33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

ICAS 2022 SWEDEN

CONCEPTUAL DESIGN OF FUTURE MILITARY AIR SYSTEMS - AN EDUCATIONAL APPROACH

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Abstract

The development of a 6th generation fighter weapon system will exceed former ways of combat aircraft design, as it is understood as a system of systems, comprising a fighter aircraft, and in some way associated unmanned systems with effectors and sensors. This paper presents an educational and research approach for a systematic conceptual design of a 6th generation air combat system.

The key challenge of modern air combat systems design is to find a way to cover advanced technologies in the conceptual design approach and especially the various potentials of multi platform arrangements. Further the applicability of commercial conceptual design tools for such modern system air combat design has to be investigated.

The paper describes the re-projection of actual fighter aircraft to investigate the applicability of existing tools. It presents some experiences with special fighter technologies and their representation in the design. Eight different new concepts have been designed for specific missions to investigate similarities and differences. The paper concludes with a summarized experiences about the achieved designs and the use commercial tools. It gives an outlook to the next steps of work.

Keywords: Military Aircraft, Fighter, Future Combat Air System, FCAS, Aircraft Design, System of Systems

1. Introduction

Designing military or air combat systems is a very specific task, which requires a lot of knowledge in various disciplines far beyond classical aircraft design disciplines like aerodynamics or structural layout. Multiple sensors, communication systems and deployable payloads dominate the value of such a system. Typically, at universities, particularly in Europe, graduate students are educated in aircraft design looking at civil and especially passenger or transport aircraft. Such aircraft are operating in the subsonic flight regime and perform simple A to B missions. Economic efficiency is the key cost function for the design optimization. Further the payload, which is stored in the fuselage consists of passengers and cargo. Consequently, such aircraft are composed as a classical but very successful and efficient tube and wing configuration most.

Military combat operations are completely different to such transport missions and therefore mission efficiency in terms of assertiveness, survivability and availability are the key performance indicators, [6]. With the increasing importance and performance of radar and communication systems the value of modern 4th and 5th generation air vehicles is mainly defined by its command, control, communication, intelligence and interoperability (C^3I^2) capabilities, which are implemented into the avionics. The performance of these capabilities determine the successful use of effectors like electronic counter measures or weapons. Such air vehicles operate in a different flight regime and perform more complex missions than simple A to B missions. High speed, high agility, and operation in a wide range of altitudes and speed are typical characteristics of fighter aircraft. The payload of such aircraft has been stored in the past externally under the wings mainly. Since the 4th generation of fighter aircraft, like the F-117, survivability is more realized by low detectability using stealth characteristics, rather than by the performance capabilities of speed and agility to evade from threads. Here, in a first step radar absorbing materials (RAM), internal load storage and smooth surfaces provide low detectability. Today special shaping for stealth characteristics affects much more the overall conceptual aircraft design.

Other technologies like variable sweep wing, thrust vectoring, canards and externally attached payloads are typical features of military air vehicles, which might be considered in the conceptual design.

Also unmanned flying systems expand since nearly 20 years the design range of military air systems.

Further, disciplines about sensors, communication, effectors and others are relevant today for a good military combat aircraft design.

Most of those aspects are normally not taught at civil universities. Further, teaching aircraft design is mainly focusing on the conceptual design level, which is based on empirical and semi-empirical methods, which comprise statistical data and simplified physical descriptions. Mass estimation and geometrical sizing are the major disciplines in the conceptual phase, where flight physical performance estimations are based on simplified calculations.

There is no doubt, that current systems like the Eurofighter, Rafale or Saab Gripen will be in service also for about the next 30 years. Currently the development of the 6th generation air combat systems starts in many countries, also in Europe to replace the existing systems in the 2040, [1], [2], [3], [4], [5].

Figure 1 – Artist Impression of networked Future Combat Air System, FCAS, [Airbus]

The Next Generation Weapon System (NGWS) as part of Future Combat Air System (FCAS) is the German-Franco-Spanish project, which aims at new manned fighter aircraft and various unmanned Remote Carrier (RC) concepts, [4]. While Germany is mainly seeking for a replacement of the 50 years old Multi Role Combat Aircraft (MRCA) Tornado, France is looking for a successor of the carrier based Rafale M. Spain is interested in a next generation Eurofighter type aircraft.

In parallel England, Sweden and Italy teamed up to develop TEMPEST, a comparable multi role fighter weapon system, [5].

Figure 2 – The Tempest and NGWS concepts [theaviationgeekclub.com]

Despite any political, industrial and military interest in these projects at all sites, the actual European war situation enforces the need to strengthen the capabilities in research and develop of powerful airborne defense systems. While during the last 30 years after the fall of the iron curtain capabilities in airborne defense technologies have been reduced to a minimum in many countries, the current situation completely changes the scene.

Consequently, also at aerospace universities and others, human and technical capabilities have to be developed to serve research, industry and military with adequate competent resources in designing modern airborne weapon systems.

Being founded as a holistic aerospace research entity in 2007, the Institute of Air Transportation Systems at the Hamburg University of Technology has started its education and research on airborne special operations and military systems based on more than 20 years industrial and governmental experience in this field.

The goals are

- Teach graduate students in multidisciplinary airborne systems architectural design from a holistic system of systems perspective
- Investigate, expand and improve commercial conceptual aircraft design tools according to modern military air vehicle design capabilities, e.g. for variable wing sweep, radar and sensor integration, thrust vectoring, etc.
- Develop and be a sparring partner for new combat air vehicle concepts to inspire industry and government to reflect current designs
- Assess new combat air systems architectures in simulated realistic operational environments

In the following the approach to achieve these goals and some results are presented and discussed.

2. Designing Military Combat Air Vehicle

In the past single fighter aircraft had been mainly developed for particular military missions, and later on its capabilities had been extended to further roles. Due to a complete change of military scenes towards asymmetric combat scenarios and the permanent increase of development and life time cost, future air combat systems have to have multirole capabilities from the beginning. While, e.g. F-15 Eagle or Tornado and Eurofighter, as single flying platforms, were designed to a core mission and further mission capabilities have been added, the Next Generation Weapon System (NGWS) composed of various manned unmanned platforms has the intrinsic capability of aquivalent multi role features.

The 6th generation air combat system will exceed these previous fighter configurations in developing a system of systems as a bundle of air, ground and space entities.

This requires a completely new approach in the design thinking and much more operational and interdisciplinary knowledge of the involved people.

On the other hand, most of the experienced engineers of the Tornado, Eurofighter or Rafale programmes retire and a lot of key knowledge is passing away.

Therefore, young graduate students must be well educated and trained to fulfil the upcoming challenge and fill the gap in industry, airforce and government for the successful development of an efficient future air combat system. Also, on governmental side well educated air combat systems engineers are needed to manage the requirements, control and assess the results.

The baseline of a good air combat system design is a full military operational understanding of the mission, which in military operations is addressing

1. Air to Air
   - Point Intercept (PI)
   - Air Superiority (AS)
   - Combat Air Patrol (CAP)
   - Air Defense (AD)
2. Air to Ground/Sea
   - Interdiction Strike (IDS)
   - Counter Air (CA)
   - Close Air Support (CAS)
   - Naval Strike (NS)
   - Maritime escort (ME)
3. Reconnaissance

The following figure shows the Interdiction Strike mission profile as an example, as it was defined in the design campaign, [18]. The flight profile shows a high altitude efficient approach and return cruise, while the weapon delivery phase is flown at very low flight level, using the ground surface for low detectability.

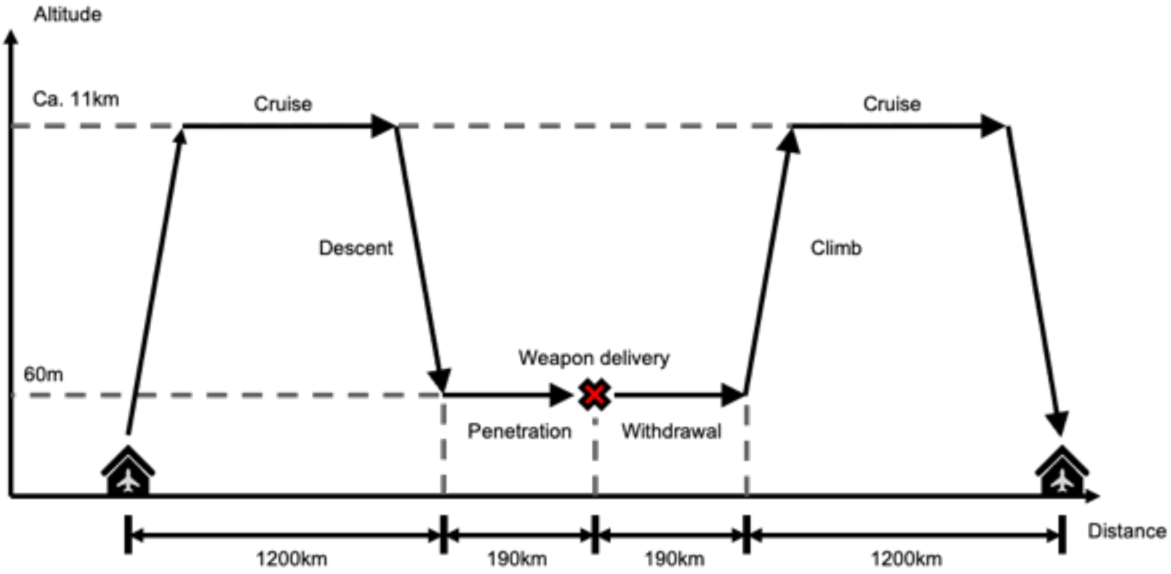


Figure 3 – Example of a typical military mission, here Interdiction Strike, [18]

There is no doubt, that the accurate formulation of requirements for these missions is very sensitive. For education and basic research activities rough quantitative descriptions are sufficient to investigate basic orders of magnitude and behavior. Also, only little public literature is available in this field of military mission description and design, e.g. [6], [12]. Most literature is of popular scientific type and not yet state of the art, e.g. [7], [8].

In order to achieve the key performance indicators of modern combat air systems in terms of

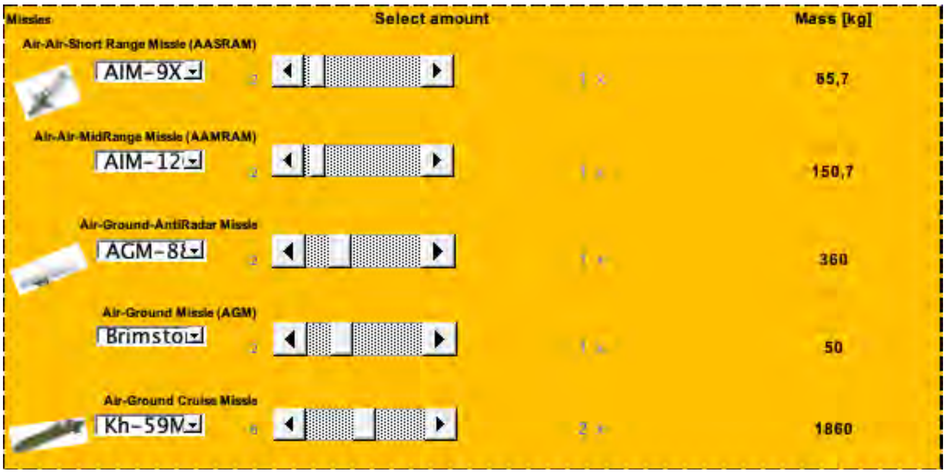
- Assertiveness (achieve military task target)
- Survivability (return without significant loss) and
- Availability (being all the time ready for mission)

it is no longer a single vehicle but a bundle of networked flying entities, which have to be considered. This is today called “System of Systems” (SoS).

Based on the mission tasks such a NGWS SoS has to perform a very first design task will be the allocation of mission capabilities to different entities. Here the system boundary for the conceptual design is set to the manned and unmanned flying air vehicles, while satellites, Airborne Warning and Control Systems (AWACS) or combat clouds and others are interfacing with information provision from beyond.

A further important system boundary in combat air systems design at civil universities is associated to weapons, which cannot be considered in detail with their special characteristics. On the other hand, mass, size and range of those affect mainly the air vehicle design. These parameters are considered in the design approach only for defining the mission range of the air vehicles, payload mass and the store geometry. Another important general information about weapon is its stand-off capability. Stand-Off capability means, after weapon launch it follows automatically and self-controlled the target either in the air, on sea or on ground. However the fighter crew is all the time able to redirect or shut off the weapon. The stand-off capability reduces the risk for the fighter crew and can extend the operational mission range also beyond the visual line of sight (BVLOS).

To cover at least those principle characteristics in the design process the weapon and equipment data base CASiMiR has been elaborated to establish a base line for realistic data.



Missles	Select amount	Mass [kg]
Air-Air-Short Range Missle (AASRAM) AIM-9X		85,7
Air-Air-MidRange Missle (AAMRAM) AIM-12		150,7
Air-Ground-AntiRadar Missle AGM-8		360
Air-Ground Missle (AGM) Brimsto		50
Air-Ground Cruise Missle Kh-59M		1860

Figure 4 – Extract of the weapon and avionics data base CASiMiR, [9]

In this data base about 60 different weapons are stored with the major parameters needed for the air vehicle system design. In addition, for radar systems and electronic counter measures data like e.g. mass, antenna size, field of view and range are available e.g. for actually about 12 different radar systems.

This database also checks, whether envisaged equipment and weapons can be integrated, depending on geometrical parameters like weight or size. But, also the origin of equipment is a criterion, since equipment e.g. of Russia or China cannot be integrated easily in European or US aircraft and vice versa.

Although available data in this field is not always accurate, for conceptual design the level of accuracy has been found sufficient and useful.

As a further baseline a detailed analysis of actual and past fighter thrust-weight-ratio and wing load data has been performed for setting initial design data, [9].

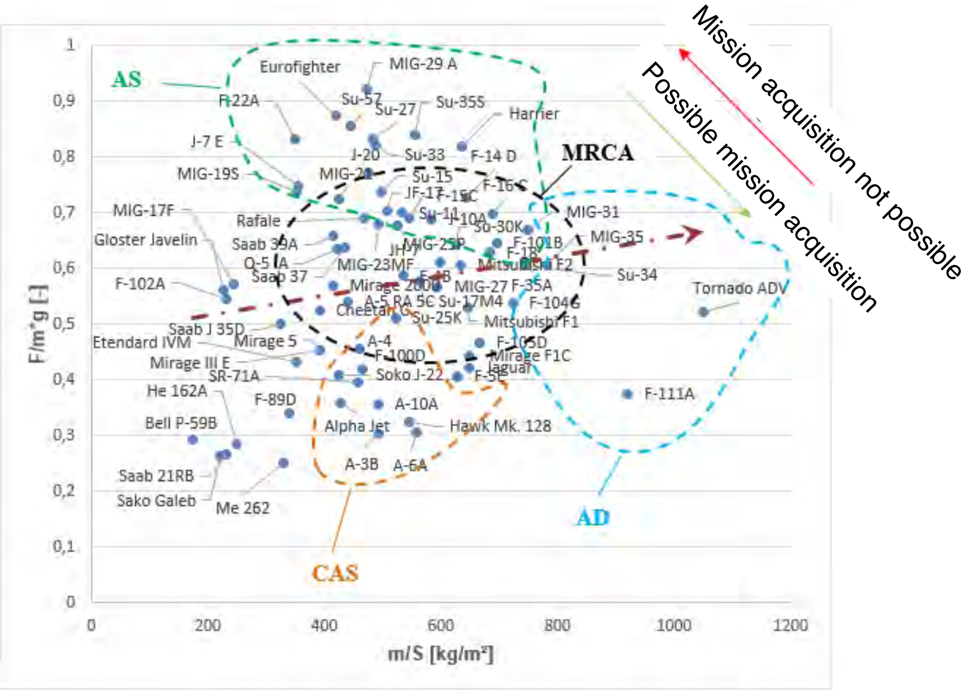


Figure 5 – Thrust-weight-ratio and wing load of actual and past fighters, [9]

This overview has been further focused on typical missions like Close Air Support (CAS), Air Superiority (AS), Multi-Role (MR), etc. to indicate, which are adequate starting values for future designs. Depending on the thrust-weight-ratio air superiority vehicle are able to perform also CAS or MR missions, while the capabilities of the vehicles in the opposite direction are limited.

The major key performances of assertiveness and survivability can be adapted to the opponent air defense capabilities e.g. by physical vehicle performances like agility and flight regime or by technologies like stealth and sensor/effector characteristics. For example a high speed low level flight profile can be also an efficient capability for low detectability as an electromagnetic wave absorbing coating or stealth geometry. Therefor it is essential for the design of modern air combat systems to understand the impact and capabilities of such different operational or physical solutions, which may lead to different layouts. Because modern systems will more rely on stealth capabilities rather than low observable mission profile for this research campaign the max speed of the air vehicles shall be defined in the range of $1.2 < Ma < 1.6$. This is lower than before because it is more energy efficient and low detectability can be contributed by stealth features.

A last general design consideration is dedicated to the perspective of manned-unmanned combined formations. The introduction of unmanned air combat vehicle has opened a complete new perspective of operations. Unmanned air vehicles (UAV) in the context of future air combat systems are understood as escorting vehicles teamed with a manned fighter aircraft, which guides the UAV. Those UAV are also called “loyal wingman”. They are intended to carry various weapons and/or sensors depending on the mission. For the design of a future air combat system this configuration

- Decreases the risk for the manned system, since the unmanned
  - Extends the mission range of an air combat system
  - Covers a wider operational combat area
- Increases the functional and payload capabilities of an air combat system
- Are reusable
- Carry payload in size and mass comparable to manned fighter capabilities

Therefor a principle design setup for future combat air systems is always a formation of manned-unmanned systems independent of its final configurations.

Figure 6 – Principle formation set up of a future air combat system, [20]

This provides more degrees of freedom in the design, because required mission functions can be allocated and distributed to more entities. Despite the larger “loyal wingman” type of UAV also smaller ones in the size of cruise missiles are actually in discussion, often called “expendable remote carrier” (eRC). They are mainly considered for as sensor or light weapon carrier, which may be used once only and could be launched from ground or by other carrier like air, sea ground vehicle.

2.1 Requirements and design approach

As mentioned above there are many military missions with a broad variety of requirements for a successful fulfillment.

In order to systemize the design process and to cope with this broad field it was decided to start the process with a parallelized mission specific layout according to the Eurofighter Air Superiority (AS) mission, the Tornado fighter bomber Interdiction Strike (IDS) mission, the Rafale M aircraft carrier (AC) mission and a Cruise Missile (CM) mission for an unmanned system. For this purpose a student team of four graduate students was tasked to develop the different concepts.

A second aspect of the design approach and the project goals addresses the use of the tools. There many proprietary and commercial conceptual aircraft design tools around the world, and because the design methodology is the prime focus of the project in a first step existing tools shall be used. Among the Darcorp Advanced Aircraft Analysis (AAA), Raymer RDSwin and Pacelab Aircraft Preliminary Design (APD) the later one has been chosen for the first design campaign, [15], [16], [17]. All these tools, but also proprietary ones are based on the fundamental work of Egbert Toorenbeek, Jan Roskam and Daniel Raymer, [12], [13], [14]. Many of the equations are derived from empirical approximations with aircraft data of the seventies to nineties, but all these tools are worldwide well verified and accepted. In Pacelab there are model templates of Eurofighter, F-35 and F-16 fighter aircraft available. They have been used and were combined with various publicly available data to setup own models of Eurofighter, MRCA Tornado, Rafale and XQ58A.

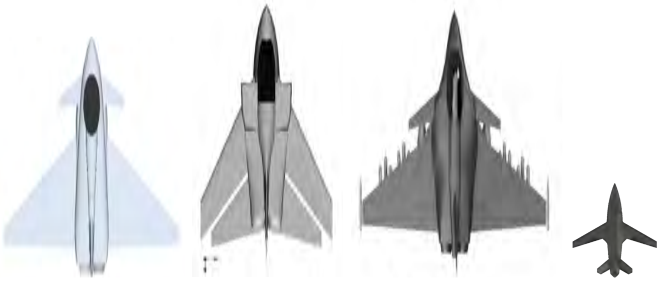


Figure 7 - Overview of the Pacelab based re-projected reference aircraft Eurofighter, Tornado and Rafale, XQ58A, [21], [18], [20], [22].

The workflow for using Pacelab SysArc/APD in this campaign is as follows:

1. load an existing aircraft from the Pace library or create a new one
2. modify the aircraft according to the needs
3. define a payload configuration
4. define a sizing mission
5. analyze aircraft
6. optimize aircraft

Concerning the requirements, a mission description table has been created, where equipment performances, vehicle performances and payload have been described for each mission. The subsequent table provides an exemplarily view in the data contents.

		Missions				
		Defense of air targets (aircraft, missiles, UAV)		Attack of ground based stationary targets (bunker, missile launcher, air bases, plants, communication systems, etc.		Attack of fast moving mobile armed groups
Capability	**Mission Phase**	**Defense Counter Air**	**Offensive Counter Air**	**Air Ground Attack**		
				Strategic Air Ground	Interdiction Strike	Close Air Support
Qualitativ/functional						
Beyond Visual Range Engagement		x				
Ballistic Missiles Engagement		x	x	x		
Sensors/effectors						
Performances						
LRAAM		>50	>50			
AGM				<50	<50	<50
Cruise Missle				>500	>500	>500
ECM-Pod				>100	>100	>100
Payload mass per piece [kg]						
external fuel tank	A-C	0	1800	1800	1800	0
SRAAM	A-F	90	90	90	90	90
MRAAM	A-F	120	120	120	120	120
Cruise Missle	A-E	0	0	1500	1500	0
ECM-Pod	A-F	0	250	0	0	0
Bombe	A-E	0	0	500	500	100
Mehrzweckeffektor	A-E	0	0	5000	5000	5000
Radar		120	120	120	120	120
Required Power per Piece [kW]						
Radar		0,2	0,2	0,2	0,2	0,2
ECM-Pod		0	10	10	10	0
Weapon control		0,1	0,1	0,1	0,1	0,1
Flight Performance						
Take Off field length [m]	A	<500	<500	<1500	<1500	<1500
climb/descent	B					
Operational range [km]	A-D	1000	1000	2000	2000	1000
Combat radius [km]	D	360	360	150	250	250
Withdrawal range [km]	F	1000	1000	2000	2000	1000

Table 1 – Extract of the Mission requirements data base

Based on the mission requirements definition the design of the new concepts has been performed.

2.2 Re-projection of existing fighter aircraft

As an example of the re-projection process the design and results of the MRCA Tornado are presented, [18]. For the IDS mission the Tornado was loaded with 3 GBU 48, 2 AIM 9L, 2 1500l external fuel tanks, 1 laser designator pod, 1 Sky Shadow 2, 1 Ejection Unit BOZ 107, which lead to 4650kg mission payload. The mass estimation has been performed following the approximations of Raymer resulting in an empty mass of 14200kg. The fuel calculation shows an overall fuel mass of 8208kg including 2400kg external fuel mass.

Due to its good accuracy in terms of geometry, mass and performance calculation the F-16 template was chosen as the baseline to create the Tornado model. For the wing layout a NACA 64210 supersonic profil was selected, following a proposal from [23].

This re-projection includes also the modelling of a variable sweep wing, which is modelled in such a way, that it is modelled only as fixed wing sweeps during defined mission phases. This approach was chosen, because a direct modeling of a variable sweep wing is not possible in Pacelab.

For the interdiction strike mission, the mission profile has been built as two separate flights as in figure 7.

The “Dummy”-elements represent in each mission the fuel consumption of the other flight regime. “Drop”-events incorporate the rapid payload loss, while “Penetration” is low level flight with and “Withdrawal” is low level flight back without payload.

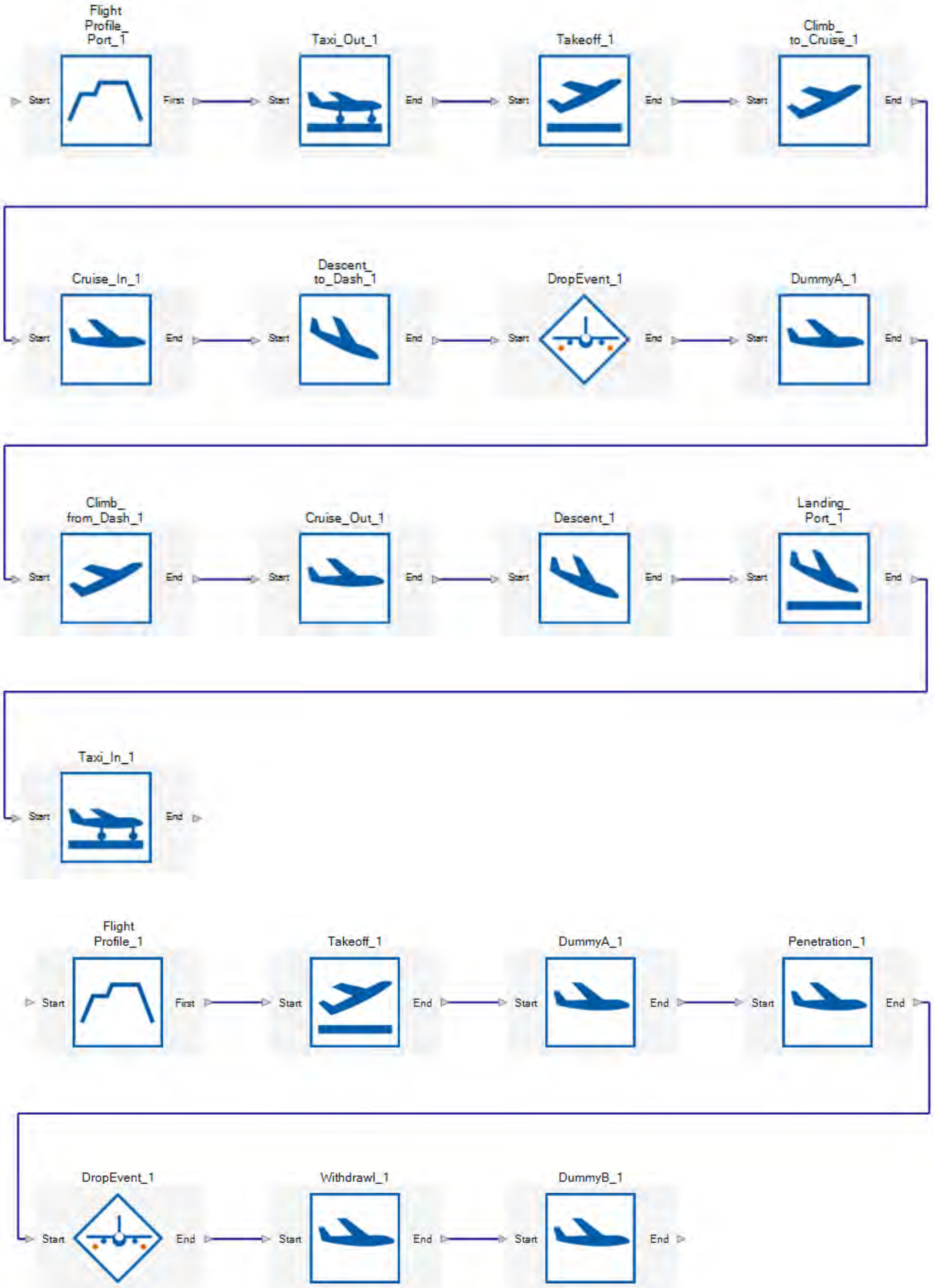


Figure 8 – Tornado IDS mission profile with 25° (top) and 67° (below) wing sweep

Further impact of the variable sweep wing technology in terms of additional structural mass and additional system mass of the wing kinematics but also additional hydraulic power is actually not reflected in the model, because no calculations and data are available. Also, a change of drag and lift due to the difference sweep angle is not yet part of the model in Pacelab APD. However, the APD performance calculation reports about 53% frictional drag, 42% induced drag and about 5% wave drag for the overall drag during the IDS mission profil.

	Literature reference	Re-projection	Difference
Range IDS-Mission	1.390 km	1.280 km	-8 %
Ferry-Mission	3890 km	4083 km	+5 %
Empty mass	14100 kg	14305 kg	+1%
Overall take off mass	27200 kg	24763 kg	-9 %

Table 2 – Verification of re-projected Tornado configuration

The re-calculations of the Tornado model, which has not been developed before, show a good compliance with literature references for the conceptual design level, although the overall take off mass is about 9% lower than given in the literature, [19]. This is remarkable, since the previously mentioned deficiencies in variable wing sweep modeling obviously affect the mass calculation. On the other hand, the two step mission profile modeling leads to good approximations of the fuel consumptions and mission length.

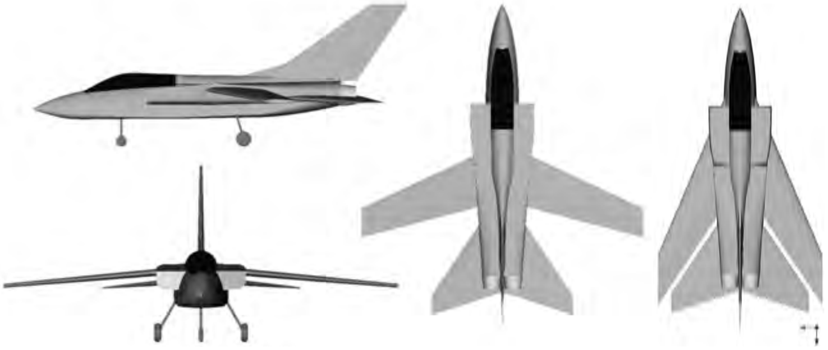


Figure 9 – Redesigned MRCA Tornado aircraft with 25° and 67° wing sweep

In a similar way re-projection configurations of Eurofighter, Rafale-M and the XQ-58A Unmanned Combat Air Vehicle (UCAV) have been developed, [20], [21], [22].

For the re-projection of the Eurofighter and the Rafale M, the Pacelab Eurofighter template was used as the initial starting point, and the sizing of the canards became a special issue. Canards are not jet covered in the aerodynamic lift and drag calculation, but are only reflected in the mass analysis with about 176 kg for Eurofighter. Especially for low speed high agility dogfight canards shall be considered for induced drag and pitch and roll maneuverability. Also the range of instability is affected by the simplified canard representation since it is only 5,5% in the model instead of around 15%, [21].

In case of the Rafale M catapult take off and arrested landing capabilities are not yet possible to calculate. For this campaign carrier operations have been only considered by an additional weight factor derived from public data analysis of 660kg, which represents the structural re-enforcement, but also the modified landing gear and the catch hook, [20]. The take off lift L_{TO} is calculated from

$$L_{TO} = \frac{\rho}{2} \cdot (v_{end} + v_{wod} + \Delta v_{thrust})^2 \cdot C_{L_{TO}} \cdot S \ (1)$$

Here, according to Raymer, the relevant speed is composed of the catapult speed at the end of the acceleration phase v_{end}, the wind over deck speed v_{wod} and the speed produced by the aircraft thrust v_{thrust}, [16]. Further, the take off and landing conditions, that means the interface between the carrier and the air vehicle are also determined by the landing and take off mass and the associated speed. That means in fact, the heavier the air vehicle the low the speed has to be in these phases, if there is a limited energy of the catapult and the arresting system.

At last the re-projection of UCAV was one of the greatest challenges, since no real reference is available. The Kratos XQ-58A Unmanned Aerial Vehicle has a relatively similar shape as a conventional aircraft and war re-projected on the base of the F-16 aircraft template in Pacelab, [22].

Figure 10 – Kratos Unmanned Aerial Vehicle XQ-58A, [22]

Due to the size and shape of the vehicle it is also a good representation of the required heavy UCAV for the overall research study.

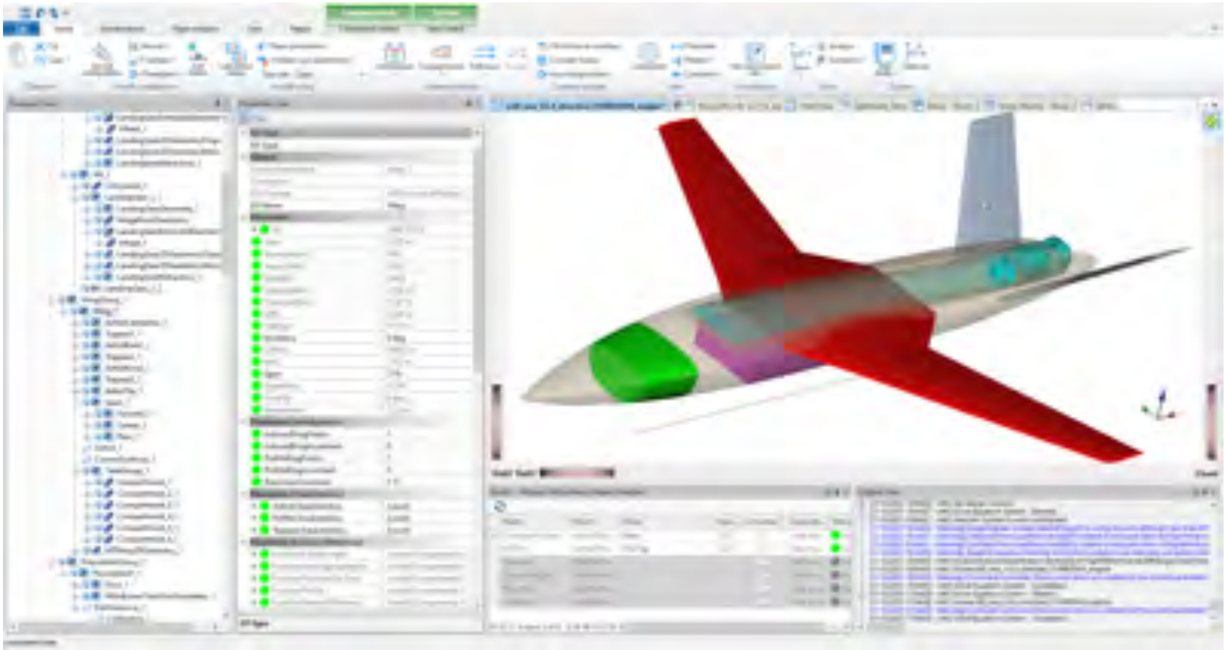


Figure 11 – Pacelab SysArch representation of the XQ-58A, [22]

The model of the XQ-58A implemented in the Pacelab SysArc environment shows a good coherence for the conceptual design level.

XQ-58A	**Reference data**	**Pacelab data**	**Difference**
Empty weight	1134 kg	1228 kg	+94 kg / + 8 %
Max. Range	~5556 km	6223 km	+667 km / + 12 %

Table 3 – Re-projection results of the XQ-58A UCAV, [22]

For a smaller RC type the Taurus KEPD was adapted, [22]. According to the ongoing design approach in industry this expendable RC is defined as single use vehicle, which is able to carry 2 IRIS-T missiles including launcher of 125kg each. The idea behind this design is to bring such an unmanned vehicle closer to the target and to multiply the weapon payload capacity of the entire weapon system.

	Concept Pacelab	**Taurus KEPD**	
T/W (MTOM)	0,47	-	
W/S (MTOM)	544 kg/m²	-	
Length	5,5 m	5,1 m	
Width Span	1,1 m 5 m	1,1 m 2 m	
Mass	1145 kg	1450 kg	
Payload	254 kg	495 kg	
Range: LoLo Max HiHi MRC	 816 km 1770 km	>575 km	

Table 4 – Comparison of Taurus KEPD and new defined eRC concept, [22]

Table 4 shows the comparison of the projected eRC and the Taurus KEPD data as an orientation. This was done to get a first baseline for future eRC designs of a comparable size. The concept layout shows, that Pacelab is in general able to compute such vehicle with logical results. However, it is considered as a first starting point. For future activities, the institute will create own empirical approximations to achieve better results in a preprocessing activity for such vehicle. Since single use concepts are assumed to be a waste of resources and cost a lot of money, the next concept will be defined as a multiuse vehicle with robust landing capabilities.

2.3 Designing new mission specific concepts

Oriented to the reference mission profile for the design of the new concepts some general considerations lead to the rough configuration baseline:

a) Which technologies can be in principle considered, e.g. thrust vectoring, stealth shaping, low detectability flight profile, …
b) Define the required radar antenna diameter, which determines the fuselage cross section
c) Define the required payload volume and weight and define internal and external storage based on the weapon, avionics database CASiMiR
d) Allocate functions (sensors, weapons) to fighter aircraft and remote carriers to define their roles
e) Remote Carrier are defined as being reusable with take off and landing capabilities
f) Choose initial wing form and sweep and define the parallel edges of the aircraft shape to achieve maximum diffusion of the reflexions. 45° would be here a good starting point.

This aforementioned design approach will be exemplary presented for the conceptual design of two carrier based concepts, which have been defined in the research campaign, [20].
The baseline mission is defined as in figure 12 as a multirole air/sea to ground mission.

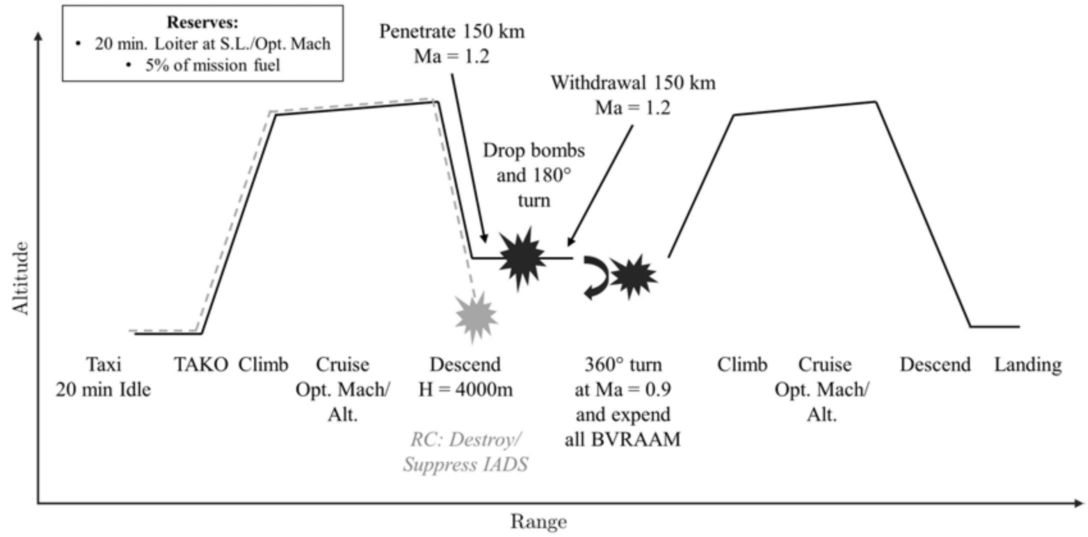


Figure 12 – Multirole Air/Sea to Ground Reference Mission, [20]

The RC considered for this mission are defined as a heavy (“loyal wingman”) and a small RC (“expendable RC”). The first, being similar to an unmanned fighter, is equipped with air-to-air, air-to-ground, electronic warefare and reconnaissance effectors and equipment and will start from a carrier catapult and may land with an arresting hook. The second one will carry specific weapons or sensors and shall be launched also by a catapult. Also, both systems are defined to operate in different speed and range regimes as shown in table 4.

	Network 1 "Heavy Strike Group"	**Network 2 "Light Strike Group"**
Takeoff and Landing	CATOBAR	NGF: STOBAR RC: Catapult launch platform
Remote Carrier	heavy, supersonic MTOM: 10-15 tons "Loyal Wingman" reusable	lightweight, subsonic MTOM: 1-3 tons "Loitering Munition" disposable
Payload	NGF: min. 2000kg RC: ca. 1000kg	NGF: min. 1000kg RC: ca. 400kg
Cruise Range	min. 2000 km Multirole Mission	NGF: min. 2000 km, RC: min. 1000 km Multirole Mission, SEAD
Teaming	1 NGF, min. 2 RCs	1 NGF, min. 4 RCs

Table 5 – Multirole Sea/Air to Ground System of Systems definitions, [20]

For such a system of systems design it is essential to understand from top to down the overall system capabilities.

The Heavy Strike Group is defined for longer distance and higher payload to attack ground or sea threats. The Light Strike Group is composed of various smaller weapon or sensors.

In the training of the design process the key challenge is to allocate and balance the capabilities, size and performance of the manned and unmanned system elements. At the end such a system of systems design is the design of at least various combat air vehicles at once. One result of this approach is the large command air vehicle for carrier-based operations, called “stingray”, which is the central vehicle in the “heavy strike group”.

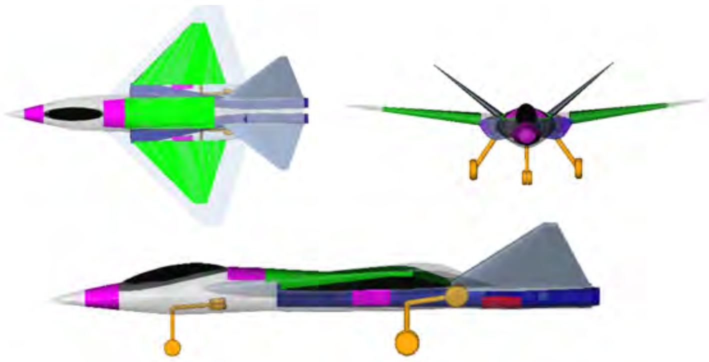


Figure 13 - 3 side view of the “Stingray” carrier-based command aircraft (Green: fuel tanks, magenta: avionics, red: flares, blue: propulsion, orange: undercarriage)

The vehicle is consequently composed by the inside out approach first considering the weapon bay defined by a selection of weapons taken from the CASiMiR data base. Second the radar antenna diameter was estimated to determine the required cockpit nose cross section. At last the propulsion system including the duct was defined and the landing gear housing was defined. Around all this the fuselage shape was built. The tail configuration and the edge shape were defined according to the stealth angular reflection rules. Based on the configurational definition the overall layout and performance analysis was performed with the Pacelab suite, leading e.g. to the flight envelope as shown in figure 14.

The entire envelope shows a logical and realistic shape. The kink on top of the envelope is an often recognized numerical error in the Pacelab software, which is using the “Brent´s method”, calculating only the first instead of the best optimum in this operational point. After some adaptions especially of the thrust to weight ratio and the wing loading, the cruise range target was only slightly missed, while the rate of climb at one engine inoperative was clearly missed as shown table 6

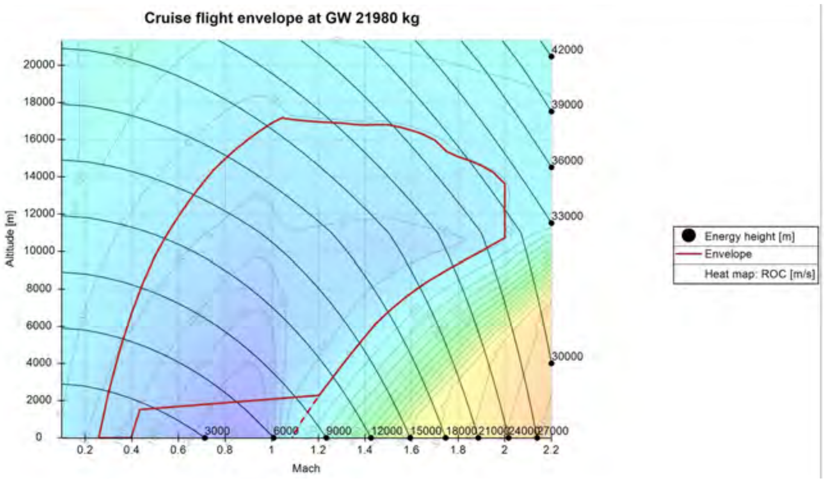


Figure 14 - Flight envelope of the “Stingray” carrier-based combat aircraft layout, [20]

Requirement	Target	Current	Deviation absolute	Deviation percentage [%]
Performance				
Cruise radius [km]	1000	920	*-80*	-8
Max. mach number [Ma]	1.8	2.0	+0.2	+11
Maneuvre Performance				
Inst. Turn Rate [°/s]	12	16.9	+4.9	+41
Acceleration time [s] to Ma 1.5 and 13000 [m]	180	87	-93	-52
ROC [m/s]	160	>340	+180	+113
Carrier Suitability Requirements				
OEI ROC [m/s] at landing mass: 24980	2.5	4.6	*+2.1*	81

[kg] and approach speed: 59.4 [m/s]				
Aircraft planform [m × m]	21.27x15.85	21.27x14.3		
Landing gear width [m]	<6.7	4.3	-2.4	-36
Maximum ramp mass [kg],(Elevator limit)	36287	33997	-2290	-6
Wing span [m]	<25	14.3	-10.7	-43

Table 6 – Design parameter fulfillment of the optimized Stingray fighter concept

As an alternative solution the Sea Eagle concept has been developed as a light weight single engine fighter, which can be operated also on smaller carrier with 182 m take off distance and a lower landing safety factor of 10%.
The resulting Sea Eagle configuration is shown in figure 15for comparison.

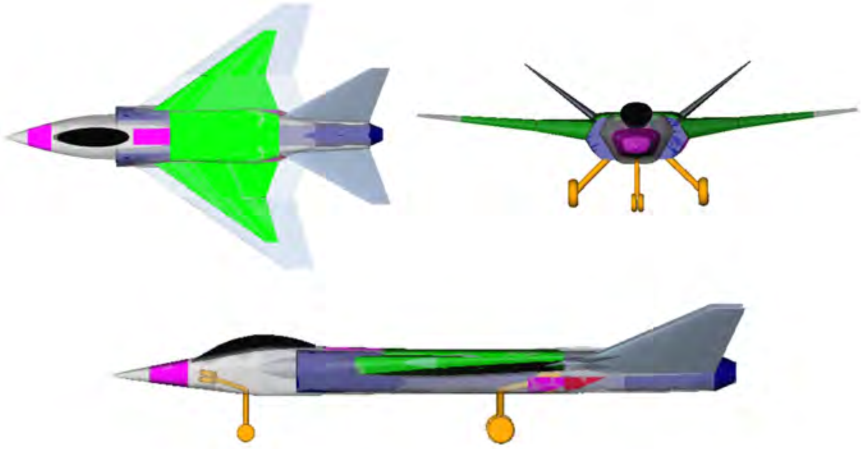


Figure 15– Alternative Sea Eagle concept aircraft

The Sea Eagle was designed in the same way as the Stingray concept but with more functions located to the Remote Carrier. It is more compact and will be equipped mainly with self-protection and self-defense systems, while mission equipment is allocated to the Remote Carrier.
Because for all these investigations no reference data are available, plausibility was checked by comparison with existing aircraft. Here figure 15 shows, that the thrust to weight ratio of the designed concepts complies quite well with the size and performance of F-35 for the Sea Eagle. The Stingray concept shows higher values than the Rafale M, also because of its larger size.

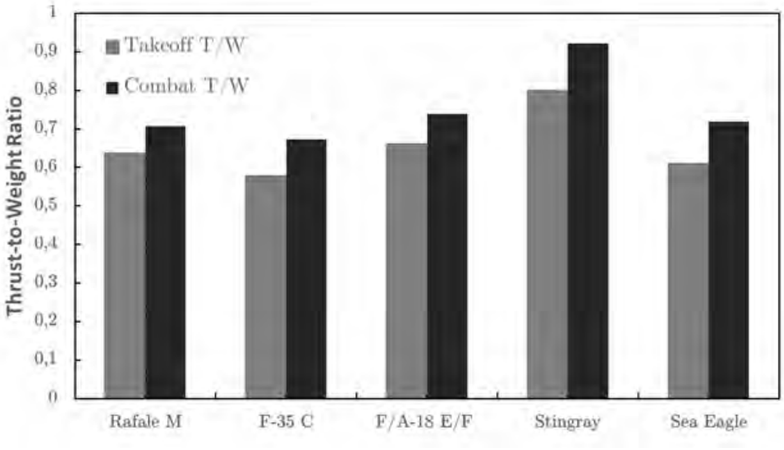


Figure 16 - Comparison of the carrier-based design with existing aircraft

3. Discussion of the findings

The purpose of the research campaign being presented is to

- develop an approach for defining new air combat systems concept definitions.

- Investigate how a next generation combat aircraft may look like if a 1:1 mission specific replacement of the precessor taking into account advanced configuration technologies
- define and design a layout of two in general different designs for each mission aircraft
- consider remote vehicle as part of the entire system
- the capabilities and usability of commercial conceptual design tool for military air systems

The previous descriptions of the various concept developments show, that the Pacelab Suite is in general appropriate to define and configure future air combat systems, if a structured design logic is followed.

Nevertheless, some shortcomings of the selected tool are obvious in the accuracy of the modeling capabilities of military air vehicle technologies, which only can be covered by simplifying workarounds. As a conclusion some additional pre- and postprocessing tasks, e.g. the radar antenna diameter and mass sizing have to be done before starting the tool chain.

The resulting design data also show some significant deviations and inaccuracies which limit the applicability of a commercial tool for such design campaigns. Further on, the consideration of state changes like payload drop or wing sweep change requires the introduction of additional dummy flight elements, which calculate an adapted fuel flow and change in mass.

Special aircraft technologies like thrust vectoring, variable wing sweep or payload drop are not simple to model. STOL and VTOL capabilities by directing thrust should be also available. Also, an automated stealth design should be implemented. Tailless designs cannot be realized, which limits the design space. Catapult take off and arrested landing are difficult to model. For the aerodynamics a better calculation to assess the wave drag through the area rule would be of advantage. Also control surfaces, like canards shall not be considered by additional weight but also in the lift, moment and drag balance.

Working with a commercial tool requires best transparency about the applied physical descriptions in the calculation workflow. The overall results show reasonable results, but due to the observed curiosity of some results the trust in the calculation method is not always given. A lot of own literature research is needed to check the correctness of the implemented equations. The team work of the design team compensates a lot of this verification effort. More model verification is needed to strengthen the created model base for future research.

On the other hand creating a student design team to perform such design tasks was a very efficient approach, because they gain a lot of knowledge about the required equipment and design features.

Also, this was an efficient setup to create quick a good model baseline for future investigations. Out of the four initial re-projections eight new concepts have been designed.

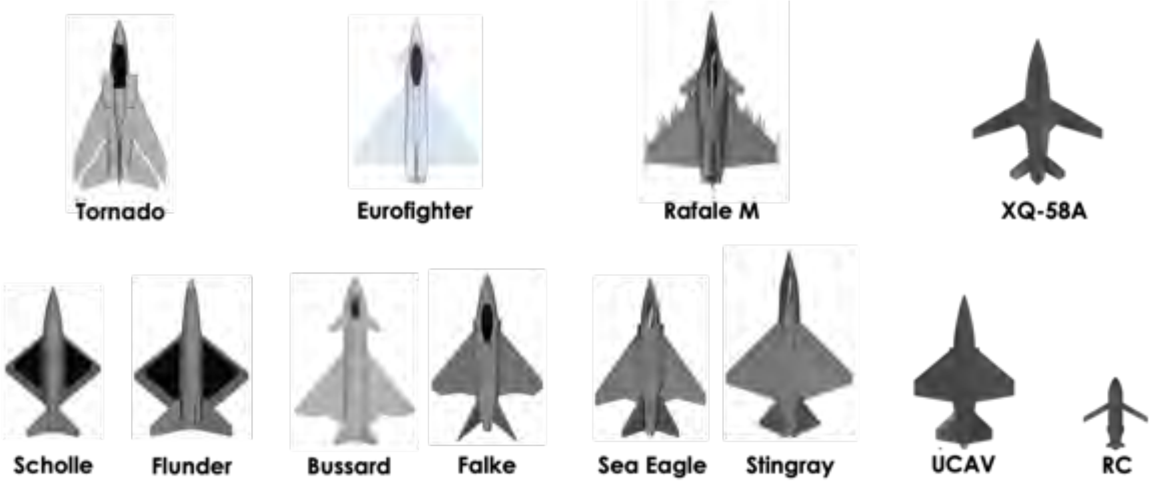


Figure 17 – Derivation of eight new concepts out of for mission specific re-projected concepts

All conceptual designs have in common, that their shape is driven by stealth contours, which led to more or less diamond shaped wings. Although a stealthy shape is not the optimal aerodynamic solution, the associated additional energy effort is expected to be lower compared to flight profiles, which changes altitude and speed to use low level flight for low detectability.

In the next phase another commercial tool will be investigated for its applicability for university education and research in military air systems. In parallel missing calculation modules for special military technologies will be developed to fil the observed gaps. Customer services of tool providers will be contact to motivate and support them to improve the calculative performance of the tools in the field of military air systems. A valuable model basleine with many variants has been established for further optimization and more detailed design and systems integration.

4. Summary and Outlook

In the light of the Ukrainian War and the upcoming development of the 6th generation air combat system effort has to be spent to provide adequate and sufficient multidisciplinary design competences in the upcoming generation of young engineers. As a future system of systems architecture, the next generation air combat systems is no longer a single platform approach.

In the presented campaign an approach was developed to teach graduate students in understanding military missions. Four main mission oriented re-projections have been performed first to create model baselines for future concepts designs for these specific missions. In a further step for these baselines two future concepts each have been elaborated to develop future air combat systems composed of manned and unmanned systems. These eight models will be the baseline for the future air combat system research on conceptual level at the institute.

A commercial conceptual design tool was used to investigate its capabilities for air combat systems design. Being mainly based on classical passenger aircraft design data and semiempirical approximations the tools as mainly capable to estimate aircraft masses. However, despite understanding and teaching much more in detail the architectural definition and further layout of future combat air systems, own pre- and postprocessing models have to be created to cover special military technologies like thrust vectoring, external loads or stealth and avionics features, if commercial tools are used.

With these achievements the initially mentioned goals have been addressed and some results have been received. Nevertheless air vehicle modelling for military systems must be improved, more designs will be developed and an operational mission environment has to be selected. Since the focus of the research is on design and assessment, modelling activities will be limited to what is necessary. The verification of the defined new concepts on the background of not fully transparent commercial tools, which at least use older semiempirical data remains a crucial task.

5. Acknowledgement

The authors like to thank very much Prof. Dr. Carsten Braun, Univ. of Applied Sciences Aachen, Prof. Dr. Ali Elham, ex Braunschweig University of Technology, Prof. Dr. Martin Wagner, Hamburg University of Applied Sciences and Dipl.-Ing. Alexander Hillebrecht, DLR for the contributions and collaboration in the project. Also the authors explicitly appreciate the openness and willingness of PACE Aerospace & IT in supporting our work with tensive own services. It gives confidence to resolve the findings presented in this paper in cooperation.

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