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ON THE WAY TO AUTONOMOUS AIR-TO-AIR REFUELLING FOR UNMANNED RECEIVERS – CONCEPT, PROTOTYPE IMPLEMENTATION AND FLIGHT TEST OF TWO KEY TECHNOLOGIES

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Abstract

A general concept of air-to-air refuelling for unmanned receiver aircraft is outlined in this paper based on available specifications and operational guidelines, with two real-life projects discussed in more detail. The concept and prototyping of two key technologies are presented. First, the automatic formation flight between a manned tanker and an unmanned receiver with special focus on the flight control concept of the speed and position autopilot and mitigation of measurement inaccuracies. Second, an automatic three-dimensional separation concept for the receiver. Both have been validated by a first flight test. The control of the receiver was successfully transferred from the ground control station to the tanker. The receiver based automatic safe separation has been demonstrated, triggered intentionally by operator input and unintentionally by data link losses during the flight test.

1. INTRODUCTION

To enable air-to-air refuelling (AAR) for unmanned receiver aircraft at least a high level of automation is crucial. There is still a long way to go to achieve the autonomous air-to-air refuelling capability.

First, an overview is given on AAR to put the two key technologies presented in this paper into context.

1.1. Hose & drogue vs. boom-receptacle

There are two different AAR systems, which are generally not compatible; the hose & drogue (H&D), which is also called probe and drogue, and the boom-receptacle (boom). An exception is the boom drogue adapter (BDA) kit, which makes the boom compatible with probe equipped receivers. Some tankers are equipped with both H&D and boom systems and both may be used on the same flight [1].

FIG 1 shows an example of AAR using the H&D refuelling system, with an Airbus A310 MRTT as a tanker and two Eurofighter Typhoons as receivers. For each, the tanker trails a hose equipped with a reception coupling and a conical shaped drogue at its end. The receivers are equipped with a rigid or retractable AAR probe, which needs to be manoeuvred into the drogue to engage the coupling.

FIG 2 shows an example of AAR using the boom system, with an F16 as the receiver. The tanker aircraft is fitted with a steerable, telescopic boom. The receiver is equipped with a reception coupling (receptacle). Here, the receiver has to maintain a steady formation flight while the boom operator moves the boom to engage the coupling.

In both cases, once the coupling is latched, fuel transfer can begin.

FIG 1: Hose & drogue refuelling system: Airbus A310 MRTT with two Eurofighter Typhoons

FIG 2: Boom-receptacle refuelling with an F16

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1.2. Levels of automation

The long-term objective, to achieve autonomous air-to-air refuelling (A4R), means having a refuelling system that performs all tasks autonomously under all conditions. On the way towards this, automatic air-to-air refuelling (A3R) describes refuelling systems that can automatically perform the task in a set of known conditions, whereas the operator monitors the task and can take over, e.g. in case of performance degradation or adverse weather conditions (depending on the level of automation). [2]

For unmanned receivers to perform AAR, an autonomous system is desirable eventually. However, development is still ongoing to reach an automatic level (A3R) as a step towards A4R. Therefore, subsequent sections of this paper reference A3R, instead of A4R.

1.3. A3R development milestones

Considerable research has been done in the last years on A3R, as well as automatic formation flight and teaming of assets, which are both useful for A3R. Some milestones are listed below:

- In 2002, two F/A-18 autonomously flew in close coupled formation as part of the Autonomous Formation Flight program by NASA.
- In 2004, two Boeing X-45A achieved the first unmanned formation flight.
- In 2012, two Global Hawk achieved close formation flight of two Unmanned Aerial Vehicles (UAV), with fully integrated fuel systems. A planned second phase with refuelling was halted.
- In 2018, an Airbus A330 MRTT A3R boom operation established a first contact.
- In 2021, Airbus Manned-Unmanned Teaming linked a Eurofighter Typhoon with two Do-DT25 in flight. The fighter successfully assigning tasks to the UAVs.
- In 2023, Airbus Auto'Mate achieved close formation flight of a UAV and manned tanker based on GNSS. The UAV was controlled from the tanker via data link.

1.4. Two real-life projects for A3R development

In this paper two scenarios developed in real-life A3R projects are presented.

The first scenario is a receiver centric approach of A3R. It is investigated as part of the EDA research project A3RH&D Phase 1, focusing on A3R for the H&D system. The scope of the receiver centric part of the research project is the derivation of top level requirements and system concepts, as well as the setup of a simulation environment including the development of guidance algorithms to enable receiver centric A3R. Furthermore, a flight test is planned for sensor data gathering with an Airbus A330 MRTT, a multi-role tanker and transport aircraft, and a Panavia Tornado, a multi-role combat aircraft.

The second scenario is an approach with the guidance, navigation and control centralized in a tanker aircraft equipped with the boom system. This paper presents the general concept of this AAR scenario, details of the prototype design and the flight test results obtained. The focus lies on the formation flight between the tanker aircraft and the receiver aircraft necessary for all AAR operations. This is developed within the Auto'Mate project in a cooperation between Airbus UpNext (Spain), working on the tanker, and Airbus Defence and Space (Germany), providing the receiver. As a surrogate receiver aircraft, the target drone Do-DT25 was chosen. The Do-DT25, pictured in FIG 3, is a medium-speed target drone. Its wing span is 2.6 m and its maximum take-off weight is 144 kg. Its main purpose is to serve as an aerial target for short-range infrared missile systems. Furthermore, it is used as a development platform for future technologies. While not being able to do AAR itself, nevertheless, it was a strong candidate for the project's goal, to achieve automatic formation flight controlled by the tanker aircraft. As a tanker aircraft the Airbus A310 MRTT was selected.

FIG 3: Target Drone Do-DT25
(Source: Airbus Defence and Space GmbH)

2. CONCEPT FOR AUTOMATIC AIR-TO-AIR REFUELLING ON RECEIVERS

2.1. AAR positions and phases definitions

One of the biggest challenges in achieving A3R is the automation of the most critical phases surrounding the contact in the AAR manoeuvre. These are the *astern* and *contact* phase, as defined in NATO Standards [1, 3]. Here, the control of the receiver aircraft has to be precise even in case of the boom system and more so in case of the H&D system.

The following position and phases of flight definitions are listed for reference:

Astern (Left, Right, Centre):

- H&D: This position is the transition point from tanker relative navigation to drogue relative navigation [3]. In manual AAR this is approximately 5-20 ft directly aft of the drogue [1].
- Boom: This position is maintained using tanker relative navigation [3]. In manual AAR this is approximately 50 ft behind and slightly below the tanker boom nozzle [1].

Contact (Left, Right, Centre):

- H&D: The position attained when the probe successfully engages the drogue and is pushed in 5-13 ft [3].
- Boom: Stabilized position within the AAR envelope [3].

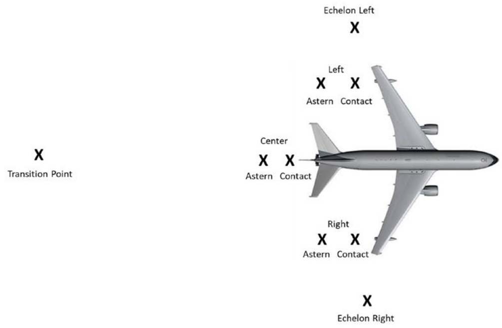

FIG 4: A3R standard positions [3]

FIG 4 displays both the astern and contact position located relative to the tanker for each case of left, right and centre.

Astern phase[*]: The astern phase covers the transition from astern position to contact position, after the UAV receives “cleared to the contact position”. The UAV approaches the contact position (boom) or engages the drogue (H&D). Normally the astern phase ends when the UAV receives “cleared to contact” and transitions to the contact phase. [3]

Contact phase: The contact phase normally starts when the UAV receives “cleared to contact”, after the astern phase. When the UAV completes refuelling, disconnects, or fails to engage, the UAV will depart the contact position and return to the astern position. Normally, the contact phase ends when the UAV sends “established in the astern position”. Afterwards, the UAV transitions to the astern phase again. [3]

In each phase and depending on the refuelling system, different tasks fall upon the receiver. The EDA A3R technical paper suggests the tasks detailed below for A3R in astern and contact phase.
With the boom system, during the astern phase the receiver has to approach to close formation after getting the “cleared to the contact position” signal from the tanker. Once the nominal refuelling position is reached and signalled as such by the tanker, the receiver has to acknowledge this. During the contact phase the boom operator or A3R boom system establishes contact while the receiver needs to ensure the nominal position keeping and acknowledge the contact. The receiver has less challenging tasks to perform than in case of the H&D system, because the main requirement is to acquire and hold formation flight in the appropriate refuelling position. [2]
With the H&D system the task to establish contact falls on the receiver. During astern phase, after receiving the “cleared to the contact position” signal from the tanker, the receiver needs to align the probe with the drogue. In the contact phase, the contact needs to be performed, with the coupler latching onto the probe. The successful contact needs to be signalled to the tanker. During the contact phase and while refuelling, the receiver needs to maintain the position within the safety cone defined by the mission lead. [2]

2.2. Sensors and equipment

For receiver centric A3R control law development sensor information w.r.t. the relative position between receiver and tanker or drogue is needed in the same coordinate system as the receiver is being controlled in (usually receiver body fixed). In case of the boom system, the receiver only needs a reference position of the tanker, because its responsibility is to establish a close formation flight, while the contact is established by the tanker side. For H&D, the relative position between probe tip and the centre of the drogue coupler and additionally a reference point on the tanker is required. Before the astern phase (large relative distance between tanker and receiver) primarily the relative position to the tanker is controlled. This changes when reaching the astern position. During the astern phase and part of the contact phase, the relative position to the drogue is the primary control aim being driven to zero in all three dimensions. Additionally, the relative position to the tanker should still be monitored by the flight control system (FCS) as a safety feature (see also subsection 5.2). During the contact phase, after the coupler is latched (i.e. contact is established), the drogue movement is no longer independent from the receiver movement. Hence, a different relative position has to be chosen as the control aim. Here, a reference point on the tanker is useful, as it is important to hold the relative position between receiver and tanker when the refuelling is taking place. It is assumed that the same control reference point as in earlier phases can be used. To determine the relative positions, two options are proposed:

1) All sensors on receiver: Here, the relative positions are computed directly on the receiver using visual, thermographic (infrared) and/or laser-based (Lidar) cameras and sensors on the receiver to estimate the tanker and drogue position (for H&D). For better detection of the tanker or drogue, especially in night or weather conditions, special markings like reflectors or lights can be integrated on the tanker or drogue reference point. To determine the relative position of the probe tip for H&D refuelling, information on the geometric location of the sensors, probe tip, IMU and GNSS antenna on the receiver is necessary.

2) GNSS sensors on receiver, tanker and drogue (for H&D): Here, tanker and receiver are exchanging position information via data link. For H&D refuelling, also the drogue position needs to be transmitted to the receiver via data link. Use of differential GNSS is necessary in order to achieve the required position accuracy for A3R. Therefore, the use of the same equipment and the selection of the same satellites is preferred. Raw GNSS data and an IMU determining the drogue’s attitudes is time-tagged and sent to the receiver. The relative position is determined by comparing the tanker or drogue position to the GNSS position of the probe tip (H&D) or reference point of the receiver (boom). In addition to the GNSS raw data from the sensor on the receiver, information on receiver attitude measurements and geometric information about the distance of the probe tip to the GNSS sensor on the receiver are necessary. For H&D refuelling, during astern and part of the contact phase, the relative distance between receiver and drogue is important. Once contact is established and other earlier phases or breakaway (see subsection 2.5) only

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[*] In the EDA A3R paper this is called “Approach” phase [2]. In ATP 3.4.4.10, “approach phase” is a different, earlier phase [3]. To avoid confusion, the ATP naming convention astern phase (from astern to contact position) is adapted for this paper.

the relative position between receiver and tanker is used for receiver control.

2.3. Data link interface

During all AAR operations, a good and efficient communication between tanker and receiver is crucial for the mission success. While this is usually handled via voice communication in manual AAR, the standard messages need to be translated for A3R scenarios. ATP 3.4.4.10 defines a message set to translate the existing voice command and control messages/procedures from manual AAR [3].

Exchange of messages between tanker and receiver can be valuable for realising the A3R control laws on the receiver. Useful signals depend on the design architecture chosen, existing sensors and other factors. Interesting for flight control is considered:

- Tanker and/or drogue (for H&D) position
- With drogue position: drogue attitudes
- Tanker speed
- Tanker altitude
- Tanker direction (i.e. track angle)

However, it would be beneficial from an operational point of view to use a generic interface specification, which is independent of aircraft type and sensor hardware.

2.4. Control laws concept

For A3R control law development on the receiver, the task is different depending on the refuelling system, i.e. whether H&D or boom is used. For H&D the task is to guide the receiver’s probe tip to connect with the coupler of the drogue. For boom the task is simpler, because only a close formation flight in the contact position has to be acquired and held by the receiver.

For the different tasks, performance requirements need to be adhered to. While these will be adapted with generated knowledge during A3R development, initial references have been published in the EDA A3R paper.
From a receiver point of view, the receiver’s commanded relative position and alignment with the tanker aircraft shall be met with an accuracy of [2]:

- Astern phase: ≤ ±3 ft
- Contact phase: ≤ ±3 ft

Additionally, for H&D refuelling the receiver’s commanded relative position and alignment with the drogue shall be met with an accuracy of [2]:

- Astern phase (H&D): ≤ ±2 ft, ≤ ±1ft/sec
- Contact phase (H&D): ≤ ±0.5 ft, ≤ ±0.5 ft/sec

There are numerous possible control law design choices on where to close the control feedback loops for A3R. Two approaches are listed here:

1) All loops are closed on the receiver: Unmanned aircraft usually already have autopilot loops that can control altitude, speed and direction. For A3R, additional loops are introduced around the inner autopilot loops to control a three-dimensional relative position. The relative position is either the relative position between receiver and tanker or between receiver and drogue.
a) The relative position to the tanker is used in all phases for boom refuelling and for H&D refuelling in early phases until astern position has been reached, as well as while contact is established.
b) The relative position between drogue coupler and receiver probe tip is used as a primary control aim for H&D refuelling in the astern and contact phase until contact is established. Additionally, the relative distance between receiver and tanker should be monitored during these phases as well (see also subsection 5.2).
For a better control performance, information of the tanker motion received via data link can be used as a direct link in the receiver’s control laws.

2) Some loops are closed on the tanker: The tanker generates the commands for the receiver autopilot control loops. These can be on different levels of the control system, e.g.

- Commanding a three-dimensional relative position (as described above):
  - The receiver dynamic reaction depends on the autopilot properties of the receiver.
- Commanding speed, altitude and direction:
  - The receiver dynamic reaction is partly shaped by the feedback gains used on the tanker. It is expected that different gains are needed for different receivers.

If some loops are closed on the tanker, the feedback gains have to be adapted to the receiver dynamic properties. However, if all loops are closed on the receiver, the design is expected to fit to all tankers.

2.5. Safety concept

A dedicated safety concept handling different failure cases is crucial for all A3R operations but depends heavily on the chosen system architecture. Every design of automated procedures needs to follow manual AAR safety procedures defined in ATP 3.3.4.2 [1]. For manual AAR the following two safety manoeuvres are defined and need to be translated to A3R:

1) Breakaway: Can be initiated by either vehicle to send the receiver back to a pre-defined “safe” position as per ATP 3.3.4.2 [1]. For the receiver the following actions are defined in case of breakaway:
(1) Immediately disconnect.
(2) Move back and go to a safe position clear of the tanker and the refuelling equipment. [1]

2) Loss of Visual Contact: For manual AAR this means that the receiver pilot loses sight of the tanker. This translates to a loss of relative navigation for the receiver in A3R manoeuvres [3]. Any aircraft in close formation that loses visual contact with the tanker or the receiver upon which it is flying in formation with is to take immediate action to achieve safe separation from the tanker, and if necessary, other receivers [1]. A safety concept has to be developed that ensures collision avoidance with all partners, while loss of visual contact procedures are adhered to. From procedures for astern and contact phases, the receiver is ordered to immediately disconnect, make the appropriate call and initially slow down 10 kts indicated airspeed (KIAS). Subsequent actions depend on the

system used, but always include a descent of the receiver [1].

Further guidelines are made in the ARSAG concept of operations: In all cases, the receiver will descend 1000 ft below the tanker's altitude, decelerate and turn 30 degrees to the right of the tanker's last known heading and execute lost link procedures [4].

2.6. Concepts of example A3R projects

The two ongoing A3R projects introduced in subsection 1.4 are addressing some of the points presented in this subsection.

For A3RH&D different types of sensor concepts are being investigated. Sensors on both tanker and receiver are used for tracking. For a flight test campaign with a Tornado employed as receiver a visual camera will be utilized. Video data will be gathered and used to train visual tracking algorithms to derive the relative distance between the drogue and the receiver probe tip. For an A330 MRTT employed as tanker, a pod is developed combining visual and thermographic sensors. For the drogue, the feasibility of integrating a GNSS sensor with data link on the drogue is investigated. The sensors on the tanker will be flight tested to gather sensor data.
The control law concept of the receiver centric part of A3RH&D will focus on an approach with all loops closed on receiver side. A relative position autopilot will be designed in a simulation environment for a representative receiver model.

In the Auto'Mate project both receiver and tanker are equipped with the same GNSS sensors (second option in subsection 2.2). During the first flight test the flight control was solely based on GNSS data. For other sensors, namely different types of cameras (resolution, field of view) and Lidar, data gathering was performed. It is planned to use all sensors together with sensor fusion in the next flight test planned for November 2023.
The autopilot concept presented in detail in this paper is an approach where some loops are closed on the tanker. When controlled by the tanker, guidance targets determined on the tanker side are sent to the receiver, which are used as commands to the autopilot modes of the receiver. In each axis the control concept includes a basic trajectory command based on the tanker trajectory and on top of that a delta command accounting for the error in relative position. Combined, commands for speed, altitude and track angle are created. For more details on the Auto'Mate control law concept see subsection 6.1.
A dedicated safety concept for the receiver, using a three-dimensional automatic safe separation, was developed in the scope of Auto'Mate. For more details, see section 4.

3. AUTOMATIC AIR-TO-AIR REFUELLING AUTOPILOT CONCEPT

For A3R development a position autopilot is needed that is precise in position acquisition with little overshoots and robust against measurement errors and biases. A concept for a position autopilot is presented in this paper based on delta and reference commands and special consideration to steady-state error elimination from measurement inaccuracies. The concept is explained with the example of the speed axis, which is challenging to control in the precise positioning scope of A3R, because it is usually slower than the pitch and lateral axes. For most operations fast, i.e. high bandwidth, throttle commands are avoided to protect the engine but for AAR this is sometimes necessary to achieve the adequate crispness for precise horizontal control (e.g. to establish contact for H&D refuelling).

The autopilot concept discussed in subsections 3.1 and 3.2 is intended for the astern and contact phases of A3R. In other phases, when the distance between tanker and receiver is large, different concepts may be employed.

3.1. Reference and delta commands concept

Rather than controlling an absolute command or solely a derived delta command, a combined concept is proposed. A reference command based on the tanker movement (or drogue movement for some phases of H&D refuelling) is combined with a delta command accounting for the error in relative position between receiver and desired receiver position. The reference command can be derived from sensor measurements on receiver side or sent via data link from the tanker (or drogue).

In the speed axis, it is proposed to use the tanker speed as a reference command for the autopilot.

3.2. Speed and x-position autopilot with mitigation of steady-state error from measurement inaccuracies

For speed control a differential PI-algorithm is proposed, illustrated in FIG 5 and based on the concept in Ref. [5]. With this concept, all signals that are proportionally added to the control surfaces are first differentiated, multiplied with their respective gains and then integrated. In the simplified example in FIG 5, V_c is the proportional feedback signal that is first differentiated and then multiplied with the

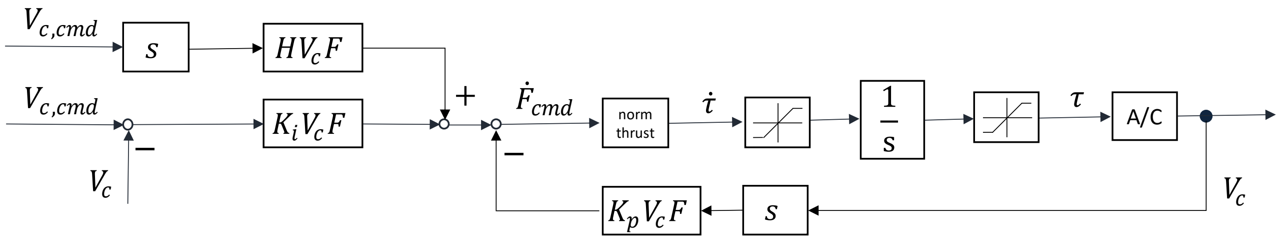

FIG 5: Speed autopilot with differential PI-algorithm

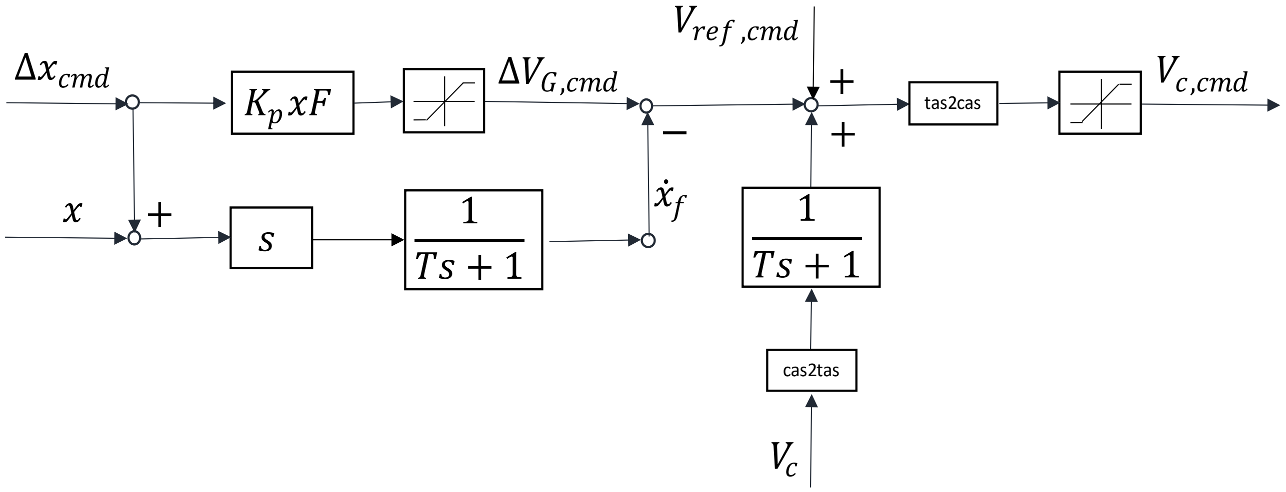

FIG 6: Position autopilot with speed measurement bias compensation

proportional gain (K_pV_cF) before integration. After deriving a power lever rate command $\dot{\tau}$ from the thrust rate command $\dot{F}_{cmd}$ by means of normalization (engine dependent), a power lever command τ is obtained by integration and subject to rate limiting, which is phase loss free by this scheme. With the limit on the power lever command itself integrator windup is prevented. The architecture in FIG 5 also has the option of a direct link, directly adding a speed command to the path, after prior differentiation and multiplication with the respective gain (HV_cF). The direct link for speed command can be used as a means of changing the speed more directly, e.g. when establishing contact for H&D refuelling by increasing the speed and thereby driving the probe tip into the drogue coupler. In the integral path, the delta speed command is created by subtracting the measured speed V_c from the speed command $V_{c,cmd}$. By multiplication with the integral gain (K_iV_cF) a thrust rate command is created.

Having different types of sensors on the tanker and the receiver leads to systematic measurement inaccuracies (bias) of speed, altitude rate and direction measurements also in failure-free scenarios. Even taking the differential GNSS approach proposed in subsection 2.2, the issue still needs to be considered for failure cases. Errors on the speed and position measurement result in a steady-state error in Δx position, if the loop is closed using only proportional feedback control. The introduction of an integral control element to the control system would be one possible solution to eliminate this steady-state error. That however slows down the performance of the system and makes it more difficult to achieve A3R.

A control law strategy is proposed here (see FIG 6) to ensure steady-state accuracy in the speed axis without slowing down the system. When the relative commanded delta position Δx is driven to zero, only the measurement error of the delta position is left as the remaining error. By first adding the low-pass filtered speed feedback signal V_c to the reference command $V_{ref,cmd}$, the bias at low frequencies and in steady-state is removed. Then, by differentiating the target position ($x + \Delta x_{cmd}$), a speed is obtained which has no measurement bias w.r.t. the delta position Δx. This speed is low-pass filtered with the same time constant, thereby obtaining the filtered speed $\dot{x}_f$, and then subtracted from the reference command $V_{ref,cmd}$. As a result, the low frequency part of the speed feedback is replaced by the feedback of this differentiated delta position. The filter time constant should be higher than both the time constants of the phugoid motion and the position feedback so that the dynamics of the closed loop system remain unchanged.

3.3. Phase advance for receiver autopilot

A basic trajectory command referencing the tanker motion has the effect of a direct link. This kind of phase advance is useful to avoid an increase of relative position error following a change of tanker motion, e.g. in the horizontal axis the tanker speed signal $V_{ref,cmd}$ (see. FIG 6). However, the phase advance obtained depends on the distance between receiver and tanker.

For example, at the transition point (1500 ft aft of the tanker [3]) the phase advance at 200 kts Calibrated Airspeed (KCAS) translates to 4.5 seconds and can be used to make the receiver react faster to tanker trajectory changes. In contrast, the astern position as introduced in subsection 2.1 is 50 ft behind and slightly below the boom nozzle for boom scenarios. When flying with the same speed of 200 KCAS, this translates approximately to a phase advance of only 0.15 seconds. The impact on the close position control is therefore small.

4. AUTOMATIC SAFE SEPARATION

Having two or more aircraft, tanker and receiver(s), in close proximity like in AAR manoeuvres comes with challenges when automating the manoeuvre. It needs to be ensured that a safe three-dimensional separation is always achievable when needed. Use cases for this separation are failure cases, but also normal operation for detachment of the two or more aircraft.

One solution to the three-dimensional separation manoeuvre is based on standardized manoeuvres for manual AAR. As discussed in subsection 2.5, the safety manoeuvre “Loss of Visual Contact” for manual AAR must be translated to a safety manoeuvre for A3R in case the receiver loses its relative navigation. This happens depending on the architecture chosen (see subsection 2.2) either in a failure case of the receiver's relative distance sensors or if the receiver has a total link loss of the data link to the tanker. The ability to perform the safety manoeuvre must not depend on the tanker but can only rely on the receiver in both sensor failure or link loss conditions. The receiver's control needs to go back to its basic autopilot, without inputs needed from the relative distance sensors or the tanker. Depending on the architecture, other (non-failed) sensors on the receiver can help de-escalating the total link loss situation. However, a standardized safety manoeuvre should always be implemented. Based on manual AAR safety procedures [1], the ARSAG guidance document recommends that the receiver should descend by 1000 ft, decelerate and turn 30 degrees to the right of the tanker's last known heading [4].

This approach ensures a safe separation between tanker and receiver. In case of more than one receiver, the individual automatic safe separation commands should either be agreed upon before the mission or be transmitted by a flight leader (e.g. the tanker) before close proximity is reached. It is crucial to ensure not only a safe separation between the tanker and receiver, but also to any other receivers taking part in the mission.

For the Auto'Mate project an automatic safe separation concept was developed that is not only triggered in case of the beforementioned total data link loss and other safety critical events, but also as a general procedure when transferring the control back from the tanker to the ground control station (GCS). This is to always ensure a safe separation in the three-dimensional space between the tanker and the receiver, especially after the tanker was in control of the receiver. The principle of the automatic safe separation developed for the Do-DT25 in the scope of the Auto'Mate project is illustrated in FIG 7. Prior to the receiver's transfer of control to the tanker, three autopilot delta commands, reflecting the three control axes, i.e. delta altitude, delta track angle and delta Calibrated Airspeed (CAS) are sent to the Do-DT25 by the tanker. These commands are frozen once the control is transferred to the tanker and applied once the automatic safe separation is triggered. The information about the commands is also communicated to the GCS operator via voice communication from the tanker operator, so that the operator knows the expected behaviour of the Do-DT25 in case of automatic safe separation. In the Auto'Mate scenario, the tanker knows the positions of all receivers from sensors and through a data link, but the receivers are not communicating with each other. The tanker has the best situational awareness and therefore determines the commands for each receiver. Once the automatic safe separation is active, the Do-DT25 FCS applies the delta commands to acquire a new altitude, track and speed, derived from the last value while the tanker was in control added with the delta commands. At any moment of the automatic safe separation the GCS operator can take over the control by sending a new command.

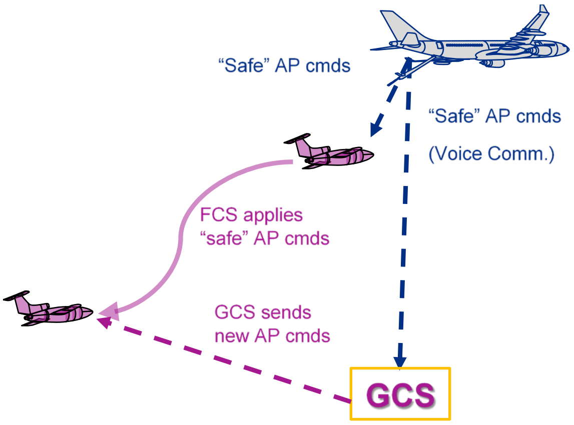

FIG 7: Automatic safe separation concept for Auto'Mate project

5. FAILURE CASE HANDLING

When developing prototypes for A3R, it is essential to account for failure cases. In the scope of this paper, three failure cases are presented. Possible solutions are suggested, including examples from the Auto'Mate project that were demonstrated in flight test.

5.1. Loss of receiver relative navigation from data link loss

In case the receiver loses its relative navigation, "Loss of Visual Contact" Procedures need to be followed [3]. Using the second concept described in subsection 2.2, with the relative position information coming from an exchange of information via data link, the loss of relative navigation translates to a loss of the data link.

Via the data link packages with the signals are transmitted and confirmed upon reception. The data link has a fixed time frame and update rate. A cyclic redundancy check is necessary to detect accidental changes (corruption) to the signals. If a package is not confirmed, the link loss counter is incremented. It is beneficial to distinguish between temporary and total link loss. In reality it happens constantly that a few data packages are lost during transmission. Aiming for a smooth manoeuvre and robust operational implementation of A3R, it is not beneficial to abort the mission whenever a single package is lost. Therefore, a different strategy should be pursued when dealing with temporary link losses, compared to total link losses.

The definition of a temporary link loss will depend on the specific aircraft and data link architecture but it can be assumed that it will be defined as a low number of cycles lost. When the data link is lost for a few cycles, a strategy has to be defined on how to apply commands to the receiver. The most critical situation during a link loss would be the receiver accelerating towards the tanker, even though the tanker is already sending deceleration commands (which are not received by the receiver due to the link loss). Therefore, it is advantageous to stop the acceleration of the receiver during a temporary link loss and either decelerate or continue with a reference "safe" speed command. Special considerations should be made to engine dynamics, which are usually slower to react compared to other control means in other axes. Use of aerodynamic means of braking, if available, can speed up the reaction. The situation of the tanker slowing down during a temporary link loss is not considered critical, because during normal AAR manoeuvres the tanker maintains a constant speed and in addition to that, the effect on the change in relative speed in the short time of the temporary link loss would be minimal for heavy tankers.

Another critical command is the altitude command, especially when close to the contact position for boom A3R. If the last known command from the tanker is to climb it is beneficial to stop the climb when close to the tanker until a stable link is restored, in order to avoid the receiver hitting the tanker or the refuelling equipment from below.

In the Auto'Mate project a dedicated strategy has been implemented for the case of temporary link loss, matching the overall control strategy, when the tanker is in control, see subsection 6.1. In the speed axis, it is ensured that either the receiver speed command is equal to the tanker speed or lower, i.e. any previously commanded acceleration is immediately set to zero, while a previously commanded deceleration is kept. In the lateral axis, the command is kept constant from the last known good value. In the vertical axis, the delta altitude command is faded out to zero with time, while the altitude rate command is limited to zero or negative values.

The situation of total link loss has to be defined along with the one for temporary link loss based on aircraft and data link architecture. A total link loss is declared when the restoration of the data link fails for a predefined number of cycles. At this point, a three-dimensional separation between both aircraft is crucial for a safe operation. Based on manual AAR safety procedures, a three-dimensional separation where the receiver decelerates, descends and possibly turns is proposed. Additionally, the tanker could accelerate and climb.

In the Auto'Mate project it was decided that 10 cycles is the trigger for a total data link loss. Total link loss triggers the automatic safe separation described in section 4.

5.2. Minimum distance violation

In addition to loss of receiver relative navigation (due to sensor failures or link loss) scenarios, a safety concept needs to be developed that ensures that the relative distance between tanker and receiver never goes below a certain threshold. This safety concept also needs to work in case the relative position to the drogue is the control aim (for H&D refuelling in astern and parts of the contact phase). Depending on the overall concept, this functionality could lie on tanker or receiver side or both.

In the Auto'Mate project, the position measurement relied solely on GNSS for the first flight test campaign. A redundant distance measurement was not yet available. To counter measurement or algorithmic corruption on tanker side, a safety function in the form of a safety distance trigger was implemented on receiver side. The automatic safe separation is triggered if the distance between Do-DT25 and tanker becomes too small, i.e. if a sphere around the tanker is violated. For the first flight test a sphere of 30 m was used. As a further safety measure, distance determination and monitoring were done during the flight test by the A3R operator on tanker side, who could trigger the automatic safe separation at any time.

6. RECEIVER FCS DESIGN FOR AUTO'MATE PROJECT

6.1. Receiver autopilot control laws

The feedback control loops of the Do-DT25 are designed sequentially as a cascade control system, based on the concept described in [6]. In the inner loops, normal load factor control is provided for the pitch axis and bank angle control for the roll axis. The intermediate loops, controlling flight path related variables, i.e. altitude rate in the vertical, speed in the longitudinal and track angle in the lateral axis, are closed next. Last, the feedback loops for position/trajectory related variables, i.e. altitude in the vertical and longitudinal and lateral position changes in their respective axes, are closed.

Within the Auto'Mate project, the three autopilot modes for altitude, speed and track control are made accessible for the guidance targets sent by the tanker.

In the vertical axis, the tanker sends a delta altitude command and a vertical speed command. The altitude command is translated to an internal vertical speed command using a proportional feedback gain and then added to the vertical speed command sent by the tanker. After limiting this command, the derived vertical speed command directly replaces the vertical speed command of the Do-DT25 altitude acquire and hold autopilot.

In the longitudinal axis, the tanker commands for the Do-DT25 are a reference ground speed command and a delta ground speed command. These are added in the speed and longitudinal position control autopilot to build an absolute ground speed command. When in straight flight the ground speed command is directly used as guidance target of the automatic speed control function of the autopilot.

In wind conditions the use of ground speed as a control variable is challenging when flying a turn. The tanker mostly flies steady-state turns during AAR manoeuvres with constant CAS, while the ground speed changes according to the direction of the wind. Due to the distance between the tanker and Do-DT25, they will experience different local wind conditions when in a turn. When the Do-DT25 flies behind the tanker, the tanker always starts the turn earlier than the Do-DT25, hence the ground speeds of both aircraft can be systematically different. Because the tanker ground speed is used as a reference command to the Do-DT25 speed autopilot, this may cause the Do-DT25 to accelerate/decelerate relative to the tanker. To counter this wind effect, the control algorithm changes if a turn is detected.

Turn detection is realised by monitoring a first-order low-pass filtered track angle rate. The filter ensures that small amplitude excitation due to turbulence or the Dutch roll motion of the Do-DT25 does not trigger a turn detection. If the filtered signal is above a predefined threshold, the control algorithm switches to CAS control. A tanker will mostly fly a turn with a constant CAS; hence it can be used as a control value and it is independent of wind conditions. The Do-DT25 knows its CAS through an air data system. During detected turns the ground speed reference command from the tanker is replaced by the low-passed filtered measured CAS of the Do-DT25 and summed with the delta ground speed command converted to delta CAS. Consequently, only the delta ground speed command is active as a feedback signal.

In the lateral axis, the tanker generates a track angle command from the lateral position offset and sends it to the Do-DT25. From this, a delta track angle to the track angle measurement is calculated. The algorithm for calculating the delta track angle command makes sure that jumps in track angle when passing from π to $-\pi$ (or zero to 2π) do not lead to jumps in the delta and that always the shorter path (left vs. right turn) is chosen to reach the commanded track angle. Using a proportional feedback gain, the delta track angle command is translated to a track angle rate command within the autopilot.

6.2. Analysis of disturbance response to vertical gusts in altitude loop

To check the controller against the accuracy requirements listed in subsection 2.4, its robustness towards disturbances is evaluated. The disturbance response of the system for the altitude loop of the Do-DT25 based on the linear model of its longitudinal controller is studied using the transfer function from a vertical speed (i.e. angle of attack) disturbance input to the altitude output. A root-mean-square (RMS) vertical turbulence amplitude based on JSSG-2001B [7] is used to describe the magnitude of the disturbance.

FIG 8 shows the Bode plot of the transfer function. The maximum amplitude is -3.7 dB. For an approximation to the accuracy requirement of 3 ft for the relative commanded position between tanker and receiver aircraft, an RMS magnitude of 1.5 ft is chosen. At the maximum amplitude this relates to an RMS turbulence amplitude σ of 2.2 ft/s. Considering a representative altitude for AAR of 20,000 ft, this leads to a probability of exceedance between 10^{-1}/fh and 10^{-2}/fh as per JSSG-2001B, representing common gusts [7]. At 200 kts the frequency of the short period mode of the Do-DT25 is ~8.5 rad/s, indicated by the red line in FIG 8. It is plausible to see the maximum amplitude at lower frequencies than the short period frequency, because its effect on the altitude is attenuated by integration.

For successful A3R operations the FCS should able to handle common and uncommon gusts. The disturbance rejection achieved here would therefore not be sufficient for the task. However, the inner control loops of the Do-DT25 were designed for robustness and the elevator loop has a large gain and phase margin (see also FIG 12). With an increase in the gains that have a damping effect on the system, the maximum amplitude of the transfer function could be reduced, leading to higher robustness against disturbances caused by vertical gusts. However, considering that the small-winged and lightweight Do-DT25 is more sensitive to turbulence compared to a common fighter aircraft, the issue would not be completely resolved.

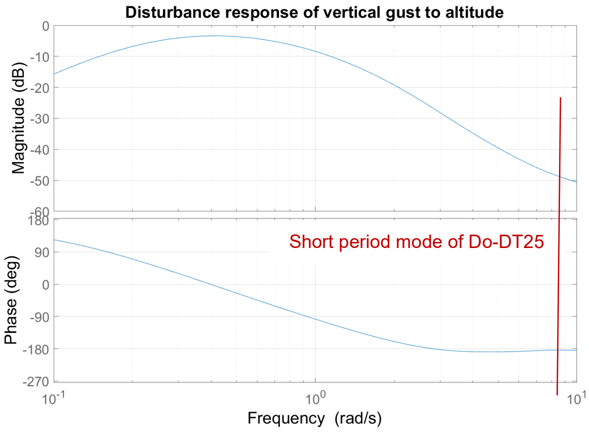

FIG 8: Bode plot of disturbance response of a vertical gust in the altitude loop

6.3. Receiver autopilot moding

The process of transfer of control to the tanker is managed by a state machine in the Do-DT25 FCS.

6.3.1. Overview of receiver moding

To ensure safe transfer of control from the GCS to the tanker a double confirmation logic was developed. Consequently, transfer of control is only possible after both the A3R operator on tanker side and the GCS operator have activated the transfer of control. This avoids unintentional hand-over of control.

The state machine of the Do-DT25 consists of four main states, as shown in FIG 9, with transitions between the states only possible in one direction (with one exception). This one-way principle was chosen as a safety feature to always ensure a safe separation between tanker and receiver, especially after the control was transferred to the tanker.

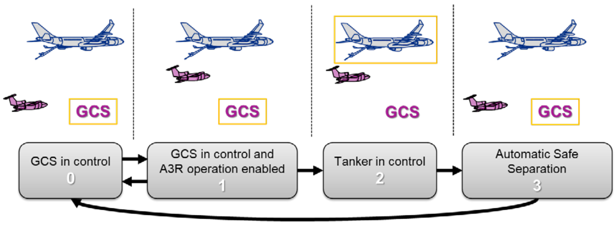

FIG 9: Do-DT25 state machine: the orange box indicates who is in control of the Do-DT25 at the current state

6.3.2. State transitions during transfer of control operation

The basic state of the Do-DT25 state machine is reflecting the same condition as the operation when the GCS operator is in control, without any tanker. This is state 0, “GCS in control”.

From state 0 the transition to the next state, state 1 “GCS in control and A3R operation enabled”, is usually solely achieved by the GCS operator enabling the transfer of control from the Do-DT25 side, by pressing a dedicated armed button on the GCS (the GCS A3R button). In state 1, the GCS operator is still in control.

The only exception to the one-way principle of the state machine is the possibility to transition back to state 0 after reaching state 1. This transfer is triggered when the GCS operator goes back to normal control or in other words, if the GCS operator switches off the GCS A3R button.

While the control laws do not change internally with the transition from state 0 to state 1, the transition to state 2 comes with a lot of changes, because the control gets transferred to the tanker and the receiver has to follow guidance targets received from the tanker. For that reason, the following conditions are checked before enabling the transfer to state 2 “tanker in control”:

- Are valid automatic safe separation commands available?
- Is the data link to the tanker stable?
- Has the A3R operator requested control?

If all conditions are fulfilled, the state machine goes to state 2 and the tanker is in control, now guiding the receiver by sending commands.

Consistent with the one-way principle of the state machine, the Do-DT25 can only go back to the normal operation state 0 by going through the automatic safe separation, no matter if the tanker in control operation was ended through normal procedure or by a safety trigger. The state machine transitions to state 3 “automatic safe separation” if either the GCS operator or the tanker operator switches off his respective button for control transfer. Other triggers for the transition to state 3 are a total data link loss between the tanker and the Do-DT25 or a minimum distance violation. For more details on failure case handling, see section 5. The automatic safe separation ends if the GCS operator sends a new command or latest after a predefined time has elapsed and the state machine transitions back to state 0.

6.3.3. Failure case monitoring

To give visibility to any unfulfilled requirements for the transfer of control to the tanker, an informational signal is introduced, which is sent to the tanker. It gives information in the form of an integer corresponding to different failure cases for state transitions. The prioritization of the integer is given in the order in which it is needed to transition. Failure cases are prioritized over operational steps missing. First it is checked if the GCS A3R button is armed. Second, the data link stability between tanker and receiver is checked. Third, the automatic safe separation commands sent by the tanker are checked for their validity and range. Then, the internal primary flight phase of the Do-DT25 is checked. Last, the clearance for transfer of control from both the GCS operator and the A3R operator on tanker side via button press are checked.

6.4. Data link considerations

The closure rate or approach (i.e. delta-) speed between receiver and tanker is typically less than 10 m/s at the astern and less than 1 m/s close to the contact position. Consequently, receiving breakaway or abort commands from the tanker with a delay of one second would be fast enough to initiate safety manoeuvres. For precision control of the vertical axis however, a one second delay is considered challenging, in particular when trying to engage the drogue in the H&D scenario and when lost messages are taken into account. Therefore, a higher update rate is targeted.

In the Auto’Mate project, a 10 Hz update rate was used. This allowed to decide on a total data link loss within a one second timeframe and to smoothen the command signals used in the 50 Hz receiver FCS. With the limited number of signals (i.e. the variables presented in subsection 2.3, the control commands and a number of moding signals) a low bandwidth data link of around 10 Kbps was considered sufficient.

7. FLIGHT TEST RESULTS FROM AUTO’MATE PROJECT

The automatic formation flight of a Do-DT25 as receiver and an Airbus A310 MRTT as tanker aircraft, as well as the receiver based automatic safe separation, were demonstrated during a flight test campaign in March 2023. During the flight tests the transfer of control of the Do-DT25 from the GCS to the tanker was accomplished and the Do-

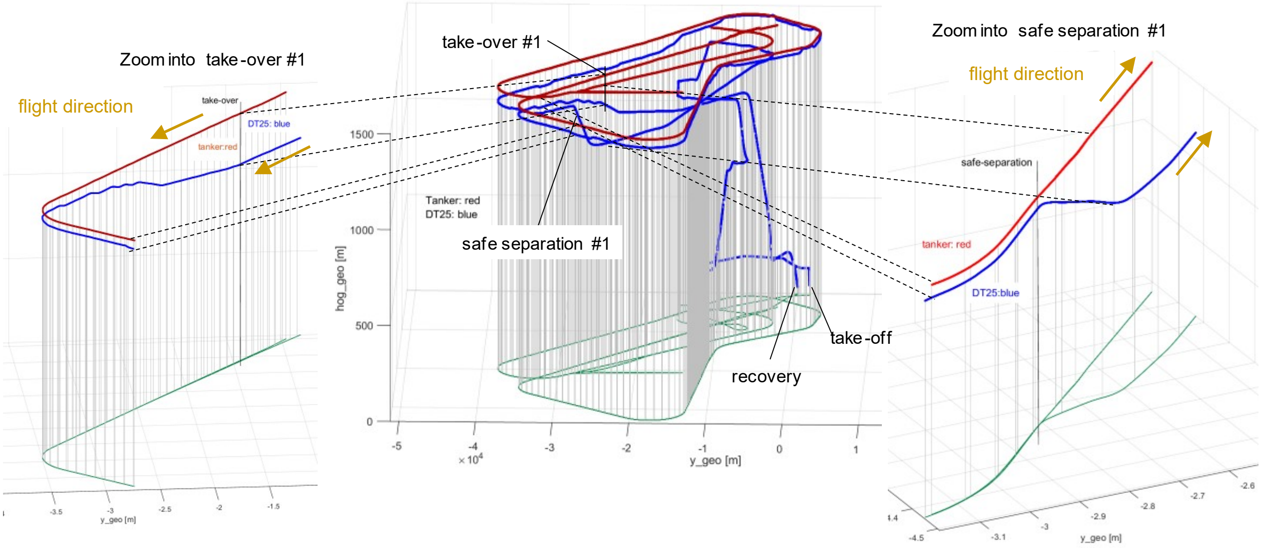

FIG 10: Flight test trajectory showing control take-over and automatic safe separation

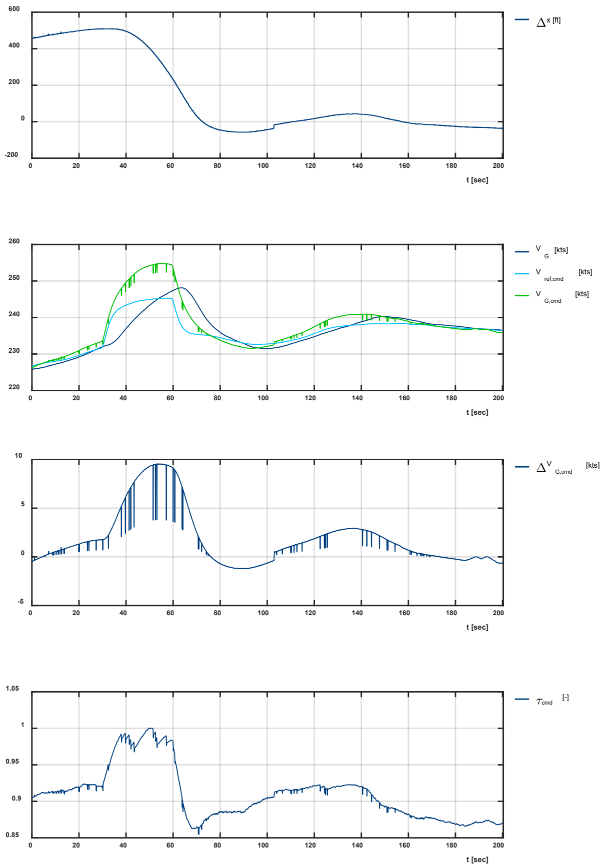

FIG 11: Flight test results for position control in x-direction

DT25 was brought in close formation with the tanker to a minimum distance of less than 250 ft. FIG 10 shows an example of the three-dimensional trajectories of both receiver (blue) and tanker aircraft (red). In the centre of FIG 10, the complete flight of the Do-DT25, including take-off and recovery, is shown. The tanker trajectory is shown for the equivalent time of the Do-DT25 flight. The zoomed-in section on the left shows the first take-over of control of the tanker. With the initial separation in altitude the Do-DT25 starts climbing towards the tanker after the take-over. Once the commanded relative position for the Do-DT25 is reached, the two aircraft fly in formation. On the right of FIG 10 another zoomed-in section shows an example of the receiver based automatic safe separation. After it is triggered, a three-dimensional separation is achieved, visible here as a separation in altitude and lateral offset.

FIG 11 shows flight dynamic parameters of the speed axis gathered during one of the test flights. In this example, the tanker is already in control of the Do-DT25 and commanding it to accelerate to close the relative distance Δx to the desired position (where $\Delta x = 0$), shown in the first line of FIG 11. An initial relative distance Δx of around 500 ft is reduced to approximately 0 ft. The second plot shows the ground speed of the Do-DT25 V_G (dark blue), as well as the reference command sent by the tanker $V_{ref,cmd}$ (light blue), as described in subsection 6.1. The ground speed command in the autopilot of the Do-DT25 $V_{G,cmd}$ (green) is derived by adding $V_{ref,cmd}$ and the delta speed command sent by the tanker $\Delta V_{G,cmd}$, shown in the third plot. The last plot shows the power lever command τ_{cmd} computed by the autothrottle from $V_{G,cmd}$. In the position control it is clear that while the general task, to close the relative position Δx, is achieved, the behaviour of the time response should be improved. There are strong position overshoots in the x-position due to a resulting deficiently damped low frequency oscillation. While this was no safety risk in this flight test campaign, because the Do-DT25 and the tanker were far enough apart, overshoots in general should be avoided in A3R, as they can pose a safety risk. In this specific case the inner loops for the Do-DT25 auto throttle should be designed to be faster. The current autothrottle is designed for robustness with large stability margins to account for different engine types and measurement inaccuracies. With faster inner loops, the overshoots in position could be removed. Nevertheless, the speed axis is slower compared to both pitch and lateral axis, due to slow engine dynamics. Another noticeable thing about the flight test data are the jumps in $\Delta V_{G,cmd}$, resulting in jumps for $V_{G,cmd}$ and consequently also in jumps for τ_{cmd}. This can be explained by the temporary link loss strategy described in subsection 5.1. It was decided to immediately put $\Delta V_{G,cmd}$ to zero (or leave it at its negative value) once a temporary link loss is detected, to ensure that the Do-DT25 will never accelerate into the tanker during link loss. From the flight test data, it is clear that a temporary link loss happens often without endangering the mission, because the link is usually recovered fast. Therefore, it is expected that a less conservative approach to temporary link losses could be sufficient and ensure a smoother control behaviour. It is also considered beneficial to tailor the temporary link loss approach to the different AAR phases, i.e. depending on the distance between the receiver and tanker.

During a total of six flights, different data link options were tested. In addition to the low bandwidth data link mentioned in subsection 6.4, a second data link option with a higher bandwidth of around 20 Mbps was tested. No significant advantage for the receiver control could be determined with the higher bandwidth data link. The Do-DT25 autopilot was able to follow the commands sent by the tanker adequately in both cases.

Elevator and aileron sweeps were performed during the flight test campaign. The subsequent analysis of the stability margins of the Do-DT25 with the tanker in the loop showed a robust behaviour. FIG 12 shows the elevator cut in the Nichols plot with sufficient gain and phase margin. It

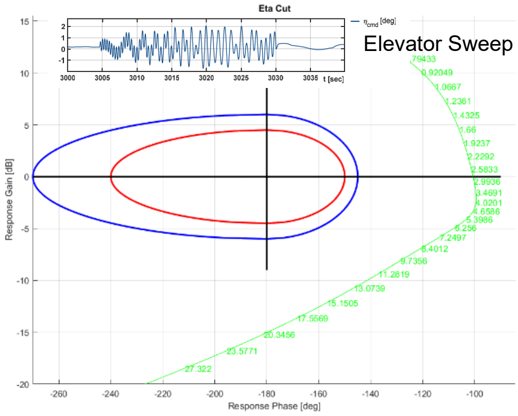

FIG 12: Stability margins of Do-DT25 with MRTT in the loop (elevator cut)

is clear that the control law gains could be increased to speed up the elevator control loop, without endangering the robustness and stability of the system.

8. CONCLUSIONS

This paper presents the flight test results achieved for an automatic formation flight – a key technology necessary for autonomous air-to-air refuelling. A control law concept for speed and position control including mitigation for a bias in speed measurement is discussed.

The design and flight test results for a second key technology for autonomous air-to-air refuelling – an automatic safe separation function – are presented. The safe separation was successfully demonstrated after being triggered both intentionally by operator input, as well as unintentionally by a loss of data link.

The demonstrated key technologies are argued to be independent of the tanker aircraft and refuelling system (hose & drogue or boom-receptacle) used.

The next necessary step for advancing towards autonomous air-to-air refuelling is the automation of the contact phase, including establishing the contact automatically. Algorithms for the contact phase will however be dependent on the refuelling system and possibly on the tanker properties.

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Abbreviations

A3R	Automatic Air-to-Air Refuelling
A4R	Autonomous Air-to-Air Refuelling
AAR	Air-to-Air Refuelling
AV	Air Vehicle
BDA	Boom Drogue Adapter
boom	Boom-receptacle system
CAS	Calibrated Airspeed
FCS	Flight Control System
GCS	Ground Control Station
H&D	Hose & Drogue or probe and drogue system
KCAS	Calibrated Airspeed [kts]
KIAS	Indicated Airspeed [kts]
RMS	Root-Mean-Square
UAV	Unmanned Aerial Vehicle