Bringing Highly Efficient RLV-Return Mode "In-Air-Capturing" to Reality

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Abstract

An innovative approach for the return of reusable space transportation vehicles has been proposed by DLR: The winged stages are to be caught in the air and towed by subsonic airplanes back to their launch site without any necessity of an own propulsion system. This patented procedure is called *in-air-capturing*.

The performance gain by this advanced method shows a possible increase in delivered payload between 15 % and 25% or allows for significantly reducing the size of a reusable system without any loss in payload mass when comparing to winged fly-back.

The paper gives an overview of ongoing experimental and numerical work at DLR in raising the TRL and proposes a development roadmap on how to bring this efficient technology to reality.

Keywords: *RLV, return modes, "in-air-capturing"*

Nomenclature/Acronyms

ACCD	Aerodynamically Controlled Capturing Device
AoA	Angle of Attack
CAD	computer aided design
CFD	Computational Fluid Dynamics
CoG	Center of Gravity
DRL	Down-Range Landing
FE	Finite Element
GLOW	Gross Lift-Off Mass
IAC	In-Air-Capturing
L/D	Lift to Drag ratio
LFBB	Liquid Fly-Back Booster
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
RTLS	Return To Launch Site
TRL	Technology Readiness Level
TSTO	Two-Stage-To-Orbit
UAV	Unmanned Aerial Vehicle

1. Introduction

Return To Launch Site (RTLS) and Down-Range Landing (DRL) are currently employed by SpaceX for the first stages of the Falcon 9 and Heavy launchers, requiring significant amounts of fuel for deceleration and landing. Techniques of turbofan-powered return flight like winged LFBB are more efficient, however, obligate an additional propulsion system and its fuel, which also raises the stage's inert mass. A completely different and innovative approach for the return of RLV-stages with better performance offers the patented "In-air-capturing" (IAC) [1]: The winged reusable stages are to be caught in the air and towed back to their launch site without any necessity of an own propulsion system for this phase [2].

A schematic of the reusable stage's full operational IAC-cycle is shown in Figure 1. At the launcher's lift-off the capturing aircraft is waiting at a downrange rendezvous area. After its MECO the reusable

winged stage is separated from the rest of the launch vehicle and afterwards follows a ballistic trajectory, soon reaching denser atmospheric layers. At around 20 km altitude it decelerates to subsonic velocity and rapidly loses altitude in a gliding flight path. At this point a reusable returning stage usually has to initiate the final landing approach or has to ignite its secondary propulsion system.
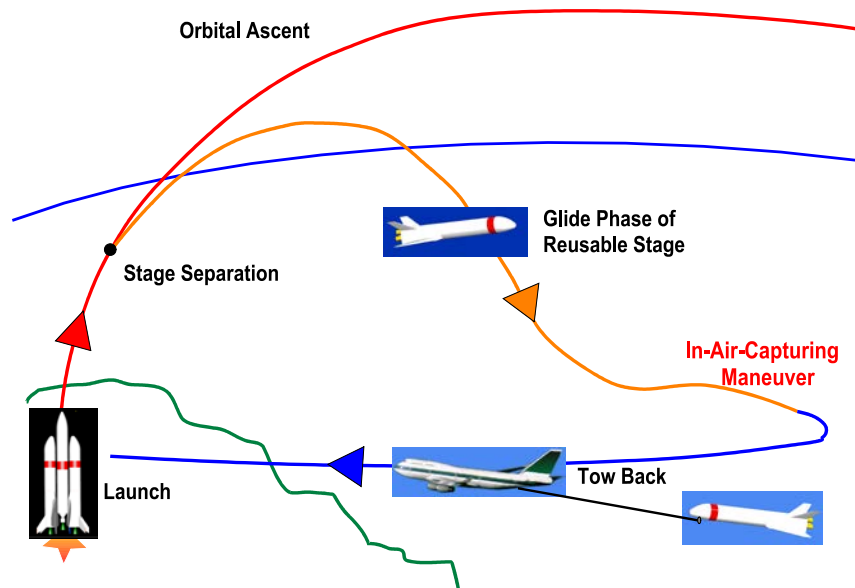

Figure 1: Schematic of the innovative "in-air-capturing"

Differently, within the in-air-capturing method, the reusable stage is awaited by an adequately equipped large capturing aircraft (most likely fully automatic and unmanned), offering sufficient thrust capability to tow a winged launcher stage with restrained lift to drag ratio. The entire maneuver is fully subsonic in an altitude range from around 8000 m to 2000 m [3]. After successfully connecting both vehicles, the winged reusable stage is towed by the large carrier aircraft back to the launch site. Close to the airfield, the stage is released from its towing aircraft and autonomously glides to the landing runway similar to a conventional sailplane.

After DLR had patented the "in-air-capturing"-method (IAC) for future RLVs, two similar approaches have been proposed. However, those named *mid-air retrieval* or *mid-air capturing* are relying on parachute or parafoil as lifting devices for the reusable parts and helicopters as capturing aircraft. The first proposal was made by the Russian launcher company Khrunichev [5] and the most recent one by the American company ULA for its newly proposed Vulcan launcher. The ULA proposal intends recovering not more than the first stage's engine bay instead of a full stage [6], [7].

1.1. Potential performance advantage

Any RLV-mode degrades the launcher's performance compared to an ELV due to additional stage inert mass. A comparison of the different performances is of strong interest because these are related to stage size and hence cost. Since a reliable and sufficiently precise estimation of RLV costs is almost impossible today, the performance impact comparison gives a first sound indication of how promising the modes are.

The performance impact of an RLV is directly related to its (ascent) inert mass ratio or net-mass fraction, reasonably assuming that the engine Isp is not considerably effected. Inert masses of the stage during ascent flight are its dry mass and its total residual propellants including all those needed for controlled reentry, landing, and potentially fly-back. A specific inert mass ratio is then defined as:

$$\text{inert mass ratio}_i = \frac{m_{i,inert}}{GLOW_{stage}}$$

The higher the inert mass ratio of a stage, the lower is its acceleration performance if propellant type and engine performance are unchanged. The overview in Figure 2 shows RTLS far above all other types while the IAC-stages obviously have a performance advantage not only when compared to the LFBB (as already claimed in the past, see [2 - 4]) but also in comparison to the DRL-mode used by

SpaceX for GTO-missions. The smaller the inert mass ratio and the smaller the propellant loading for the same mission, the better the system performance and hence potential cost reduction.
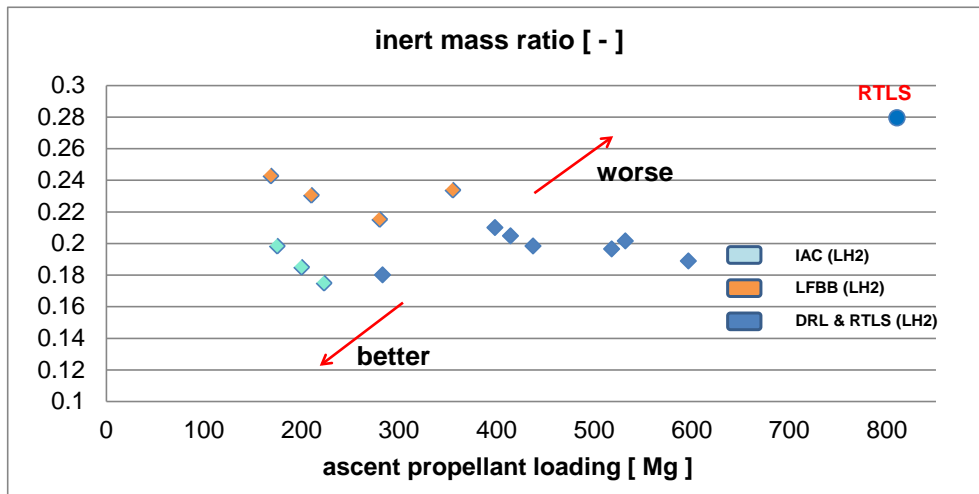

Figure 2: Inert mass ratio depending on RLV-return modes and ascent propellant loading, GTO-mission

A direct comparison between two winged RLV first stages with the same GTO-mission requirement and similar separation Mach-number around 12 but different return-modes is depicted in Figure 3. Data for both launch vehicles have been generated in preliminary sizing loops taking into account ascent trajectory optimization and atmospheric re-entry and return flight. The turbofan-powered LFBB mode requires a significantly heavier and larger stage compared to an IAC-mode RLV.
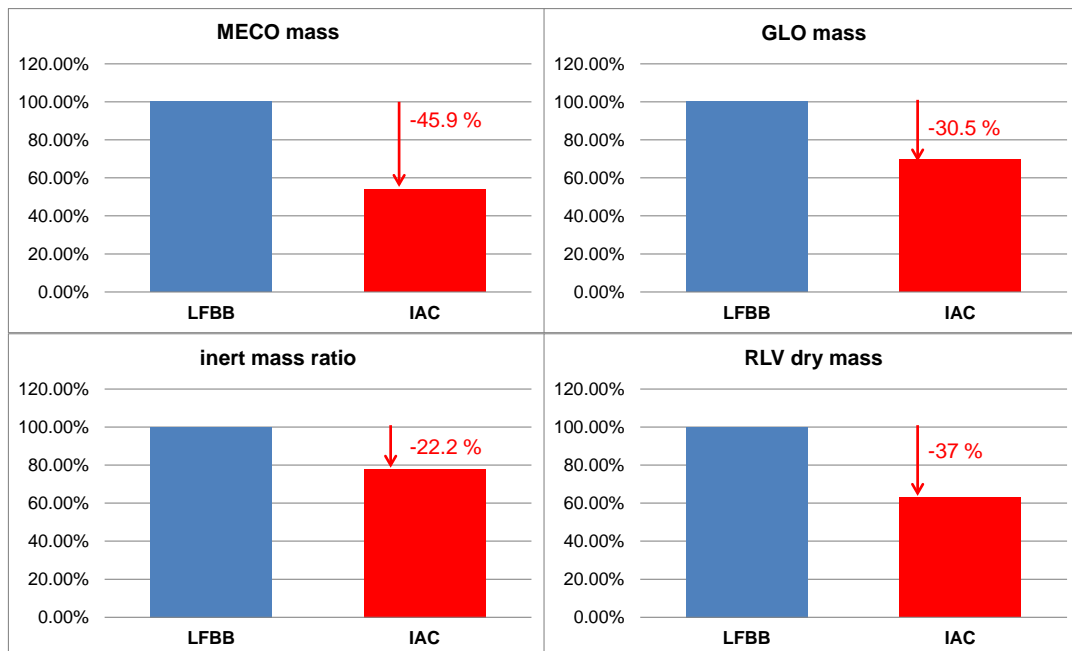

Figure 3: Relative comparison LFBB-mode with "in-air-capturing"-RLV mode, GTO-mission

The potential for improvement when using the "in-air-capturing"-mode is found between 22% and almost 46% in this example using realistic sizing conditions. The stage dry mass, usually correlated with development and production costs, is reduced by 37% compared to the reference LFBB-configuration. Even when taking into account the additional infrastructure costs of operating the capturing aircraft, the huge cost reduction potential of "in-air-capturing"-RLV compared to more conventional approaches becomes obvious with these numbers.

2. How "in-air-capturing" (IAC) works

The winged reusable stages are to be caught in the air, and towed back to their launch site without any necessity of an own propulsion system [2]. The idea has similarities with the DRL-mode, however, initially not landing on ground but "landing" in the air. Thus, additional infrastructure is required: a relatively large-size capturing aircraft. Used, refurbished and modified airliners should be sufficient for the task.

A schematic of the reusable stage's full operational cycle has been shown already in Figure 1. At the launcher's lift-off the capturing aircraft is waiting at a downrange rendezvous area. After its MECO the reusable winged stage is separated from the rest of the launch vehicle and afterwards performs a ballistic trajectory, soon reaching denser atmospheric layers. At around 20 km altitude it decelerates to subsonic velocity and rapidly loses altitude in a gliding flight path. At this point a reusable returning stage usually has to initiate the final landing approach or has to ignite its secondary propulsion system.

Differently, within the in-air-capturing method, the reusable stage is awaited by an adequately equipped large capturing aircraft (most likely fully automatic and unmanned), offering sufficient thrust capability to tow a winged launcher stage with restrained lift to drag ratio. Both vehicles have the same heading but on different flight levels. The reusable unpowered stage is approaching the airliner from above with a higher initial velocity and a steeper flight path, actively controlled by aerodynamic braking. The time window to successfully perform the capturing process is dependent on the performed flight strategy of both vehicles, but can be extended up to about two minutes. The entire maneuver is fully subsonic in an altitude range from around 8000 m to 2000 m [3]. After successfully connecting both vehicles, the winged reusable stage is towed by the large carrier aircraft back to the launch site. Close to the airfield, the stage is released from its towing aircraft and autonomously glides back to Earth like a sailplane.

The selected flight strategy and the applied control algorithms show in simulations a robust behavior of the reusable stage to reach the capturing aircraft. In the nominal case the approach maneuver of both vehicles requires active control only by the gliding stage. Simulations (3DOF) regarding reasonable assumptions in mass and aerodynamic quality proof that a minimum distance below 200 m between RLV and aircraft can be maintained for up to two minutes [3].

2.1. Simulated approach maneuver

After deceleration to subsonic speed at an altitude around 20 km, the winged stage is actively heading towards the capturing aircraft. Under nominal circumstances the latter is assumed to be in a 'passive' mode, just cruising at constant altitude (e.g. 8000 m) and relatively low flight Mach-number of about 0.55 which corresponds to the equivalent earth speed 400 km/h. It has to be assumed that both vehicles are now permanently in communication with each other. During descent the reusable stage is able to perform some position-correction maneuvers and to dissipate kinetic energy, if required. It plays the 'active' part in the approaching maneuver.

The absolute value of the angle between both vehicles η decreases gradually during descent. At the instant when this angle becomes smaller than the winged stage's glide path ($| \eta | < | \gamma_{gl} |$), the capturing aircraft receives a signal from the reusable stage to also start its descent flight at a pre-chosen capturing angle $\gamma_{as} = \gamma_{capt}$. The launcher stage itself adapts the path angle such, to follow the capturing aircraft. As a result, after a short time both vehicles fly in line with an inclination angle corresponding to the chosen capturing glide path angle.

The winged stage follows the capturing aircraft reducing its distance ΔS and its velocity V. The approach maneuver has been simulated for different reusable stages (see [3] for type description) according to the above explained method, and the control constraints are applied. A reusable stage with separation velocity around 2 km/s is used as an example case.

The aerodynamically controlled approach as shown in Figure 4 is initiated when the reusable stage reaches the denser atmospheric layers and decelerates to the subsonic regime. The steep glide angle of around –18 degrees is performed with a slowly decreasing air speed of around 265 m/s. After the capturing aircraft has received the appropriate signal, both vehicles are descending on nearly the same glide slope (600 s). As can be clearly seen, the returning stage is still the active vehicle, since it

is subject to some control deviations in flight path angle γ_{capt}. The winged stage actively reduces velocity up to the point where its minimum safety distance is achieved (675 s).
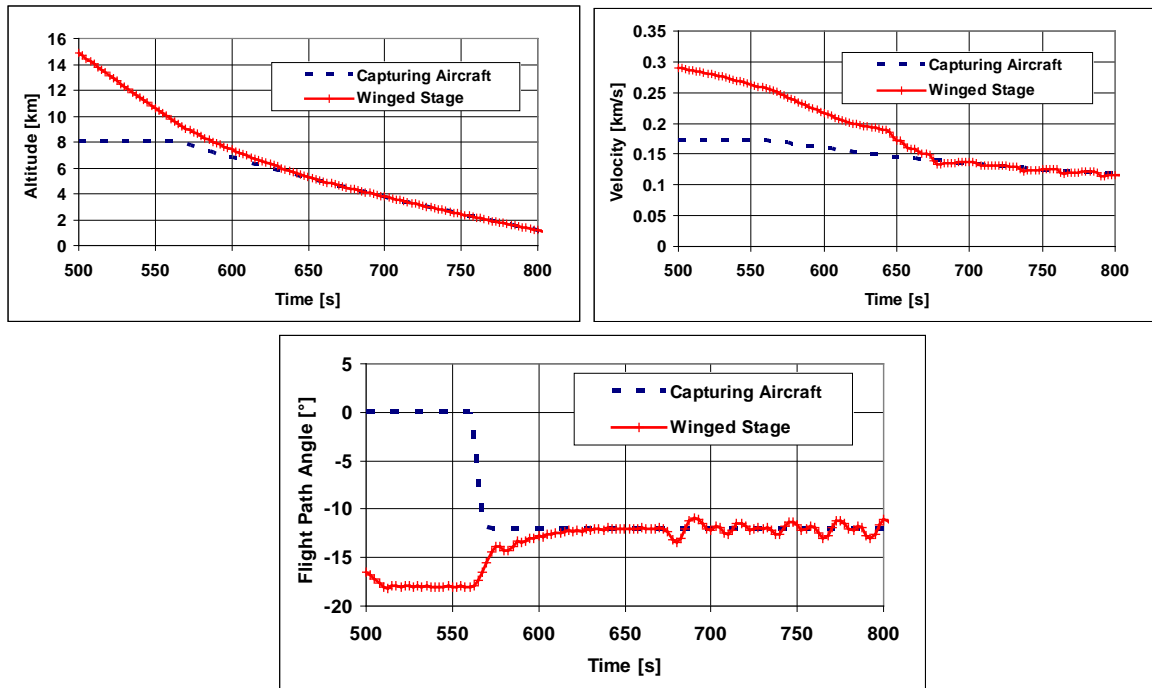

Figure 4: Simulation of the reusable stage's final approach procedure to the capturing aircraft starting 500 s after separation from launcher [3]

As can be seen from Figure 5, the total distance between the two flying craft falls short 0.5 km around 655 s after separation. Subsequently the distance could be controlled in this simulation at a minimum range between 155 and 200 m for duration of 130 s. The upper boundary is not set by vehicle control, but by a minimum acceptable level above ground. The final altitude in this simulation is as low as 1.2 km. A time for capturing up to at least one minute is nevertheless well within reach, since the altitude after this period still accounts for more than 2.8 km.
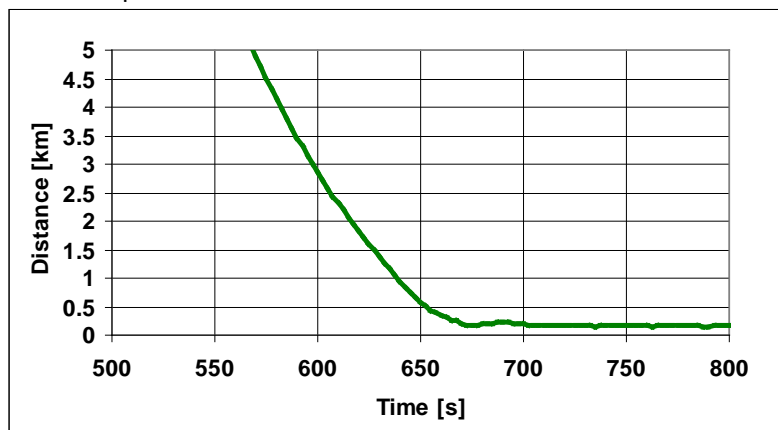

Figure 5: Total distance between the two stages in final approach procedure starting 500 s after separation from launcher [3]

2.2. Potential capturing hardware

The most promising capturing technique is using an aerodynamically controlled capturing device (ACCD), showing the best performance and lowest risk [3, 4]. The ACCD is to be released and then towed by the airplane. This device (a preliminary artist impression is shown in Figure 6) contains the connecting mechanism and simply advances the stage by its own drag and lift, provided by small wings (typical span 1.5 m). Actuators control the ACCD's orientation and the approaching velocity might be further controlled by braking of the towing rope from inside the aircraft. With a release

initiated at 230 m distance between the two crafts, the whole maneuver takes about 14 s in the nominal case. All loads remain below 3 g and the final relative velocity is at 5 m/s.

Aerodynamic stability and at the same time sufficient maneuverability of the ACCD during the subsonic capturing process are required. A preliminary configuration has been defined and will be assessed by 6DOF-simulations.
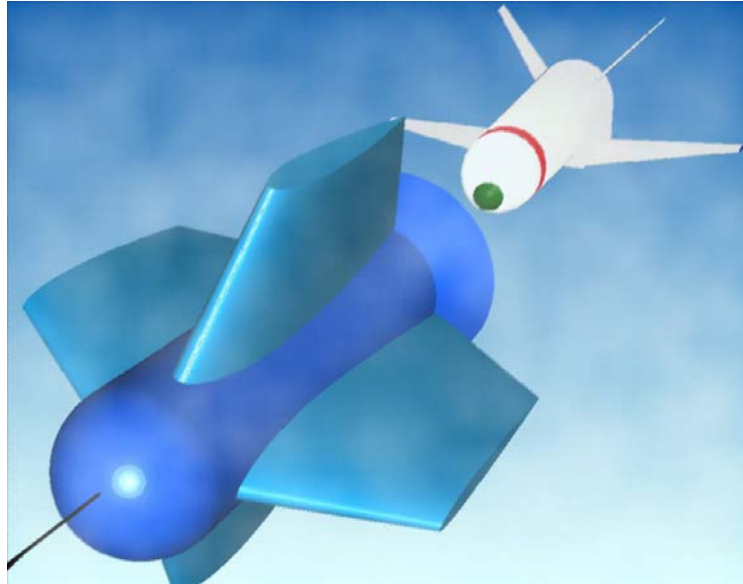

Figure 6: Rendering of the ACCD and the returning stage cautiously approaching each other [3, 4]

The capturing mechanism inside the ACCD is a critical part which has been preliminarily designed [4] for the static load conditions encountered when capturing and towing a large fictive RLV stage. The mechanism lay-out has to be defined for correct kinematic functioning in capturing-, towing-, and release-mode, as well as for good shock attenuation.

A preliminary design of such a capturing mechanism has been developed (see first design iteration in Figure 7) and has been subsequently mechanically sized supported by Finite-Element stress and de-formation analyses [4, 9, 10]. All elements of the mechanism fit into the ACCD fuselage and consist of
- a ball-shaped head with ball jacket,
- industrial shock-absorber,
- different spring and damping elements, and
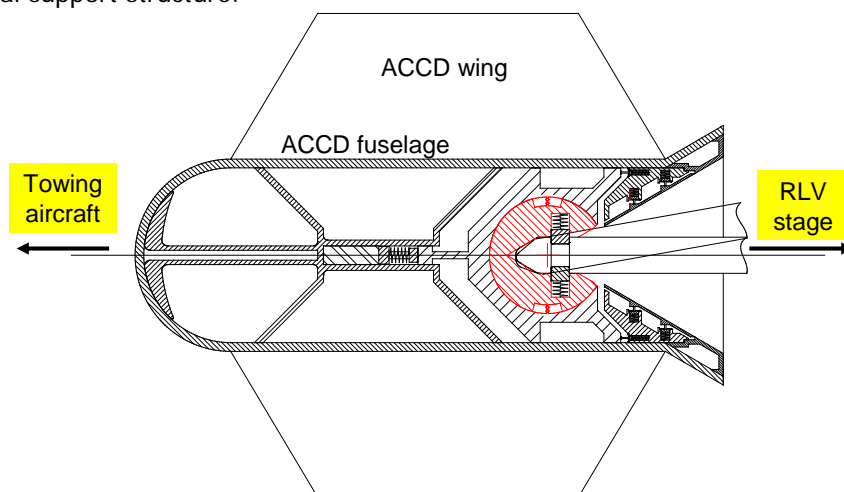- additional support structure.

Figure 7: Sketch of the capturing mechanism inside the ACCD geometry highlighting the ball-shaped head in red and the RLV stage anchor shown in parallel and deflected position [4]

The principal idea of the mechanism is to direct a long passive anchoring device from the RLV to the capturing- and hold mechanism inside the ACCD. A funnel like opening at the ACCD's back with a 30

deg. cone opening allows for the mechanically steered guidance in case of small flight position imperfections prior to connection and for the required axial deflection between both flying items in the capturing procedure and also thereafter in towing flight. Inside the ACCD all axial loads as well as the relative pitch and yaw movements between the different flight vehicles are transferred through a ball joint to its jacket capable of axially gliding inside the ACCD fuselage. Relatively high local pressures between the ball and the jacket will require also a good lubrication between those two metallic parts. The connecting shock between both vehicles is transferred in the ACCD's forward direction to an industrial shock absorber (in the center of Figure 7). Such a device allows for a constant deceleration with a moderate axial force and rapid oscillation damping.

Two load cases have been identified as dimensioning and have been analyzed in static structural stress and strain calculations [4, 9]. Load Case 1: capturing with connecting or coupling shock which has been calculated at 27 kN based on the assumption of an industrial linear shock absorber decelerating the ACCD with velocity 4.9 m/s relative to the RLV. Load Case 2: towing of the RLV-stage with 174.4 kN which is equivalent to the static towing force for a large winged stage of 80 tons empty weight and subsonic L/D of 4.5.

The finite element method has been used to obtain the stresses in the complex-shaped parts. The FE-tools ANSYS [4, 9] and in a second iteration I-DEAS MS11v4 [10] have been used. All of the parts have been separately analyzed to avoid modeling of complicated surface interfaces. Instead, such interfaces are replaced by a set of distributed loads or boundary constraints delivering the respective reaction forces. Although this approach might not always fully represent the actual conditions, it has been considered as adequate for a preliminary sizing of the components.

Structural sizing results are presented in [4, 9, 10]. A second iteration of the capturing mechanism structures has been performed to reduce excessive weight of the first design [4, 9]. The total mass of the central core including all mechanisms but without wings, flaps, actuators, and avionics could be reduced to less than 80 kg. A combination of aluminum and steel alloys has been selected. Maximum calculated stresses remain below 200 MPa and thus stay well within the capabilities of the materials. Figure 8 shows as an example the behavior of one of the most critical parts, the spherical head, subjected to load cases 1 and 2. Despite the seemingly spectacular deformations in Figure 8, the maximum actual deformation of this part is less than 0.18 mm.
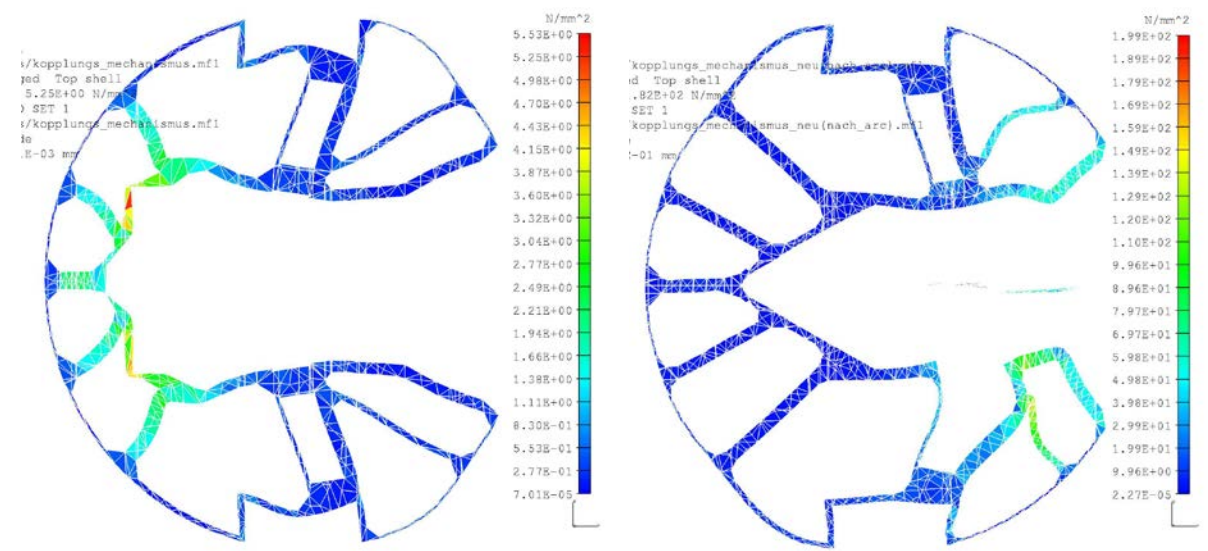

Figure 8: Von Mises stress distribution in spherical head and strongly magnified deformations, load case 1 at left, load case 2 at right [10]

Figure 9 depicts a suitable design of the ACCD capturing mechanism with major dimensions for a full scale variant capable of connecting to and towing of an 80 tons winged stage. Such an RLV with approximately more than 400 tons GLOW is a good check on the principal feasibility of the capturing devices. Obviously, smaller versions of the ACCD could be sized for reduced scale reusable stages.
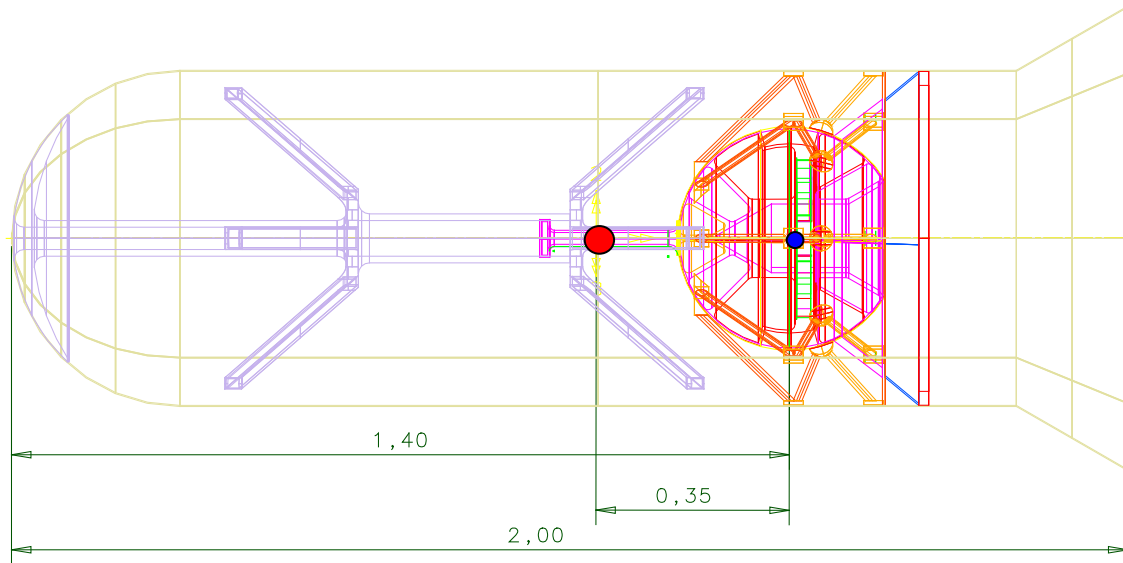
Figure 9: Latest design drawing of optimized capturing mechanism inside the ACCD geometry with major dimensions in [m] [10]

A preliminary investigation of the aerodynamic behavior has been conducted to allow for 6-DOF simulations of the ACCD in flight. The *Missile DATCOM* code [11] has been used to determine the aerodynamic coefficients and derivatives and to improve the aerodynamic design of the ACCD. The configuration shall be aerodynamically stable and at the same time allow maneuverability to enable corrections of the ACCD's position and attitude. The position of the CoG with respect to the center of pressure determines the stability and maneuverability: the greater the distance between the CoG and the CoP (with the CoG being in front of the CoP) the more stable the aircraft gets, however maneuverability is decreased.
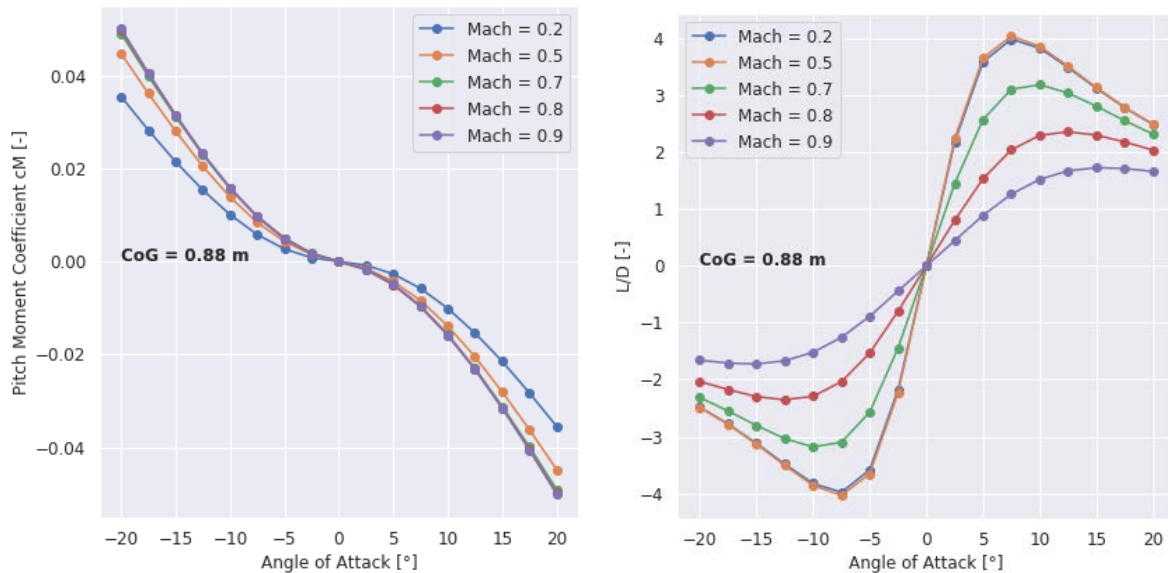

Figure 10: Preliminary pitch moment coefficient (left) and L/D (right) of ACCD at different Mach numbers assuming reference point x = 0.88 m wrt the nose

Figure 10 shows the pitch moment coefficient and L/D versus the angle of attack for different Mach numbers with the moment reference at 0.88 m with respect to the nose. The ACCD shows almost indifferent behavior regarding the pitch coefficient at Mach 0.2, all other flight points are longitudinally stable. Additionally, the ACCD is laterally stable. Positioning the CoG at 0.9 m already leads to a laterally unstable configuration. The maximum Lift-to-Drag ratio is around 4 at low subsonic speed and 2.3 at commercial airliner cruising speeds (Mach 0.8). Since the vehicle is highly stable due to its rather big control surfaces and its low mass and inertias the maneuverability had to

be increased by positioning the control surface hinges at 70% of the chord length throughout the whole span. This increases the distance between the center of the control surface forces and the CoG. The thus trimmable AoAs and sideslip angles range from –8° to 8° at low subsonic velocities and from -5° to 5° at high subsonic velocities. A repositioning and resizing of the control surfaces could be considered based on 6DOF-simulation results in order to enhance the trimmable AoA range. Furthermore, a forward located CoG at 0.88 m would require a trim mass in the range of 20 kg in the current configuration. As visible in Figure 7 and Figure 9, the available volume inside the ACCD fuselage is quite large and enables repositioning of equipment like batteries.

2.3. Towing aircraft

Technical requirements of the tow-aircraft are given in [3]. The rope and its mechanism have to be designed to withstand the pulling stress with regard to dynamic loads. The maximum values are most likely being reached during pull-up of the assembly after capturing. A towing rope diameter of 1.6 cm is estimated to be sufficient for up to 200 kN load [3].

The thrust requirements of the capturing aircraft are dependent on the reusable stage's mass and its L/D-ratio. The thrust reserve of the capturing aircraft has to exceed 50 to 200 kN (equivalent to approximately 25 to 80 tons of to be towed stage mass) in an adequate flight altitude [3]. A four engine jetliner without normal cargo loading offers sufficient thrust margins. This is corresponding to an Airbus A-340 or Boeing-747-class jet, which have been produced in large numbers. Moreover, a considerable quantity of these airplanes is available at an affordable price, since significant numbers have been retired from commercial airline service.

A catastrophic mid-air collision has to be avoided by fully automatic and redundant control avionics of both vehicles operating in a synchronized mode. Any pilot interference in this maneuver from the capturing aircraft would be far too slow, to have a positive impact. Since no real demanding pilot work is foreseeable, one should seriously consider redesigning the capturing and towing aircraft as an unmanned aerial vehicle. Taking into account the significant progress recently achieved in UAV avionics, this is not an exotic idea. By giving up on board pilot control for all capturing missions, it might be also possible to broaden the flight envelope, which will not be acceptable with men on board. This further enables high risk maneuvers – if ever required - which are otherwise excluded and would result in the loss of the returning stage. Hence an unmanned towing aircraft will augment overall reliability and safety of the in-air-capturing method. The certification process of the large unmanned vehicles is to be addressed early in the design phase. As the full capturing mission is to be performed exclusively over uninhabited areas off-shore of a launch site, the required certification is currently not assessed as a blocking point.

3. Ongoing flight experiments

DLR in its internal project AKIRA [12] is now moving on from pure simulations to lab-scale flight experiments [13] aiming for a TRL between 3 and 4. Establishing connection between the RLV-stage and the large carrier aircraft requires formation flight of both vehicles during the approach maneuver. Actual coupling is best achieved by a highly agile connecting device or coupling unit with onboard actuators like the above discussed ACCD.

The first validation during the lab-scale flight experiments are performed using smaller unmanned aircraft. One will tow the coupling device and a second will represent the booster stage. This poses certain boundary conditions, especially on the weight of the towed device, as the UAVs have limited excess power to perform the tow. Also the experiments must be performed on a racetrack course instead of a straight track for safety reasons and although the coupling maneuver will be demonstrated, the actual tow of the aircraft is not a part of the AKIRA-experiments.

3.1. Subscale coupling device

For its basic functionality, the subscale coupling device consists of a cone, ensuring the stable flight behavior by its own drag and four control surfaces, which deflect for roll, vertical and horizontal movements as shown in Figure 11.
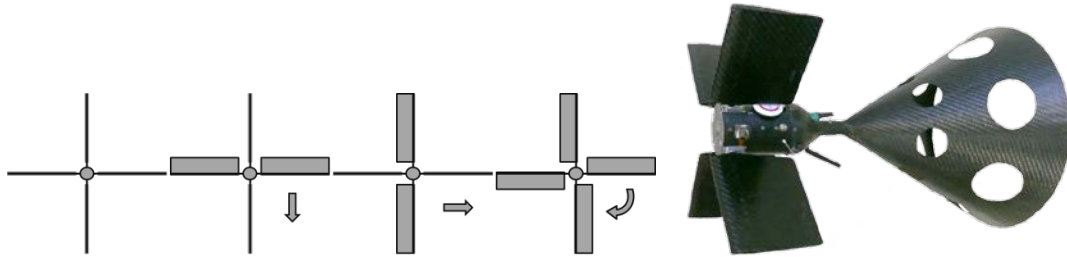
Figure 11: Surface deflections for ACD control (left) and prototype device (right)

For automatic control of the ACD, avionics, consisting of sensors and a control computer (including data logging), telemetry, actuators and a power source are required. There is a variety of possibilities to mount these different devices. Two approaches have been considered for integration:

- control computer, telemetry and power source are stored in the towing aircraft and just the actuators and sensors are implemented in the ACD

- the ACD is completely equipped, including its own power source

The first variant allows for a much lower weight of the ACD. However, it is necessary to transfer all signals over the towing rope length, which will be approximately 20 to 30 m in the scaled scenario. In practice, this is challenging without the use of amplifiers that are difficult to integrate into a scaled setup. Furthermore, it is more complicated to use the device with other tow-vehicles because they need to be equipped with the necessary modules. Therefore, variant 2 was chosen, i.e., to have a completely equipped ACD.

For the experiments a first demonstrator of the coupling device was build. The main material is CRFP to remain as lightweight as possible. Table 1 summarizes some basic data of the device.

Table 1: Key parameters of the finished test coupling device

length	$\approx$ 450 mm
cone diameter	370 mm
weight (incl. avionics)	650 g
control surface span (each)	120 mm
control surface width (each)	100 mm
maximum control deflection	+/- 45°

The avionics consist of a commercial Pixhawk autopilot system which comes with various equipment and sensors, as a u-blox M8N GPS with compass module, 433 MHz telemetry, RC receiver, UBEC voltage regulator and a voltage monitor for the battery and already provides a way for internal logging of flight data. The control system is realized by adapting the commonly used autopilot software of the Pixhawk hardware. The basic open source software is 'PX4 Firmware', which is based on a 'NuttX' real-time operating system that runs sensor drivers and a flight controller. In order to have full control of the actuators, the preinstalled flight management is replaced by a user application generated from a Matlab$^{©}$/Simulink model with automatic code generation and the 'Pilot Support Package' (PSP) provided by Matlab, including a number of libraries to use Pixhawk interfaces (e.g. sensor data or RC input) within the Simulink environment. Based on the toolchain, a modular, model-based design of the controller with automatic implementation of the generated code into the basic software of the autopilot was realized. Figure 12 illustrates the process of the controller implementation. For the later testing of different control modes, a model structure is constructed, where different, switchable modes are implemented.
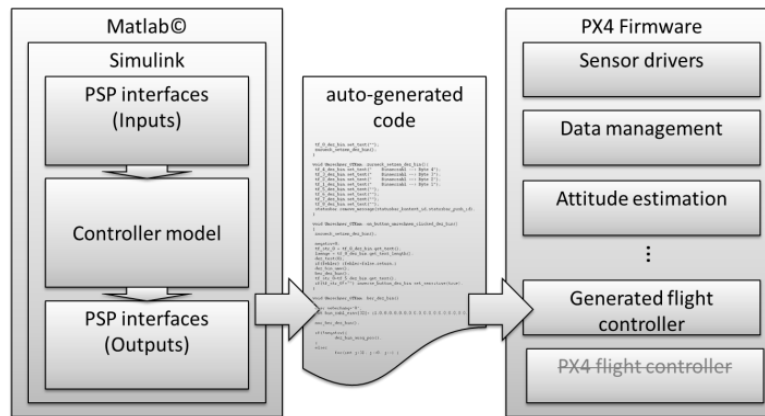
Figure 12: Schematic of controller realization of the coupling device [14]

In order to make coordinated movements towards the nose boom of the UAV representing the booster stage, the device must be stabilized around its roll axis at a specified angle. This was done in a first step by implementing a PID roll angle controller simply using the feedback of the attitude estimator.

3.2. Flight evaluations

The build and controlled device was tested for its functionality in ground runs and in flight tests towed by an aircraft (Figure 14) but without yet connecting to the 2nd UAV. With the enabled roll stabilization the possible deflections were evaluated. The results are shown in Figure 13 for horizontal movements and vertical movements. For these experiments the roll stabilization commands were mixed with control inputs from a remote controller. The displacements can be evaluated from the changes in height offset between coupling device and tow aircraft for the vertical movements and the offset of the coupling device to the flown aircraft track for the horizontal movements. Due to heavy wind conditions only short inputs could be evaluated during the tests.
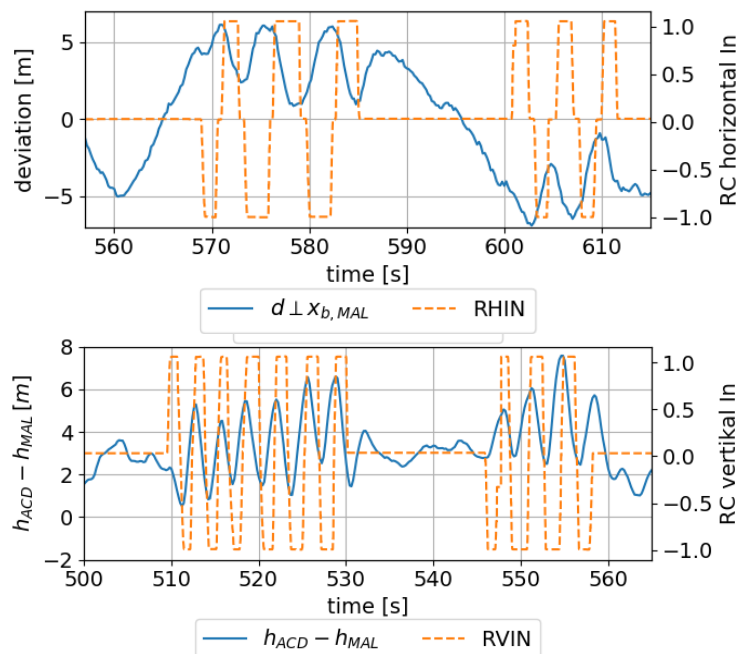

Figure 13: Horizontal (top) and vertical (bottom) displacement during control inputs [14]

The first evaluation showed satisfying results for the coupling device movements from 2.5 m to 3 m per side which spans a 6 m x 6 m frame for positioning. Especially when regarding the wing span of the towing vehicle which is in the same size as the movements, this seems to enable for sufficient maneuvering.
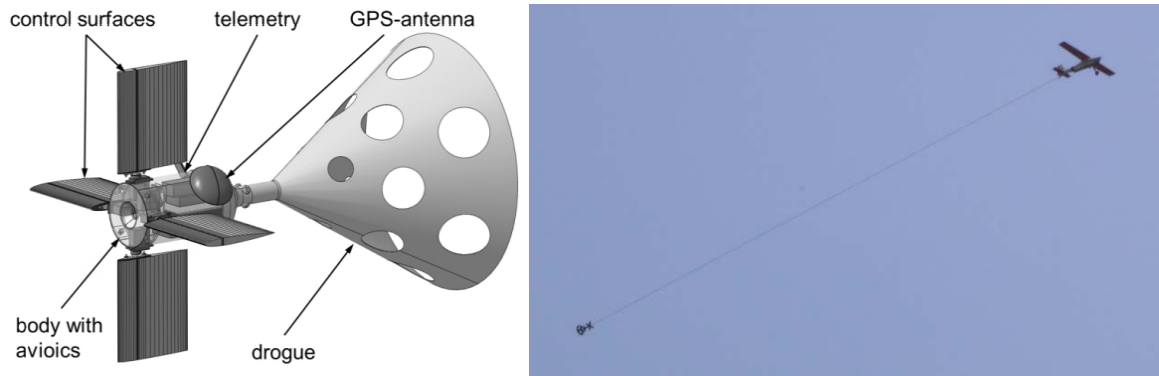
Figure 14: Coupling unit (left) and in flight test (right) with towing UAV "MAL" of DLR

The next step for performing the in-air capturing demonstration is to set-up a GNSS based formation between the two vehicles which is based on a communication link. The resulting error from the GNSS data is expected to be within the positioning capabilities of the coupling device. Two commercial autopilots are used which are modified for the formation flights. One is set to be the 'master' system which sends waypoint and speed commands to the 'slave' system. These waypoints contain a relative position based on the navigation data of the master system. First flights are performed using two very lightweight test vehicles (takeoff mass <3 kg, Figure 15) to keep the risk and effort at a minimum. These planes are nevertheless fully equipped to perform automatic missions and capture video data. Experiments with such a communication established have already been completed and are currently evaluated for their potential.

Figure 15: Test vehicles for automated formation flight testing

In parallel, ongoing work is the detection of the position from the device with respect to the booster demonstrator. This is done by camera and laser based environment perception at the RLV-stage demonstrator. The reason for equipping the sensors on side of the booster is simply the weight limitation of the device. In a real scenario it might be more feasible to equip the coupling device.

The originally planned flight and connecting tests of AKIRA are partially adapted in order to be synchronized with the new, more ambitious project FALCon which is described in the following section 4.

4.   Outlook: H2020 research project FALCon

In order to bring the promising "in-air-capturing"-technology forward, a new project proposal with the name FALCon (**F**ormation flight for in-**A**ir **L**auncher 1st stage **C**apturing dem**on**stration) has been submitted early 2018 to the Horizon 2020 call SPACE-16-TEC-2018 *Potential Launch system reusability technologies and their applicability for European needs* [15]. The evaluation of the

proposal was positive and grant negotiations with the European Commission are close to completion. The project kick-off is intended for February 2019, scheduled duration is 36 months and with total funding of 2.6 M€ the FALCon project will address three key areas:

- "in-air-capturing"-Development Roadmap and economic benefit assessment

- "in-air-capturing"-Experimental Flight Demonstration

- "in-air-capturing"-Simulation (subscale and full-scale)

The development roadmap for "in-air-capturing" is to be defined in cooperation with the European stakeholders e.g. ESA, CNES, ONERA, CIRA, VKI, and industrial primes. This process will consider the classical Technology Readiness Level (TRL) definition (e.g. [16]). Although, the TRL-approach is helpful, it has been found not necessarily sufficient for successful development of RLV. Therefore, a NASA working group has proposed a "Phased Development Approach (PDA) using Integration Readiness Levels (IRLs) to facilitate selection, sequencing and staging of flight test demonstrations to reduce the risks inherent in technology development." [16] Exactly this methodology will be implemented in FALCon for the establishment of the "in-air-capturing" roadmap.

Starting point of all activities concerning "in-air-capturing" is the most recent technology development status from the ongoing DLR AKIRA-project [12]. Results from this activity will become available to FALCon-project partners. Completion of AKIRA will also finish PDA Phase 1 and will approach a TRL of 4. The Horizon2020 FALCon-project will initiate PDA Phase 2, will consolidate the TRL of 4 and is planned to bring all relevant technologies close to a TRL of 5.

Based on the achievements in FALCon (e.g. better, more accurate simulations, windtunnel measurements, sensor data integration procedures, etc.), the next demonstration steps are in-flight verification of the RLV-demonstrator, of the capturing aircraft and of the coupling unit to confirm the aerodynamic qualities, ballistic coefficients and control margins of the system. At this stage the TRL of 6 and system integration IRL between 1 and 2 will be achieved. Funding could be provided by relevant ESA technology development programs like FLPP which are considered as a suitable framework.
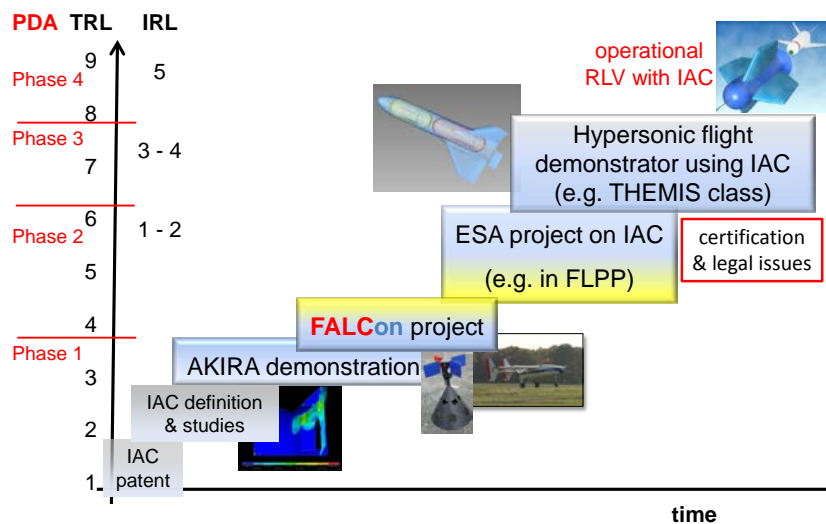

Figure 16: "in-air-capturing"-Development Roadmap

The experimental test and validation processes in FALCon are the key objectives of the project. Half of all the workpackages are dedicated to this goal. The demonstrator for the reusable launch vehicle will be completely designed and built from scratch while an already available vehicle is used as tow aircraft. The coupling unit will be a redesigned and upgraded version of the device developed and used for research studies of the AKIRA project. An integrated communication and data fusion strategy will be developed in FALCon. A sensor package is to be integrated into the flight experiment coupling unit with an infrared camera system in combination with optical markers. The hardware including on-board computers must be lightweight for not influencing the flight performance but powerful enough to run the state machine and the formation algorithms.

Adequate simulation of the "in-air-capturing"-process is the other key-element to increase its TRL in FALCon. This is done in two workpackages which should have a close interaction and fruitful exchange of requirements, methods and procedures. Experiment simulation is supported by windtunnel tests in subsonics at VKI. Return simulation of full-scale RLV first stages is enabled by CFD calculations of the flow field around the three full-scale vehicles/objects in formation flight and the dynamic modeling of all these vehicles including the flexible dynamics of the towing rope.

5. Conclusion

The innovative method for the return to the launch site of reusable winged stages by "in-air-capturing" is described and its major advantage of increased payload mass to orbit is quantified for different missions and RLV-separation conditions.

The selected flight strategy and the applied control algorithms in 3DOF-simulations show a robust behavior of the reusable stage to reach the capturing aircraft. When considering reasonable assumptions in mass and aerodynamic quality of the vehicles, a minimum distance below 200 m can be maintained in the simulations for up to two minutes.

The most promising capturing technique is using an aerodynamically controlled capturing device (ACCD), showing the best performance and lowest risk. A capturing mechanism has been preliminarily designed for the ACCD. The structural parts have been pre-dimensioned for two static load cases supported by finite element calculations. Component masses have been minimized by iterative resizing.

DLR is currently progressing with the "in-air-capturing"-technology by performing lab-scale flight experiments aiming for a TRL between 3 and 4. Soon a new European research projects FALCon will be initiated within Horizon 2020 which should bring the TRL beyond 4 in 2021. Subsequently, the advanced method is to be refined in more complex integrated systems of increased scale bringing "in-air-capturing" to operational reality.

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