flight with an unmanned wingman is the increase in workload for the crew of the manned helicopter due to an increase in tasks, like controlling and monitoring the UAV or using the UAV payload. Therefore, this project aims to identify different formation flight strategies to reduce the workload caused by the additional UAV control task as well as to increase flight safety. The developed strategies were evaluated and verified in two simulator campaigns with four pilots and followed by two flight test campaigns. The project ended in 2018 concluding with the data analysis and evaluation of the formation flight strategies.

Giving an overview of this MUM-T project this paper starts with a short literature overview and the project motivation. In the subsequent chapters of the paper the different formation flight strategies are introduced and the test methodology is presented. The paper concludes with the description and the test results of the conducted simulator and flight test campaigns.

RELATED WORK

MUM-T related topics have been extensively studied in the recent years and are well summarized in Ref. [4]. The broad research spectrum reaches from general operational concepts presented in Refs. [5, 6, 7, 8], which define the needed tasks and capabilities, to live firing trials using various aircraft types by McGonigle in Ref. [9]. The level of interoperability (LoI), sometimes referred to as level of control (LOC), increased over the years and was studied regarding the influence on the crew's workload as shown in Refs. [10, 11, 12]. In this context it is often stated that an increasing LoI leads to a consequent increase in workload, see Refs. [10, 11]. This is a major topic and can be addressed in different ways. One approach is to define the essential crew skills needed for a successful MUM-T operation, which is initially presented in Ref. [13] and continued in Ref. [14, 15] with presenting tailored content for pilot training and introducing performance measures for the involved drone pilots and manned helicopter pilots. Other approaches aim for more accessible command and control interfaces like voice interfaces or touchscreens (see Ref. [16]). These approaches are clearly helpful in improving crew task management, but they do not lower the amount of tasks assigned to the crew. This might be achieved by adequate automation and control methods. The perception management presented in Ref. [17] automates payload sensors and condenses the information of the payload data. Furthermore, recurring tasks like object recognition in video streams or frequent sensor attitude

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adjustments could be transferred from the pilot to an onboard assistance system.

Another approach utilizes a heavily instrumented cockpit to assess the crew workload in real-time. With this measured workload information, a variable degree of command and control could be achieved over a fully autonomous UAV (see Ref. [11]). The goal is to create an optimal degree of workload during a MUM-T mission by reducing the crew workload through autonomy if the crew is occupied with a different task. Several studies were conducted to increase the level of autonomy and to solve the formation flight control problem. Ways to increase the autonomy of the unmanned wingman concept were studied within a desktop simulation utilizing X-Plane in Ref. [18]. In another study Sadraey proposed in Ref. [19] a linear state-space model to find a generalized solution for the formation flight control problem.

Flight test campaigns involving a relatively high LoI were demonstrated in the past years within a military and civil context. An extensible list is given below:

Table 1: Overview of MUM-T Flight Tests/Demonstrations

Company/ Institution	Test content	Year	LoI	Ref.
Airbus Helicopters, Schiebel	Police Missions	2018	5	Press release; 24.4.2018
Advanced Technologies/ US Army Applied Aviation Technology Directorate (AATD)	Military, live firing	2005	4+	[9]
AMUST-D Program	Military, tactical integration of UAV for F/A-18 and AH-64	2007	3	[20]

MOTIVATION AND PROJECT GOALS

In a research program, set up and funded by the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support, different MUM-T applications were studied including the assessment of operational aspects and technical issues of a helicopter two-ship formation with an unmanned wingman. MUM-T formation flight is a critical topic in this context due to the inherent collision risk and the required short reaction time in case of an emergency. However, formation flight has distinct military advantages such as lower detectability compared to separate flight, proven training concepts for pilots, and providing a standard initial situation for flight maneuvers and military tasks. Therefore, a project was initiated to determine possible approaches for a safe and low workload MUM-T formation flight. In the remainder of this paper the project is referred to as the DLR MUM-T study. The procedures used in the DLR MUM-T study are close to the procedures used in purely manned two-ship formations. This is based on the assumption that MUM-T is a bridge technology for all unmanned formations or swarms. However, the formation flight behavior of swarms can be radically different and therefore the simplifications of human-like UAV flight patterns are used. The scope of the DLR MUM-T study is on the formation flight itself with a focus on the technical and procedural aspects. Other operational aspects like usage of payload or integration into tactical mission systems were not considered. The project started in 2015 and ended in 2018 with a final flight test campaign demonstrating controlled MUM-T formation flight with a cooperative UAV.

MANNED-UNMANNED FORMATION FLIGHT

During the DLR MUM-T study three general formation strategies were investigated.

The first approach was used as a baseline during the evaluation process. This approach is called Waypoint Mode and it assumes the crew of the manned helicopter commands the movements of the UAV with a waypoint based interface. Such waypoint based navigation is a state of the art capability for unmanned helicopters. Due to the time consuming nature and possible input errors a significant amount of preparation time is needed to fly a mission. With such inflexibility the UAV is considered to be the leader of the formation. Therefore, the manned helicopter follows the flight pattern of the UAV and holds the formation while monitoring the spatial separation for collision avoidance. In this mode the manned helicopter can leave the formation at any time but must monitor the distance between both aircraft as long as the formation is established. Flight safety is ensured by introduction of a minimum distance or radius, called safety radius R_{Safety}. A brief overview is given in Figure 1.

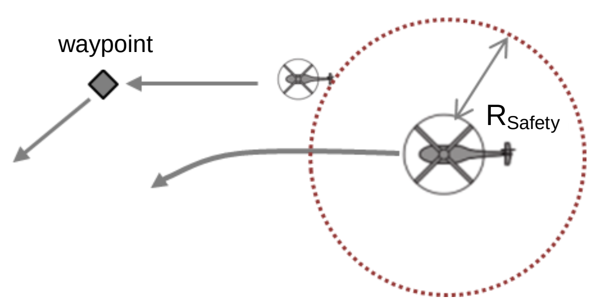

Figure 1: Waypoint Mode

Please note that the leader of the formation is the aircraft defining the flight parameters such as speed or direction.

The UAV was always in front of the manned helicopter for safety reasons during the DLR MUM-T flight test campaign.

The second approach based on relative navigation is referred to as RelNav in the following. In this mode the UAV uses a controller to hold a relative position to the manned helicopter. For a detailed description of the formation flight control modes see Ref. [21]. In this mode the unmanned helicopter is directly coupled with the manned helicopter and the UAV follows the manned helicopter without any prescribed mission. In RelNav mode the manned helicopter is commanding the formation while the UAV maintains a relative position. Additionally, a safety area in front of the manned helicopter was defined where the unmanned helicopter is visually detectable from the cockpit to improve flight safety. In Figure 2 this area is shown as the allowed area whereas the minimum distance is denoted as safety radius.

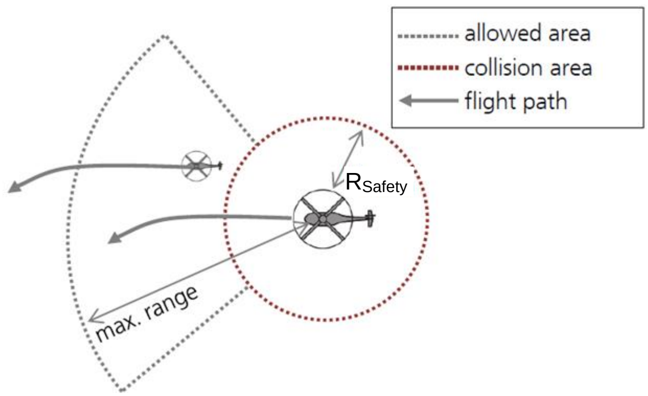

Figure 2: Relative Navigation Mode

The third approach is designed to combine the flexibility of changing the flight path during a mission as done in RelNav mode with the not direct coupled movement of the manned helicopter like in waypoint mode. This mode is named Corridor Mode due to its defining feature: the corridor. The corridor is a waypoint like mission with defined speeds and turns, but instead of defined waypoint positions an allowed obstacle-free area is used. In the Corridor Mode the UAV follows the corridor, but it reacts with additional speed commands if a prescribed boundary is due to be violated. Such boundaries could be the maximum or minimum distance as well as a certain direction relative to the manned helicopter. With this mode the UAV is capable to react on the manned helicopter's behavior but is less sensitive to minor course or speed changes. The UAV behavior in Corridor Mode can be distinguished in two different cases. First, in the nominal behavior the UAV is well within the boundaries of the corridor. Thus, the UAV is following the prescribed corridor. The boundaries have predefined buffer zones were a speed command for the UAV is given to prevent the boundary violation. The UAV changes the behavior close to the boundaries of the allowed area or the boundaries of the allowed corridor. In both cases and if both boundaries are reached, a speed command is generated to prevent a boundary violation; the detailed calculation can be found in Ref. [21]. In case of a boundary violation of the allowed corridor the UAV should change to RelNav. Or if both the corridor and the allowed area of the manned helicopter is violated, the UAV should change to Waypoint Mode. In Figure 3 a schematic overview of the Corridor Mode is given.

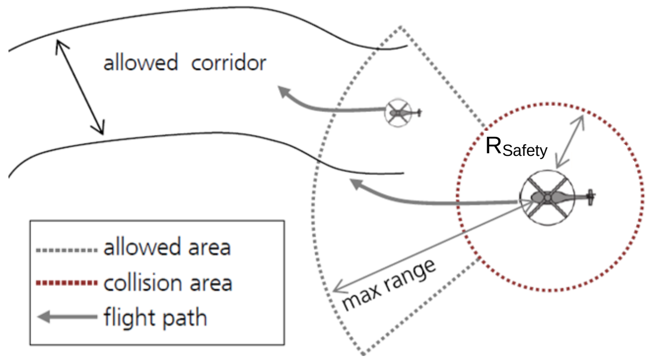

Figure 3: Corridor Mode

Another emergency mode was developed in the project to ensure flight safety; this mode was named Break-Away Mode. This sub mode is always available during any MUM-T formation flight. It is engaged if a safety-critical boundary is violated or in case of a technical defect. This mode decouples both aircraft and triggers a predefined behavior of the UAV. The break-away behavior of the manned helicopter was defined as a 90° turn away from the UAV and a climb for about 150 ft. The UAV reaction differs for each formation flight mode.

The introduced MUM-T modes work with different levels of automation. However, there are several common tasks that have to be carried out for a safe MUM-T formation flight. These are namely:

Leading the formation
One aircraft, denoted as the leader, defines the formation parameters (e.g. speed, altitude or track).

Collision avoidance
This task requires the monitoring of the distance between the aircraft and reaction to any safety critical violations.

Holding the formation
The monitoring of the formation leader position and holding the relative position constant is the task of holding the formation.

These three tasks are used to directly compare the three modes and to illustrate their differences, see Table 2.

Table 2: Overview of crew and UAV tasks for MUM-T formation flight modes

Task	Way-point Mode	RelNav Mode	Corridor Mode (nominal)	Corridor Mode (close to boundary)
Leading the forma-tion	UAV; uncoupled	Manned helicop-ter	UAV; uncoupled	Manned helicopter
Collisi-on avoidan ce	Manned helicopter	UAV; Manned helicop-ter oversight	UAV; Manned helicopter oversight	UAV; Manned helicopter oversight
Holding the forma-tion	Manned helicopter	UAV	Manned helicopter; UAV oversight	UAV; Manned helicopter oversight

Waypoint and Corridor Mode allow the UAV to continue its preprogrammed mission after the break-away, until the ground crew or helicopter crew commands it to hover or to return home. The RelNav Mode does not have such a preplanned mission and thus holds the position in case a break-away was commanded.

TEST METHODOLOGY

The evaluation of the MUM-T formation flight modes was done starting with a simulator campaign involving several pilots in the first stage followed by a flight test campaign in a second stage. Both campaigns used the same evaluation techniques to ensure their comparability.

Pilot questionnaires were used to assess the flight crew's workload during the flight experiments. The first part of the NASA-TLX was used and the pilots were asked to rate mental, physical, and temporal demands as well as the level of performance effort and frustration. Another main source of information were the pilot comments documented during flight and briefings. It was also attempted to set up a modified version of the Cooper-Harper rating scale, but the initial levels to determine adequate and desired behavior were difficult to establish, due to the limited knowledge of the optimal behavior. Thus, the rating scale was not used to determine the workload and formation flight quality. Both aircraft were also equipped with dedicated sensors to determine speed, position, and attitude as a quantitative data source. The FHS is equipped with a reference navigation sensor suite. The superARTIS logs the data provided by the autopilot.

As a first step representative evaluation maneuvers were defined and derived from use cases found by a previous DLR MUM-T study [22]. Four evaluation maneuvers were designed. Each starts with both vehicles in a hovering formation. The Maneuvers are denoted Mission Task Elements (MTE). The speeds during those maneuvers were defined by the UAV flight performance and the maximum intervention distance of the safety pilot of the UAV. For the superARTIS the maximum intervention distance is assumed to be about 400 m. The first maneuver is an Acceleration/Deceleration maneuver, displayed in Figure 4.

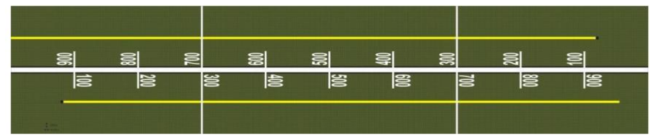

Figure 4: Ground marking of Acceleration/ Deceleration MUM-T MTE

The maneuver's task is the coordinated acceleration, forward flight and deceleration of the formation. The goal was to accelerate both vehicles on a straight leg of 300 m to a speed of 40 kt followed by a leg of 400 m in steady forward flight. The last leg of 300 m is used to decelerate the vehicles to a full stop.

Please note that the white track marks the ground track of the manned helicopter whereas the yellow track shows the ideal track of the UAV.

The second maneuver starts and ends similarly to the first maneuver with an acceleration and deceleration phase, but the steady forward leg is replaced by a 180° turn to increase the flight crew's coordination effort. The optimal speed of the maneuver was estimated to be 40 kt.

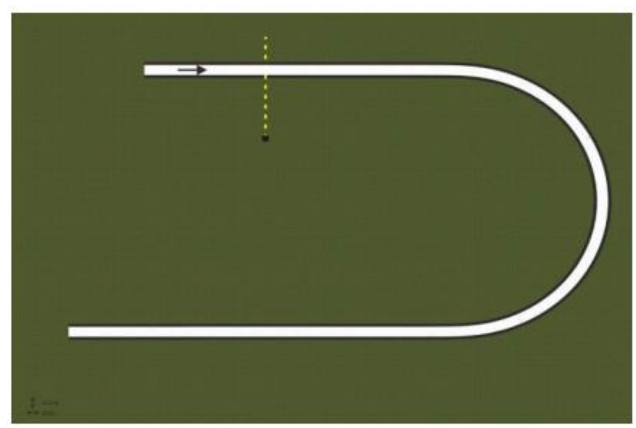

Figure 5: Ground marking of U-Turn MUM-T MTE

In Figure 5 the ground marking of the U-Turn maneuver is shown. The start hover position of the UAV is marked with a black dot and the position of the FHS is at the beginning of the white FHS ground track.

The third maneuver is a complex turning maneuver with the ground track similar to an eight. This maneuver is more challenging than the U-Turn due to the different turning rates and turn directions. The whole maneuver should be flown with 40 kt for the manned helicopter.

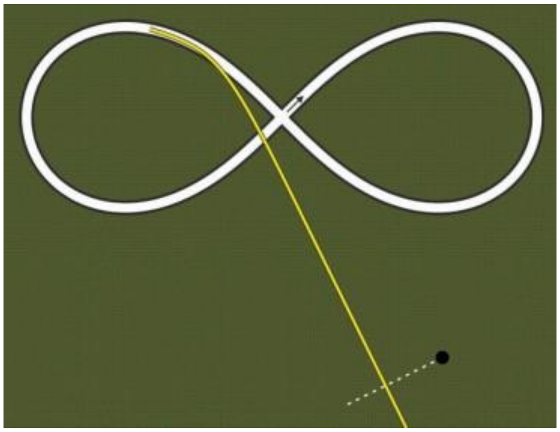

Figure 6: Ground marking of Eight MUM-T MTE

The markings in Figure 6 are generally similar in type to the markings described in Figure 5, but here the yellow line marks a support line to lead the formation from the starting position into the maneuver.

These MTEs were used for the evaluation simulator campaign. The Acceleration/Deceleration MTE was used within the first flight test campaign. For the second and final flight test campaign a combined maneuver was designed to evaluate the modes and to evaluate the safety requirements. In this maneuver the start and end point is the same for the manned helicopter while only the unmanned helicopter needs to be repositioned after each test run. This reduces the time between the experimental flights. In the maneuver the straight level flight part before and after the turn merge the Acceleration/Deceleration MTE with the U-Turn maneuver which reduces the overall number of test maneuvers. The resulting maneuver was called the Cornetto maneuver due to its distinct shape. The Eight MTE was not used in real flight test, because it was considered too complex.

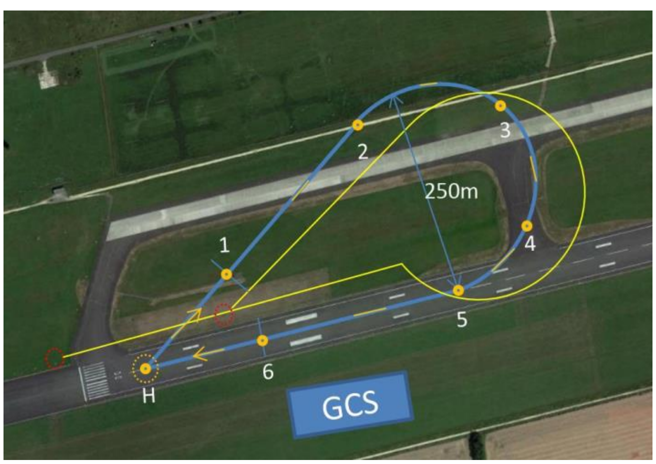

Figure 7: Cornetto MTE with enumerated ground markings

The Cornetto maneuver was designed for a nominal speed of 40 kt for the manned helicopter. In Figure 7 the Cornetto maneuver is depicted with both the ideal path of the FHS in blue and the assumed flight path of the UAV in yellow. The used ground markings are shown in orange and are enumerated. The size of the maneuver was designed to never exceed the maximum intervention distance from the UAV safety pilot to the UAV flight path. The safety pilot is often located close to the ground control station (GCS).

ANTI-COLLISION DISPLAY

An anti-collision display was used based on a design from a previous MUM-T study Ref. [22]. The main features of the display are shown in Figure 8. In the anti-collision display the MUM-T mode is presented on the left hand side of the display as a big box. The color of the box changes between:

Black – if no MUM-T mode is engaged.

Yellow – if a MUM-T mode is selected but the coupling is not yet completed.

Green – if a MUM-T mode is engaged. In that state the type of MUM-T mode is presented as well.

Red – if the Break-Away Mode is engaged. Additionally the commanded evasive direction of the manned helicopter is displayed for the possibility of a loss of situational awareness of the crew. The evasive direction is determined via the current relative position to the UAV.

The indication of the distance between the manned and the unmanned helicopter divided in vertical and horizontal separation in meters is also a part of the anti-collision display. Additionally the tendency of both the vertical and horizontal distance is displayed with an arrow pointing up or down (not shown in Figure 8).

Figure 8: MUM-T anti-collision display

SIMULATOR CAMPAIGN

The simulator of the ARTIS framework and the AVES simulator were coupled to exchange position and attitude of the aircraft. The AVES (Air VEhicle Simulator) is a simulator facility with a motion and a fixed platform and a modular cockpit setup. For this study the EC-135 cockpit, which is almost identical to the FHS cockpit, was used on the fixed simulator platform. According to pilot observations, the flight model of the FHS real-time simulator is a little more aggressive than the actual FHS, especially in the 20 to 40 kt range. The AVES has the same experimental electronics setup as the FHS. Therefore, the MUM-T equipment used is the same as later used during flight test.

The ARTIS framework is a modular software framework with a real-time simulator for HIL (Hardware in the loop) simulation [23]. It also features visualization and is capable to exchange data with the superARTIS avionics.

The overall simulator setup is presented in Figure 9. The data transfer between the FHS, superARTIS, and the GCS was realized with a data link. The same data link and hardware setup (GCS, FTE Tablet, and superARTIS avionics) was used during flight test. In both visualizations the models of both aircraft were added.

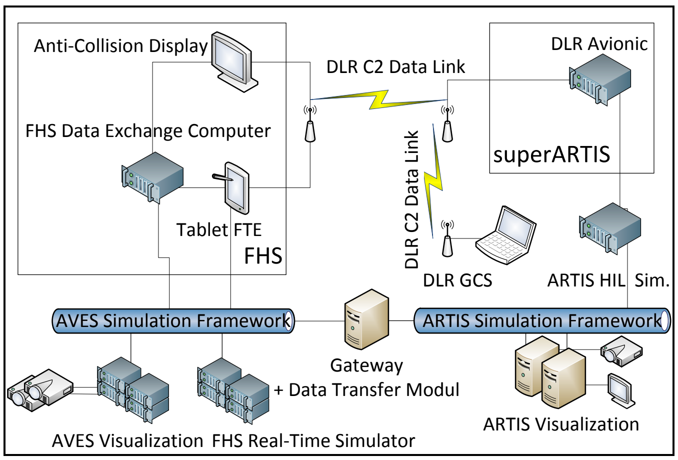

Figure 9: Coupled simulator setup

With that setup two simulator campaigns were performed.

First Simulator Campaign

Concerns regarding the visibility and assessability of motions of the UAV from a manned helicopter raised by the previous study [22] were investigated within the first simulator campaign. Another goal was to find the optimal position and distance of the UAV in relation to the manned helicopter. The maximum visual range and minimum distance were also identified. The test was conducted with two pilots with military and formation flight experience and over 1000 flight hours. During the test the pilots were asked to hold defined hover positions, attitudes, and altitudes within certain boundaries to ensure a moderate workload. Meanwhile the UAV was positioned at different distances, relative altitudes, and different bearings to the manned helicopter (see Figure 10).

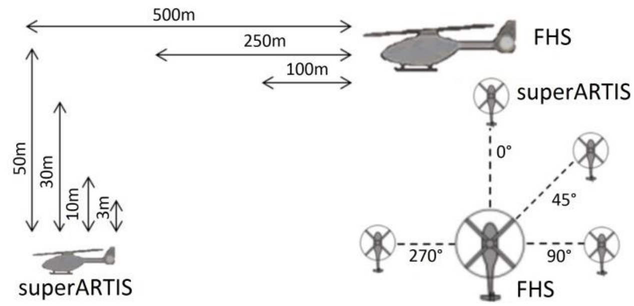

Figure 10: Test parameter variations

After the initial UAV positioning a series of motions was performed, while the pilot identified and announced the UAV movement. A UAV series of motions comprises a total of 10-12 single UAV motions, each with a duration of about 10 seconds. The potential movements of the UAV are presented in Figure 11.

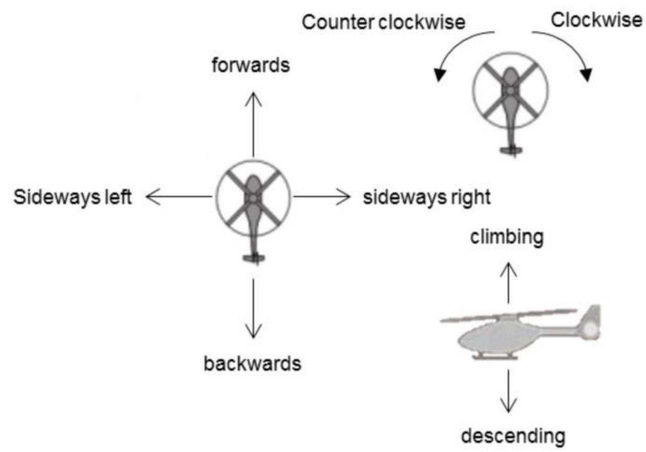

Figure 11: Variation of UAV motions

The results show a correct detection rate of 70% or higher below 250 m distance, at a vertical offset of 10 m combined with a bearing of 0 to 90° of the UAV. The detection rate was crucially influenced by the bearing to the UAV. This was explained by the pilots with the additional effort of moving their heads to be able to watch the UAV and the cockpit instruments. Generally speaking, the closer the direction of the UAV to the direction of the instrument panel of the cockpit, the less time it takes for the crew to visually find the UAV. However, if the UAV is visually too close to or behind the instrument panel, the pilot is forced to lean forward in order to get a clear view on the UAV.

During the simulator campaign the pilots were asked to position the helicopter in an optimal formation in hover. The result was a distance from 70 to 80 m with a bearing to the UAV of about 15° to the right side of the experimental pilot. Therefore, a test position of the UAV was assumed to be 30 m to the right, 10 m below the manned helicopter, and at a distance of overall 100 m (with added safety margin). The safety radius around the manned helicopter was first estimated with 60 m and was later increased to 80 m after gaining flight test experience. The maximum visual range was found to be at 500 m. This resulted in a parameter set for the following experiments given in Table 3.

Table 3: Experimental Safety Parameters

Variable	Value	Remark
R_{Safety}	80 m	Min. safety radius
$R_{b,min}$	120 m	Lower radius of operation
$R_{b,max}$	170 m	Upper radius of operation
R_{max}	500 m	Max. visual range
Θ_{max}	90°	Max. lateral angle
Θ_b	45°	Lateral boundary of operation
Δz_{max}	5 m	Max. vertical separation
Δz_b	0 m	Upper boundary of vertical separation
η_{max}	30°	Max. vertical angle
η_b	20°	Lower vertical angle of operation

In Figure 12 an overview of the allowed formation flight areas are given. The operational volume in green is considered to be the areas the UAV should operate. Furthermore the yellow volumes are the buffer zone where the UAV will change to the close to boundary behavior in Corridor Mode.

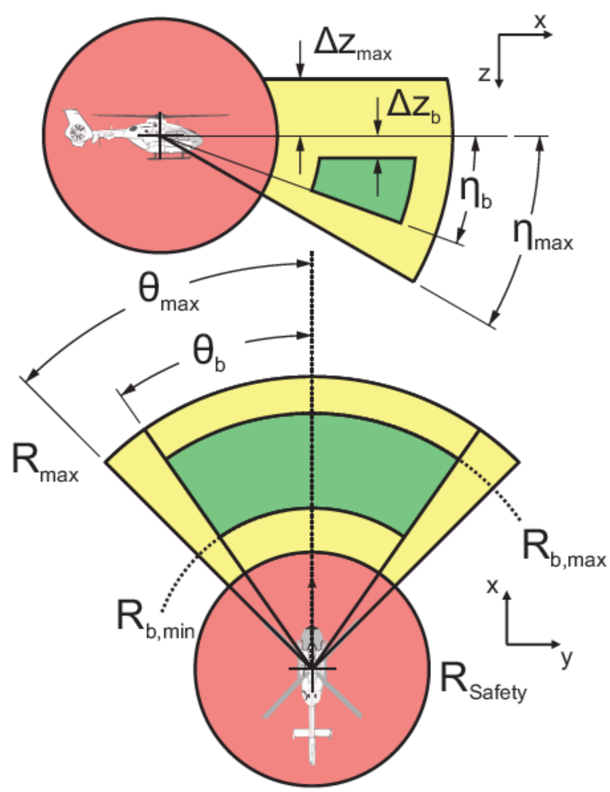

Figure 12: Formation flight areas; green: allowed; yellow: buffer zone; red: forbidden [21]

Second Simulator Campaign

A second simulator campaign evaluated the developed formation flight strategies. Each of the four experimental pilots flew the Acceleration/Deceleration, U-Turn and the Eight MTE in mostly four runs. The first and sometimes the second run were considered warm-ups and in the following three runs a NASA-TLX [24] and a modified Cooper-Harper rating scale were used for workload estimation (for each run). In one of the last three runs a break-away command was issued and indicated by the anti-collision display and the reaction time of the pilot was monitored. This run was not evaluated with one of the workload rating scales. The formation used during these experiments was established with a 100 m longitudinal, 30 m lateral, and 10 m vertical separation.

Figure 13 presents the results of the NASA-TLX. The figure shows a reduction in every aspect of the TLX questionnaire. In both modes with active MUM-T controller (RelNav & Corridor Mode) compared with the Waypoint Mode the workload in every aspect is significantly reduced. In the simulator evaluation the RelNav was found to be the mode with the lowest overall workload. In direct comparison of the RelNav to the Corridor Mode the temporal demand and the performance of the RelNav mode is lower. However, the Corridor Mode during these experiments was limited to less than 10 corridor waypoints and was therefore suboptimal in its implementation. Nevertheless, both active MUM-T modes were considered to lower the workload in comparison to the Waypoint Mode and were both further developed for evaluation during the flight test campaigns.

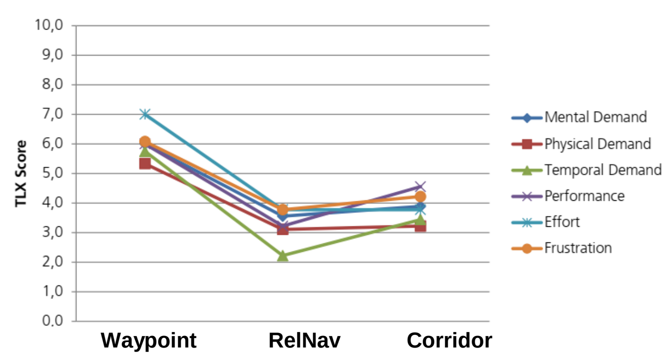

Figure 13: Mean NASA-TLX score over all pilots and all MTEs

FLIGHT TEST CAMPAIGN

Two flight test campaigns were conducted as a part of the DLR MUM-T study. The test setup used for both flight test campaigns was the same and comprised an air crew situated in the FHS and a ground crew located around the mobile Ground Control Station (GCS). The air crew was mainly responsible for operating the FHS, while the ground crew was in charge of the superARTIS. On the ground, the coordination of the flight test experiment was conducted by the ground flight test engineer (FTE). The communication between the ground FTE and the ground crew was established over radio. A different radio set was used for communication between ground FTE and the FHS crew and the air FTE. An overview of the test setup and communication structure can be found in Figure 14.

The MUM-T equipment of the FHS consisted of a MUM-T tablet PC with a data link modem for direct data exchange to the unmanned helicopter and the ground control station. The MUM-T tablet had an interface to the FHS navigation data and to the anti-collision display.

The first flight test campaign validated the test methodology, the developed flight test procedures, and provided tests of the involved hardware and software. The flight test maneuvers in the first flight test campaign were used to train the correct emergency behavior of the crew and to verify the results from the first simulator campaign.

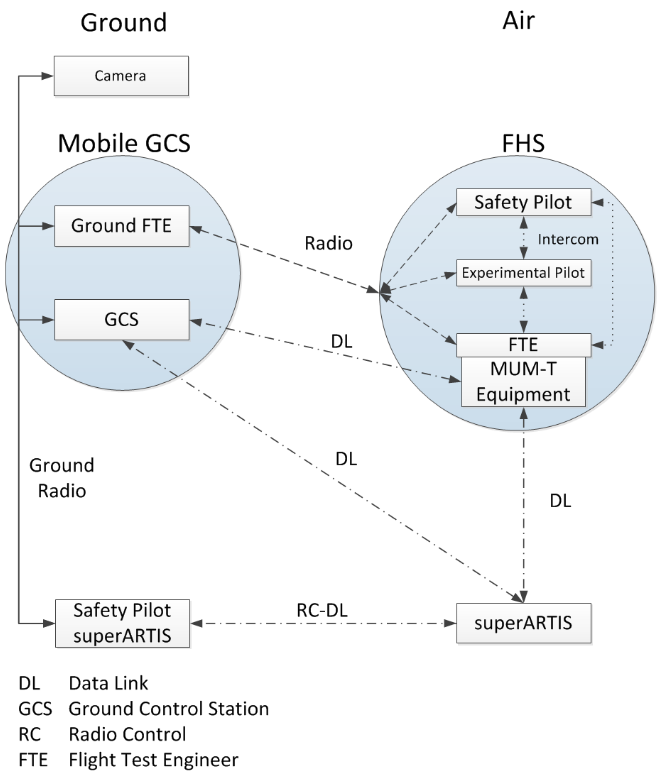

Figure 14: Flight test communication structure overview

The second flight test campaign started with a warm-up phase to familiarize the crews with the new flight test maneuver called Cornetto MTE, introduced earlier in this paper, and to train the break-away behavior. These tests during the warm-up phase were also used to ensure proper hardware and software function.

In the subsequent formation flight trials the nominal speed of the formation was defined with 30 kt; this reduction of the speed in comparison to the planned speed of 40 kt is a result of observed high-speed instabilities of the UAV.

The formation position of the UAV was chosen to be 140 m longitudinal in front, 30 m lateral to the right, and 10 m vertical below the FHS. These distance values are a result of pilot comments from the first flight test campaign. During the second flight test campaign 11 formation flights were conducted. The Waypoint and Corridor Mode were tested and evaluated. However, the RelNav Mode was not tested with the MTE due to technical difficulties in the implementation of that mode and the early end of the flight test campaign due to technical issues with the flight control system of the FHS. More details of the issues with the RelNav Mode can be found in Ref [21].

RESULTS

The flight test was evaluated using the NASA-TLX and the measured flight test data. Table 4 shows the statistical deviation between the nominal relative formation flight position and the measured flight test position. This data is taken from the last evaluation flight of each mode. More specifically, the 6th flight for the Waypoint Mode and the 5th flight for the Corridor Mode were used to ensure a comparable training level. The table shows a clear improvement in both the standard deviation and the mean error in longitudinal direction. A more detailed review of the flight test data, presented in Ref. [21], did show a clear support of the formation flight controller during the Corridor Mode to correct the longitudinal distance. The other dimensions, namely lateral and vertical, were not influenced by the formation flight controller, because the buffer zone where a reaction is enforced was not reached during the flight test.

Table 4: Mean error and standard deviation between nominal position difference and measured position difference between superARTIS and FHS

Errors		**Waypoint Mode**	**Corridor Mode**
Longitudinal	$\bar{x}$	19.95 m	7.33 m
	σ_x	14.35 m	8.09 m
Lateral	$\bar{y}$	7.83 m	-6.88 m
	σ_y	15.53 m	16.02 m
Vertical	$\bar{z}$	-4.82 m	-4.33 m
	σ_z	2.60 m	2.34 m

The improvement of the longitudinal position error is clearly visible in the heat maps of Figure 15. The shown heat maps picture the whole Cornetto maneuver flown in both modes. The longitudinal error is significantly reduced by the Corridor Mode. Also the maximum distance (170 m) is not violated.

Please note that the boundaries for that flight test in Corridor Mode were chosen to be 120 m minimum distance and 170 m maximum distance.

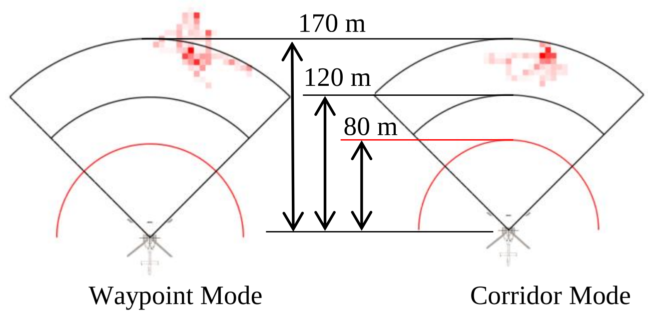

Figure 15: Relative formation position during Cornetto MTE as a heat map

These data show that the control strategy for the Corridor Mode is working. The impact of such a cooperative formation flight controller on the crew workload is given in Figure 16. The figure shows the NASA-TLX ratings of both modes. In comparison to the TLX ratings of the simulator campaign in Figure 13 a clear difference can be found in workload rating in overall score and distribution over the different aspects. The NASA-TLX ratings during flight test show the general tendency for constant or slightly lower overall workload in the Corridor Mode if both modes are compared. The clear tendency of all aspects of the TLX to lower workload as seen in the simulation results cannot be found that clearly in the flight test results.

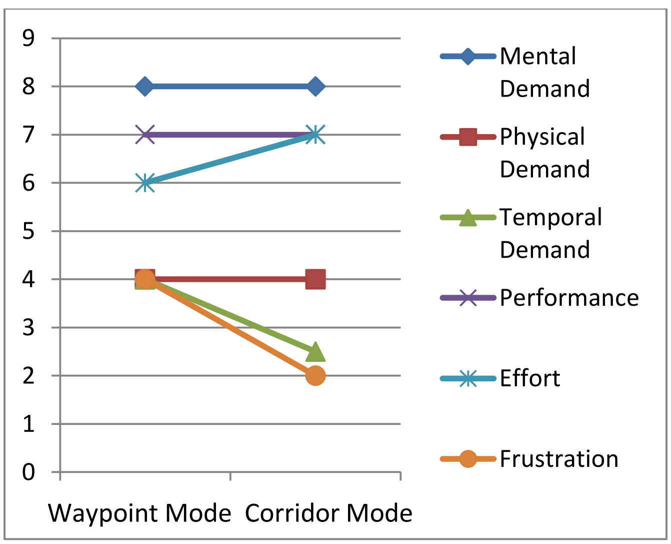

Figure 16: Flight test results of the NASA-TLX

However, the pilot comments on the Corridor Mode are clearly in favor of the developed mode in terms of workload reduction and flight safety. For example, the crew of the FHS reported that the safety pilot supports the evaluation pilot by announcing the speed on a regular basis during the Waypoint Mode. In contrast, as soon as the Corridor Mode was engaged the evaluation pilot started to announce speed and altitude. This is assumed to be a clear sign of lower workload in the Corridor Mode compared to the Waypoint Mode.

The final flight test did show the need to rework the RelNav Mode due to the lack of sufficient filtering of the inherent yaw oscillation of the manned helicopter. This resulted in an oscillating flight path of the UAV amplified by the greater than originally anticipated horizontal distance between the manned and the unmanned helicopter. Therefore, it was difficult to find stable parameters for the complex Cornetto maneuver.

The anti-collision display was considered as useful by the pilots and the break-away maneuver was easy to implement for the crew.

A limiting factor of the MUM-T study was the difference in flight performance of both aircraft. Therefore, the maneuver speed was limited to 30 kt for the FHS and 45 kt for the superARTIS during the flight trials. However, the FHS is capable of 140 kt, and the flight performance of the FHS was therefore severely reduced to not violate the UAV's flight limitations. This shows the need for higher flight performance for MUM-T UAVs, especially in terms of forward flight speed.

Another result of this study is the need for improvement of inflight workload measurement. Using pilot questionnaires for that purpose could lead to inconsistent results and is very subjective. A more objective workload determination method could be beneficial for further and more precise development of automation methods with the purpose to lower the crew workload.

CONCLUSIONS

In this paper an overview is given of a 4-year MUM-T project with the goal to demonstrate the cooperative behavior of a UAV in a manned-unmanned helicopter formation flight. Therefore, general approaches to this topic are studied and three formation flight strategies were developed. These three approaches can be divided into one method using an approach used by manned-manned formations (Waypoint Mode) and two approaches in which the motion of the manned helicopter commands the unmanned helicopter. All three methods were evaluated in two simulator and two flight test campaigns. During the final flight test campaign the first coupled manned-unmanned helicopter formation flight was achieved. The flight test results, based on pilot comments and the NASA-TLX rating, show a reduction of workload when using a cooperative UAV behavior. Additionally, measured flight test data show that the position during formation flight is maintained more precisely when using a controlled formation flight mode. Generally, the project did show the feasibility of a controlled MUM-T formation flight and that the developed methods to increase formation flight quality reduce the crew workload.

In the future, additional research should be conducted gaining more operational experience by involving more experimental pilots. Furthermore, a combination of the developed methods and new technologies like in-flight workload measurement for adaptive task allocation should be studied. In addition, it is of interest whether an improvement of the situational awareness with helmet-mounted displays or with active side-stick technology could be beneficial for such methods. In particular the active side-stick technology could assist the pilot with tactile cues to improve the awareness regarding safety or flight performance boundaries during formation flight.

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