NATO STO/AVT-251: A Joint Exercise in Collaborative Combat Aircraft Design

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ABSTRACT

This article provides an overview about the activities performed within the NATO STO Research Task Group AVT-251 on "Multi-Disciplinary design and performance assessment of effective, agile NATO Air Vehicles". After a brief introduction to the preceding task groups and the research questions that led to the formation of AVT-251, the selection of design requirements is discussed and the approach for developing the MULDICON UCAV configuration out of its predecessor, the SACCON concept, is described. A short summary presents the work performed by the four design teams, each of which was responsible for one of the major topics on which the design task had been focused (aerodynamic shaping, control concept, engine integration, and structural concept). The task of a fifth team was two-fold: initially, it was responsible for the specification of the design requirements; later in the process, it had to join together the results of the other four teams into an overall aircraft concept and to assess this concept with respect to the initially specified set of requirements. Finally, a concluding summary of the MULDICON concept, as well as of the research questions of the AVT-251 task group are presented.

1 INTRODUCTION

The ability to accurately predict both static and dynamic stability characteristics of air vehicles using CFD[1] methods could revolutionize the air vehicle design process, especially for military air vehicles (McDaniel

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[1] **C**omputational **F**luid **D**ynamics

et al., 2007). A validated CFD capability would significantly reduce the number of ground tests required to verify vehicle concepts and, in general, could eliminate costly vehicle 'repair' campaigns required to fix performance anomalies that were not adequately predicted prior to full-scale vehicle development (Meyn and James, 1996; Lovell, 2003; Jacobson et al., 1998; Hall et al., 2005). This article outlines the extended integrated experimental and numerical approach performed within the NATO[2] STO[3] Research Task Group AVT[4]-251 on "Multi-Disciplinary design and performance assessment of effective, agile NATO Air Vehicles" and its predecessor groups. While the focus of the previous groups was placed on the assessment and validation of the CFD capabilities to predict complex vortical flows accurately, AVT-251 was dedicated to the application of CFD in the early phase of aircraft design.

1.1 Background

In order to evaluate and improve the prediction of S&C[5] characteristics of highly swept wings at medium to high angles of attack, a number of NATO RTO[6] and STO task groups have been formed in AVT during the past decades. AVT-080 focused on determining the ability of CFD to predict vortical flow structures on delta wings (Vortex Breakdown over Slender Delta Wings, 2009). In AVT-113 (Hummel et al., 2009; Hummel, 2008) the focus was on experimental and numerical investigations on delta wing configurations with various leading edges from sharp to different round radii. AVT-113 started from given fundamental wind tunnel data by NASA followed by several pre-test CFD results which supported the wind tunnel investigations with advanced experimental methods.

Following these groups, the NATO RTO AVT-161 Task Group was established to determine the ability of modern CFD methods to accurately predict both static and dynamic stability of air and sea vehicles. The goal of the group was to understand the developing flow structures of configurations with vortex-dominated flow fields and to provide best practice procedures to predict their static and dynamic behavior. For the investigations, two candidate configurations were chosen: the X-31 and a generic UCAV[7] configuration called SACCON[8]. The latter one was designed especially for the AVT-161 task group, with the aim to exhibit a highly complex aerodynamic behavior, serving as a challenge for numerical flow prediction using CFD methods. An overview of the AVT-161 Task Group is provided by (Cummings and Schütte, 2012b; Cummings and Schütte, 2012a).

During AVT-161, the SACCON configuration exhibited a number of very uncommon flow features, related to its variable leading edge roundness along the wingspan. As a consequence, the AVT-183 Task Group was founded to gain a deeper understanding of the separation onset and progression of the flow at round leading edges. Experimental and numerical results of AVT-183 are, beside others, published by (Hövelmann and Breitsamter, 2015), as well as by (Frink, 2015). All of these investigations resulted in improved understanding of the flow physics and new best practice methods for computational simulation of vortical flows.

While AVT-161 was focused on the numerical prediction stability and control aspects of highly swept delta-wings, AVT-201 was established to take on the additional tasks of including control surface deflections in the aerodynamic evaluation, as well as to find ways to perform full flight simulations using CFD (Cummings, Liersch, Schütte and Huber, 2018; Cummings and Schütte, 2016; Liersch et al., 2016).

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[2] **N**orth **A**tlantic **T**reaty **O**rganization

[3] NATO **S**cience and **T**echnology **O**rganization

[4] **A**pplied **V**ehicle **T**echnology Panel

[5] **S**tability **&** **C**ontrol

[6] NATO **R**esearch and **T**echnology **O**rganization

[7] **U**nmanned **C**ombat **A**erial **V**ehicle

[8] **S**tability **A**nd **C**ontrol **CON**figuration

1.2 AVT-251

After completing AVT-161 and AVT-201, a comprehensive experimental and numerical knowledgebase about the flow physics of SACCON-like configurations had been gathered – see among others (Vicroy et al., 2016; Huber et al., 2014; Zimper and Hummel, 2016; Coppin et al., 2016; Ghoreyshi et al., 2016; Schütte et al., 2016). Furthermore, a large amount of expertise was available, about how to simulate this type of configuration using CFD methods and the reliability of the corresponding results. The next logical step was to use all this knowledge and experience to re-design the SACCON configuration into a more realistic aircraft concept.

1.2.1 Objectives

AVT-251 was established to accept that challenge: Within three years, a multi-disciplinary re-design of the SACCON configuration towards a realistic, agile aircraft concept named MULDICON[9] should be performed. For this re-design the group would have to deal with vortical flow physics and control device strategies, as well as with the design aspects regarding propulsion, structures, and signature constraints – everything relying purely on CFD and other numerical methods. From the beginning, it was clear that a comprehensive investigation covering all relevant aspects of the design would be beyond the scope of the group. Instead, an attempt was made to focus the available resources and partners to some of the most critical aspects and link everything together using conceptual aircraft design methods (Cummings, Liersch and Schütte, 2018).

It should also be mentioned, that that the real task of AVT-251 was not to design a competitive vehicle. The group was formed to investigate how the design process for such an aerodynamically challenging aircraft configuration could be enhanced and accelerated by applying the validated CFD tools, as well as the knowledge and experience that were gained in the preceding AVT task groups. Especially the early phase of aircraft design, where it is essential to predict the fundamental characteristics of the aircraft correctly, could benefit significantly from the exploitation of this capability.

1.2.2 Approach

Before the group officially started, some of the partners contributed to a preparatory team, called “Design Specification Group” (DSG). The aim of the team was to prepare a set of requirements, serving as a basis for the planned SACCON re-design work. Out of this team the “Design Specification and Assessment Group” (DSAG) was then formed later on. During AVT-251, the DSAG had two responsibilities. One was to provide, extend and update the design requirements document to the other groups. The other task was to perform overall design assessment studies using conceptual aircraft design methods.

In order to improve the aerodynamic performance of SACCON and to remove its undesirable characteristics, which were revealed in the AVT predecessor groups, one of the main activities in AVT-251 was the re-design of the SACCON outer shape. This task was given to the second (and biggest) design team within AVT-251, the “Aerodynamic Shaping Group” (ASG).

The third design team of AVT-251 was the “Control Concept Group” (CCG), which had the task to investigate and specify a suitable set of control surfaces, sufficient to achieve the demanded performance requirements. Furthermore, the CCG had to investigate the performance characteristics of the overall aircraft, which came out of the overall aircraft design process. Especially the second task could only be performed in a very limited way, due to a lack of contributing partners from that field.

For such a highly integrated aircraft configuration with the general demand for low observability, the integration of the engine (including intake and nozzle) is another crucial aspect. While the design of the

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[9] **MUL**ti-**DI**sciplinary **CON**figuration

engine itself was not a direct part of AVT-251, but kindly provided by DLR, the integration of that engine into the aircraft was investigated by the "Engine Integration Group" (EIG).

The last design team in AVT-251 was dedicated to the investigation of structural and aeroelastic aspects. The "Structural Concept Group" (SCG) provided a basic concept for the structural topology and a corresponding primary structure mass to the overall aircraft design process. Furthermore, static and dynamic aeroelastic effects were investigated for the new configuration.

This article provides an overview of the selection and specification of the design requirements for the new aircraft concept (see Chapter 2), followed by an overview of the design activities of the five teams and the resulting MULDICON concept (see Chapter 3). A final section (see Chapter 4) summarizes the work of AVT-251 with respect to the design task and the other objectives of the task group.

2 DESIGN TASK

2.1 SACCON Concept

The starting point for the aircraft design work within AVT-251 was the abovementioned SACCON configuration, a tailless, lambda-shaped flying wing UCAV concept, characterized by a 53° swept wing with parallel edges for low radar signature purposes (see Figure 1). Within AVT-201 (Cummings, Liersch, Schütte and Huber, 2018; Cummings and Schütte, 2016; Liersch et al., 2016), an internal arrangement with a single, central engine (shown in green) and two payload/weapon bays aside (shown in yellow) was specified. In order to limit the CG[10] movement due to fuel consumption, a concept with two fuel tanks (shown in red) on each side having a common CG within the specified CG range was chosen.

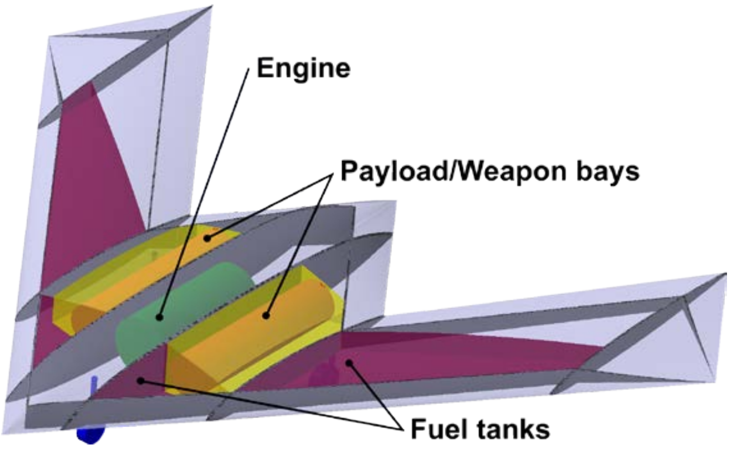

Figure 1:SACCON UCAV concept

2.2 MULDICON Design Requirements

The rationale behind the development of the MULDICON concept is to overcome the known deficiencies of the SACCON concept and to evolve it into a controllable and agile UCAV configuration which is consistent from a conceptual aircraft design point of view. In order to stay as close to the SACCON concept as possible, it was agreed that most of the requirements and the main internal arrangement from SACCON should remain the same and that the changes of the geometry should be limited to a minimum. The main design parameters are listed in Table 1 and explained briefly in the following paragraphs. A more comprehensive explanation of them can be found in (Liersch and Bishop, 2018).

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[10] **C**enter of **G**ravity

Table 1: Main design parameters of MULDICON

Parameter	Value
Outer shape	Based on SACCON, ±30° trailing edge sweep
Propulsion	Single turbofan engine without afterburner
Propulsion integration	Internal (due to signature reasons)
Static dry thrust	Thrust-to-weight ratio = 0.4 (≈ 60 kN)
Payload storage	Internal (due to signature reasons)
Payload bay size	Length: 4.2 m, Width: 1.0 m
Payload mass	2 × 1 250 kg
Design range	3 000 km (without aerial refueling)
Fuel reserve	≈ 45 min
Cruise altitude	11 km
Cruise Mach number	0.8 (all altitudes)
Stability margin	0 − 3% MAC (stable)
CG range	5.82 m – 6.00 m

The design mission for MULDICON is a rather classical long range transport mission with a radius of 1 500 km and no aerial refueling. It consists of two main parts, a high altitude cruise segment, followed by a low altitude dash approaching the target. After passing the target, MULDICON continues with a turn and returns to base over the same flight profile. The specified payload mass and the corresponding payload/weapon bay dimensions can be found in Table 1.

From SACCON it is already known that the development, movement and interaction of vortices with increasing angle of attack severely influences the pitching moment characteristics. These effects were investigated in detail by (Schütte et al., 2012) and led to a diagram which is shown in Figure 2.

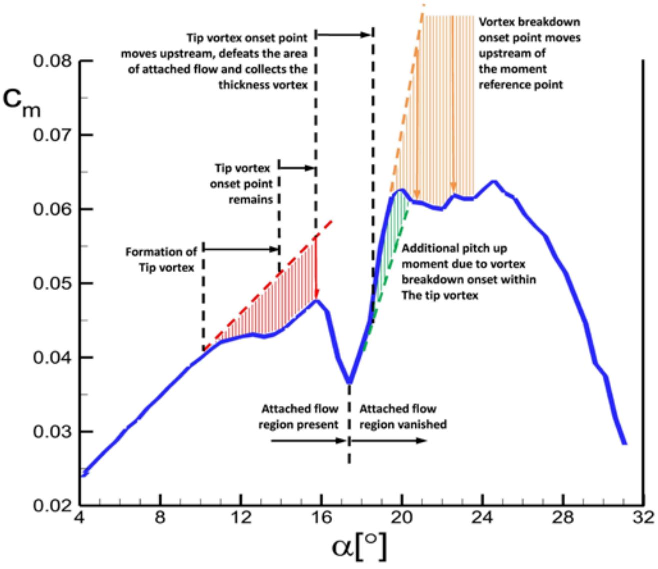

Figure 2: SACCON pitching moment coefficient, taken from (Schütte et al., 2012)

Looking at the pitching moment coefficient curve of SACCON, it becomes apparent that such a nonlinear characteristic is not acceptable for a combat aircraft operating at angles of attack up to 20° or even beyond. Thus, one major design task for the Aerodynamic Shaping Group was to modify the outer shape in such a way that the pitching moment characteristic becomes much smoother.

Another pitfall of the SACCON shape, also known from the preceding task groups, is the fact that all investigated spoilers and trailing edge devices exhibit a rather poor performance (Liersch et al., 2016; Liersch and Huber, 2014; Schwithal et al., 2016; Löchert et al., 2018). The main reason for this limited control effectiveness was identified to have its roots in the high trailing edge sweep of the wing and the corresponding flow deflection in spanwise direction. Thus, it was agreed in AVT-251 to reduce the trailing edge sweep from 53° to 30°. In order to increase the agility of MULDICON around the pitch axis (compared to the agility of SACCON), the permitted stability margin was reduced from 2 – 8% MAC[11] (for SACCON) to 0 – 3% MAC (for MULDICON), both on the stable side of the neutral point[12].

With respect to agility requirements, a set of five design points covering various flight conditions was selected and specified. Based on these five points, several requirements were formulated, including maximum load factors and corresponding lift coefficients and sustained turns[13], acceptable crosswind components for landing, and performance values for roll, pitch, and yaw. The complete table of requirements can be found in (Liersch and Bishop, 2018).

For efficiency reasons, the MULDICON configuration was assumed to be designed with a single, central engine without afterburner (see section 2.1). Based on experience from SACCON, the static dry thrust of the engine corresponded to a thrust-to-weight ratio of 0.4; for an estimated MTOM[14] of 15 metric tons, this leads a thrust value of 60 kN. The engine had to be optimized for mission cruise performance; however, the possible fan diameter was a limiting factor. Aside from the cruise performance, the engine also had to be able to deliver sufficient thrust for performing the sustained turn maneuvers mentioned above.

3 MULDICON DESIGN

The design of the MULDICON configuration was a collaborative effort within the five design teams of AVT-251. Four of the teams (ASG, CCG, EIG, SCG) were focusing on specific aspects of the aircraft and trying to find solutions to satisfy the corresponding design requirements. With respect to the amount of time and resources that were available for the design of MULDICON, these teams had to work in parallel with a very limited number of interdisciplinary iterations between them. Hence, some inconsistencies in the results could not be avoided completely. The main exchange between these teams was realized during the semiannual AVT task group meetings, where each team had the opportunity to present its most recent issues and findings and to discuss them with the other teams. A key role in this exchange was played by the DSAG, as it was the aim of this team to join together the various results and to assess them from an overall aircraft design perspective. Based on this coarse, but global view, the DSAG had to harmonize the parallel work of the other teams as far as possible and to assume and provide values of important top-level parameters when they were needed. The concept of the AVT-251 team structure and the corresponding information exchange are sketched in Figure 3. The next sections provide a brief overview of the design activities performed in the five design teams.

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[11] **M**ean **A**erodynamic **C**hord

[12] Due to the vortex-dominated flow topology, there is not one single neutral point. However, with respect to the design requirement of smoothing the pitching moment curve, it is still reasonable to assume an average position for it.

[13] “Sustained turn” means a turn without changing altitude or speed.

[14] **M**aximum **T**ake**O**ff **M**ass

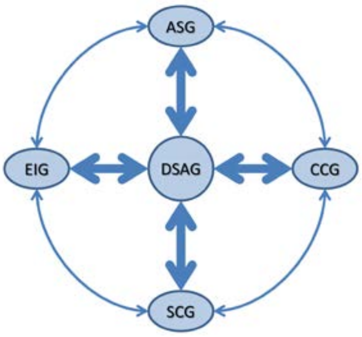

Figure 3: AVT-251 team structure and information exchange

3.1 Aerodynamic Shaping Group (ASG)

With respect to the outer shape, the Aerodynamic Shaping group provided a reference configuration first, which is identical to SACCON (same airfoils, same twist distribution), but with the modified trailing edge sweep of 30° (see section 2.2). This configuration was named "MULDICON Baseline". In order to satisfy the requirements for maximum lift coefficient and pitching moment characteristics, two different design philosophies were applied to the reference configuration. The first one was focused on the understanding of the physical principles behind the complex vortex phenomena. Therefore, based on generic airfoils, parametric studies on varying leading edge radii and twist distributions were performed. Using these physical principles, the leading edge was shaped in a way that the movement of the vortices was minimized and the pitching moment curve became much smoother. Details on this approach are discussed by (Schütte et al., 2018). The second design approach aimed at minimizing vortex effects by designing for attached flow conditions. Therefore, a complete redesign of airfoil shapes and twist distribution was performed. Finally, the discontinuities in the pitching moment could be reduced and the maximum lift coefficient was increased. Details about this second, inverse design approach are given by (Nangia et al., 2018). Table 2 shows the achievements of this second approach ("MULDICON Final Design") with respect to demanded maximum lift coefficients for the two most critical design points. It can be seen that the design target for the "Takeoff" point could be reached with the new design. For the other case "Combat High Altitude", the required lift coefficient (to fly with the specified load factor of 4.5) was reached, but not the target maximum lift coefficient (which is the required lift coefficient, increased by a safety margin of 0.1).

Table 2: Maximum lift coefficients of MULDICON compared to requirements

Flight case	Load factor	Required lift coefficient	Target maximum lift coefficient	MULDICON	
				Baseline	Final Design
Takeoff	1.5	1.0	1.1	0.84 – 0.96	1.11 – 1.14
Combat High Altitude	4.5	0.717	0.817	0.61	0.72

For the conceptual design studies, all three versions (reference configuration and the two new designs) were modeled and investigated in the conceptual design workflow. At this point it turned out that the first design is not yet usable as its generic airfoils incorporate too much camber (causing a strong zero-lift pitch-down moment) for a flying wing aircraft. Since there were no resources available to apply the leading edge design to a more suitable set of airfoils, this concept was not investigated further. Thus, the second design concept, which is the official final design from the ASG, is taken as main concept for the conceptual design studies (see Figure 4). The work of the Aerodynamic shaping Group as a whole is documented by (van Rooij and Cummings, 2018).

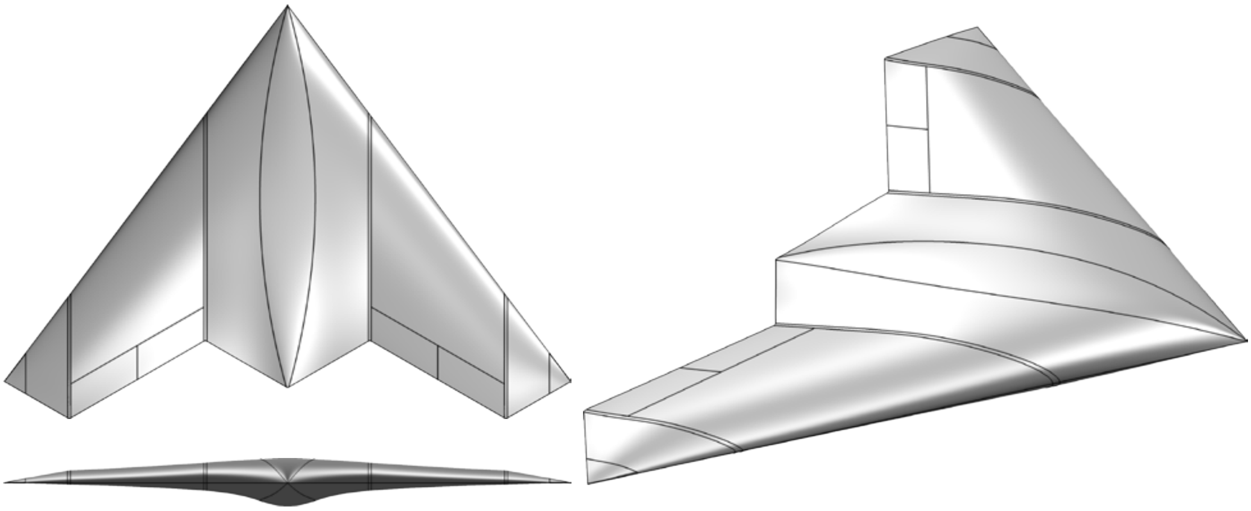

Figure 4: Outer shape of the MULDICON final configuration

3.2 Control Concept Group (CCG)

The second main task in the development of MULDICON was the design of a suitable control concept, which is discussed by (Löchert et al., 2018). After confirming that the conventional trailing edge devices for roll and pitch worked much better than they did for SACCON, the focus of this work was placed upon finding a solution for yaw control. As it was not clear at this point, how much yawing moment coefficient would be required, a target maximum value of 0.015 was chosen based on experience. In order to validate this value, an investigation with varying yaw control efficiency was performed by (Hasan et al., 2018) (Fig. 25, p. 27). Using the conceptual design workflow to simulate a landing maneuver with the maximum permitted crosswind of 30 knots, it turned out that a yawing moment coefficient requirement of 0.015 seems to be reasonable for handling this flight condition. A pair of split flaps at each wingtip was found to be a suitable concept for creating the required moments. The final control concept coming out of the Control Concept Group was applied to the MULDICON CPACS datasets.

3.3 Engine Integration Group (EIG)

Another important task was to provide an engine model which satisfies the engine design requirements, as specified in Chapter 2. This work was an additional contribution dedicated to AVT-251, in order to close a gap in the design capabilities of the group. Starting from a permitted fan diameter of 1 m, some engine design studies were performed. As it became clear, the fan diameter is still critical with respect to the integration of the engine and a corresponding intake and nozzle concept, a variation study for the fan diameter was performed. As a final result, a slightly smaller engine was selected and its performance tables were provided to the AVT-251 group. The engine design work and the sizing study are explained by (Zenkner and Becker, 2018). The main engine parameters are provided in Table 3. With respect to engine integration into MULDICON, several studies were performed by the Engine Integration Group. Due to limitations in time and resources, their final results could not be incorporated directly into the overall aircraft concept. However, their demands were considered as boundary conditions where possible. More Details on engine integration work for MULDICON can be found in References (Voß, Trost and Becker, 2018; Edefur et al., 2018; Aref et al., 2018).

Table 3: Parameters of MULDICON engine "UCAV_G"

Parameter	Condition	Unit	Value
Static thrust (dry)	*Takeoff*	*kN*	60
Bypass ratio	*Cruise*	–	1.7
Overall pressure ratio	*Takeoff*	–	30.5
Mass flow	*Takeoff*	*kg/s*	114
Turbine entry temperature	*Takeoff*	*K*	1 740
Specific fuel consumption	*Cruise*	*g/(kNs)*	23.8
Fan diameter	*all*	*m*	0.908
Length	*all*	*m*	2.2
Mass	*all*	*kg*	1 040

3.4 Structural Concept Group (SCG)

The structural concept of MULDICON was defined by the Structural Concept Group. Based on experience and Finite Element analyses, the main structural elements were placed and sized, and an estimate for the structural mass of MULDICON was given. A special focus had to be placed on the big cutouts due to engine and payload/weapon bays and on aeroelastic effects like body-freedom-flutter. Further details about the structural and aeroelastic design work for MULDICON are presented in (Schweiger et al., 2018; Voß, 2018; Voß, Schaefer and Vidy, 2018; Sakarya et al., 2018).

3.5 Design Specification and Assessment Group (DSAG))

Based on the results coming from the different design teams, the overall aircraft design work was performed at DLR. Using the DLR conceptual design system, a flexible concept design toolset being developed since 2005 (Liersch and Hepperle, 2011; Nagel et al., 2013), a workflow for MULDICON design and analysis was created. Details about this workflow can be found in (Liersch and Bishop, 2018).

One of the central elements of the MULDICON workflow is a spreadsheet containing the main components of the aircraft and a two-dimensional planform view including the CG limits (see Figure 5). Using this spreadsheet, the main internal components were arranged. As can be seen in the diagram, large components e.g. engine were placed directly. Smaller components such as avionics boxes, for which the geometric properties are not known at this stage of the design cycle, were placed in free areas, assuming that they will have sufficient space there. The filled circles within the components shown represent the CG of that component. It was a difficult, iterative procedure to arrange all the components such that they have sufficient space, while the CG positions for all 11 weight & balance cases under investigation were kept within the specified limits between the dashed red lines. The CG range from the center of the aircraft is further displayed in a magnified detail sketch on the right side. A mass breakdown of MULDICON, as calculated with the spreadsheet, is also provided in (Liersch and Bishop, 2018).

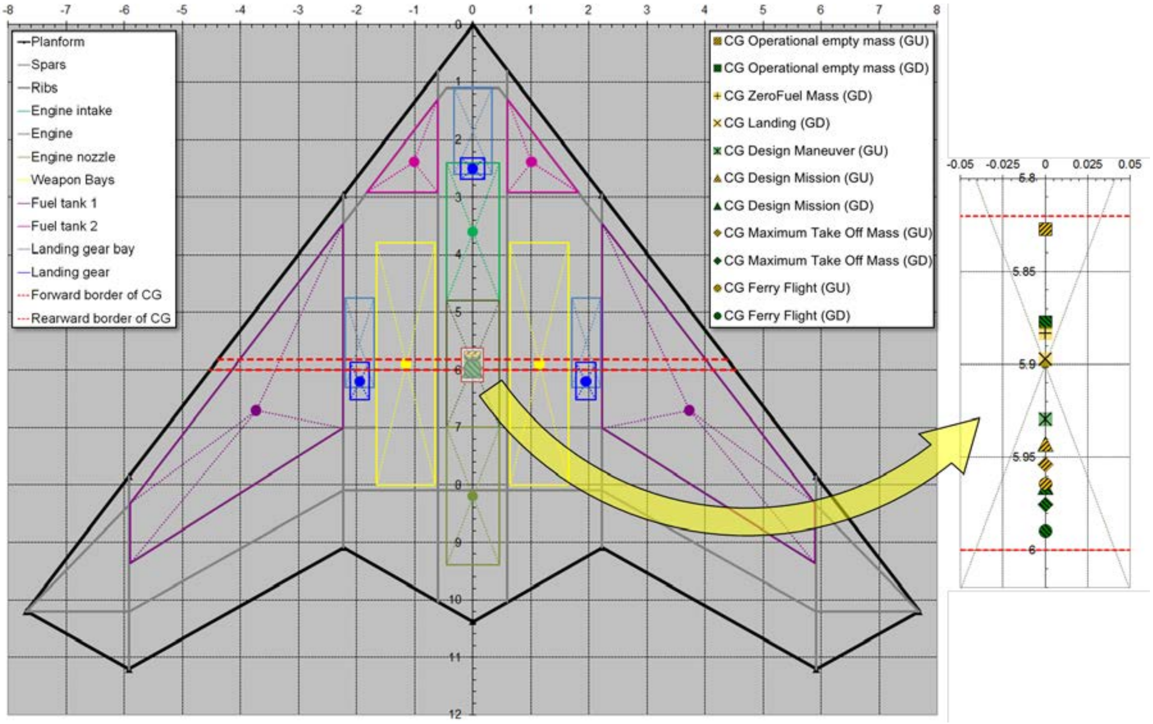

Figure 5: MULDICON planform with inner arrangement and CG locations

One drawback of the spreadsheet is that it only contains a 2D model of the inner geometry, whereas the thickness of MULDICON varies continuously over the chord. As a consequence, from this model it is not possible to sufficiently determine, whether a component really fits into the outer shape. As a solution to this problem, the spreadsheet was extended by a so-called “Design Table” for Dassault's CATIA CAD software (CATIA Homepage, [Accessed 09 September 2019]). Combined with an existing CAD model of the MULDICON outer shape, which also incorporates intake, nozzle and the control surfaces of the final control concept, the CATIA software uses the construction table to generate the inner components as specified in the spreadsheet. The CATIA 3D model of the MULDICON UCAV configuration with its main components is shown in Figure 6.

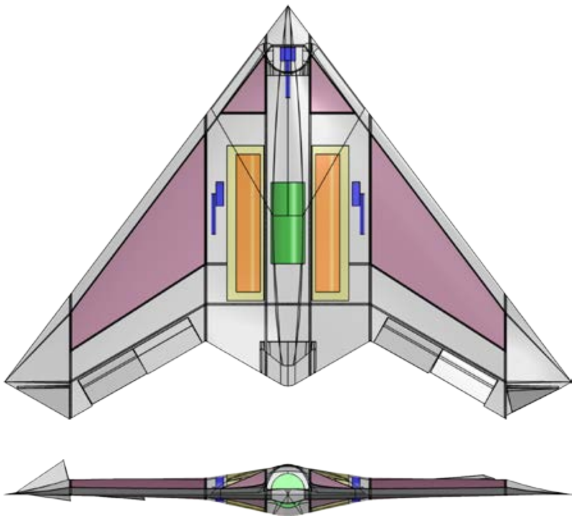

Figure 6: 3D model of MULDICON with internal arrangement

In the center of the convergence loop of the conceptual design process chain, the simulation of the design mission is located. After reaching convergence, the results for MULDICON final design show an operational empty mass of 6 767 kg and mission fuel mass of 5 341 kg. Together with a payload of 2 500 kg and a fuel reserve of 1 033 kg this leads to a MTOM of 15 641 kg. In **Figure 7**, the trajectory and some main parameters of the aircraft flying the design mission are plotted over the flight time.

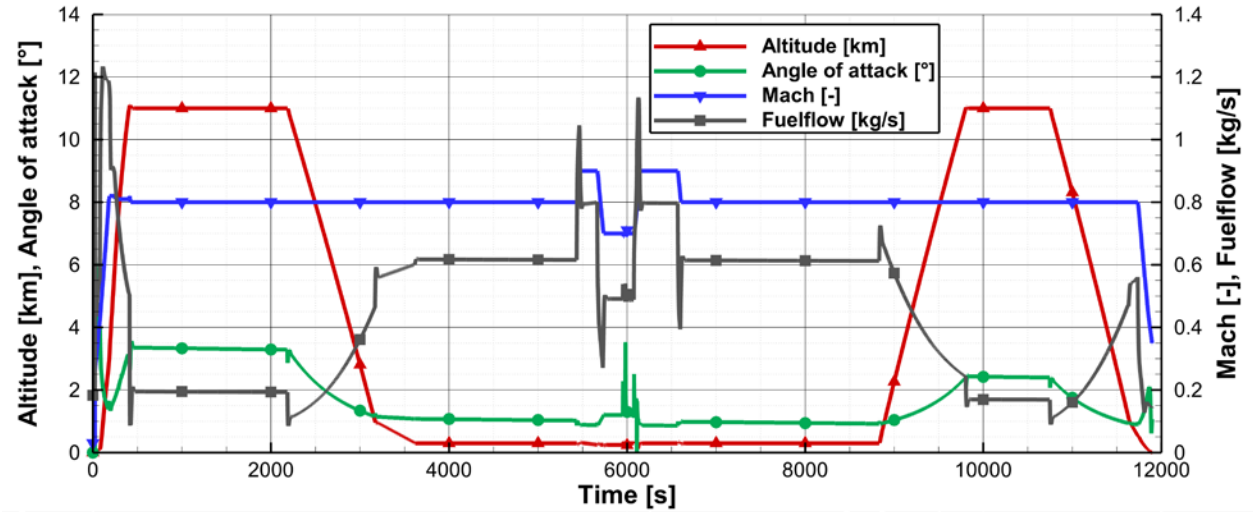

Figure 7: Trajectory of MULDICON, flying the design mission

After the end of the conceptual design workflow, a rather comprehensive dataset of the MULDICON configuration was made available, permitting further, more detailed investigations of the aircraft concept. One such investigation, which has not been published yet, was dedicated to flight performance and flying qualities evaluations. It shows that with respect to roll performance, the requirements for the “Takeoff” and “Combat High Altitude” cases could not be met sufficiently, while the other cases are within the specified limits. Furthermore, it turns out that the available thrust for the “Combat Low Altitude” case is not sufficient with respect to the sustained turn requirement – a consequence of the fact that there was not enough time to re-iterate everything between the design teams.

4 CONCLUSIONS

The foreground task of AVT-251 was to specify design requirements for an effective, agile UCAV, and then use these requirements to conduct a re-design of the SACCON configuration into a more realistic aircraft. In parallel, the background-task was to perform an assessment of how such a re-design could be performed within an AVT task group and how CFD could be effectively applied in such an early phase of the design process. Section 4.1 addresses the first question, while section 4.2 is dedicated to the second one. Finally, section 4.3 provides some conclusions drawn of the work being performed in AVT-251.

4.1 Design Task

As a first step, a set of design requirements was put together and agreed on with the contributing partners of AVT-251. These requirements were selected to be typical for such type of UCAV concepts, but highly ambitious with respect to the rather challenging SACCON configuration as a starting point. Due to the limited timeframe and resources it was not possible to work with a really comprehensive set of aircraft requirements. Instead, the demanded design targets were reduced to the most critical aspects and handed over to the various design teams. Next, a detailed design study took place with a number of aerodynamic shaping investigations. There were two distinct approaches that were followed by the Aerodynamic Shaping Group as they proceeded through the re-design: 1) design a new wing which was free of vortices during the mission. And 2) design a new wing which minimized the impact of the vortices on the aerodynamics of the vehicle. The enhancement of the SACCON concept had a number of specific goals, while still desiring to meet the mission requirements that had been applied to the original SACCON concept:

- Remove undesirable pitching moment characteristics
- Increase maximum lift coefficient
- Develop a control concept for sufficient roll, pitch, and yaw control
- Integrate an engine (intake & nozzle)
- Develop and size a structural concept, suitable for rigid and aeroelastic effects

After completing the various trade studies (including aerodynamic shaping and flow topology, structural layout and aeroelastics, as well as control concepts and flying qualities), a new configuration was found and named MULDICON. The biggest change in the planform was the new trailing edge sweep angle, which was greatly reduced compared to SACCON. It increased the internal volume, changed the CG locations, and made the control concepts more effective. A detailed engine installation study was also included as a last design detail, and while the engine inlets and outlets are still being improved, an acceptable design and internal layout was achieved for mission requirements and other constraints. Reviewing the results from conceptual design and the different design teams, it has been demonstrated that the mission and payload requirements could be met. Regarding the agility requirements for the specified design points it can be summarized that there were not enough resources to investigate all five design points to the necessary extent and that one of the selected aerodynamic design paths could not be followed up to its end. However, for the addressed points the requirements could be satisfied or at least be nearly satisfied. The pitching moment characteristics for both MULDICON aerodynamic design paths have been smoothed – at least for the required range of lift coefficients. The new control concept fulfils most of its requirements, even though the roll performance for The “Takeoff” and “Combat High Altitude” cases is still insufficient; just as the thrust for doing a sustained 4.5 g turn under “Combat Low Altitude” conditions. With respect to this, coupling the results from the assessment back to the design teams and performing another design iteration would have been useful in order to fulfil the requirements completely. With regard to structures and aeroelasticity, a suitable solution for the structural concept has been found and investigated.

All of these design trade studies were carried out within the 3 year time period of AVT-251. While done without additional wind tunnel testing, the studies were performed with a high degree of confidence based on the large amount of wind tunnel data that was available for SACCON, making the CFD studies trustworthy within regular aircraft design accuracy levels.

4.2 Assessment Task

As stated in section 1.2.1, the real task of AVT-251 was not to design a competitive vehicle. It was to find out how the early design process could benefit from the application of CFD methods and knowledge gained within the predecessor task groups. In order to answer this question, a detailed questionnaire was sent out to all participants of AVT-251 to obtain information about how well the task group operated, as well as basic information on time and computer hours that had been used to perform the work discussed in this paper.

Finally the questionnaire has been filled out by 22 participants of the task group, which represents slightly over 50% of the members, but includes most of the key personnel. The contributions of these members during the three years of AVT-251 (including the MULDICON design and analysis work, as well as attending the various task meetings and teleconferences) sum up to approximately 20 000 person-hours.

Within the ASG a total amount of 28.3 million CPU hours was used to perform the various CFD studies and analyses. In terms of how well the different design teams functioned overall, the average response from the questionnaire was quite positive (7.5)[15]. This was a very satisfactory result and showed that, overall, the members of AVT-251 found the methods of meeting and communicating fairly successful. The average answer to the question on the overall collaboration effectiveness on the design of MULDICON (across the team borders) was slightly lower (6.4), which could probably be explained by the missing time to perform more inter-team iterations to come to a consistent overall design in the end. However, based on the feedback from the questionnaire it can be stated that AVT-251 operated quite well and the results were interesting and satisfactory for a team that met for a total of three years under the constraints of an AVT task group.

4.3 Conclusions

AVT-251 was a natural follow-on task group to AVT-161 and AVT-201. While these two groups had concentrated on the aerodynamics of the SACCON configuration, AVT-251 had taken on the challenge of making the vehicle able to achieve specific mission requirements that were typical for an advanced, agile UCAV configuration. Design trade studies were conducted within the framework of multiple teams, including design, aerodynamics, controls, structures, and engine integration. These teams were able to re-design SACCON with respect to certain constraints and requirements and come up with an enhanced configuration named MULDICON, which already satisfies most of these requirements. All of these studies and design aspects were conducted within a group that lasted for three years, while only meeting in person twice a year. The details of the design studies were included in four special sessions at the AIAA Aviation 2018 conference held in June 2018, followed by a special issue of *Aerospace Science and Technology*. They are further published in the final report of AVT-251, which is currently in the publication process. The time and resource requirements of the study were recorded, as well as results of how well the task group worked and how effective the resulting design was able to achieve the requirements and constraints of the mission.

The major novelty of the AVT-251 design process is the fact that all the design work being performed was solely based on CFD (and other) simulations. During the extensive studies of the predecessor task groups, a great amount of experience on the shape of the developing flow structures, as well as on the correct application of modern CFD methods for such type of flow had been developed. Relying on this expertise and the corresponding confidence in the numerical results, the team members could perform a huge amount of different parameter studies in parallel – without the necessity to validate each single step by wind tunnel experiments. Even though this advantage cannot be quantified due to a lack of data for a comparable reference effort, it becomes obvious that a similar process incorporating extensive low- and high speed wind tunnel campaigns for a step-by-step evolving aircraft configuration (including control surface design and intake optimization) would not have been possible within a similar three-year task group.

So, this study represents a good example of how modern, well validated design and analysis tools can streamline the design process, as well as being able to come up with an enhanced configuration within a reasonable short period of time. The MULDICON configuration has similarities to a number of other modern UCAVs, and represents a predominantly satisfactory design that would have controllable flight characteristics at angles of attack that will make the configuration agile and capable of fulfilling more challenging missions.

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[15] On a scale of 1 to 10 (1 being extremely poor and 10 being excellent)

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