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Progress Summary of H2020-project FALCon

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The innovative approach "in-air-capturing" for the efficient return of reusable space transportation vehicles has been refined in the EC-funded H2020-project FALCon. Following the basic idea, 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.

The project FALCon (Formation flight for in-Air Launcher 1st stage Capturing demonstration) funded by EC in Horizon 2020 and running from 2019 until 2022 has achieved significant progress. The project finished after 45 months in November 2022.

The paper provides a retrospective progress summary. The successful establishment of significantly refined simulation models and the definition of the development roadmap for the next steps in technology maturation are presented. Further, lessons learned from the complex authorization process of the UAVs to be used in the lab-scale flight demonstrations are discussed. Finally, an outlook on the intended follow-up activities is given, including an estimate of the relatively modest investments required.

Abbreviations

ACCD	Aerodynamically Controlled Capturing Device
AoA	Angle of Attack
BVLOS	Beyond Visual Line of Sight
CFD	Computational Fluid Dynamics
CoG	Center of Gravity
DRL	Down Range Landing
GLOW	Gross Lift-Off Mass
IAC	In-Air-Capturing
IR	Infrared
L/D	Lift to Drag ratio
LFBB	Liquid Fly-Back Booster
MAR	Mid-Air Retrieval
MECO	Main Engine Cut-Off
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
RTLS	Return To Launch Site
TRL	Technology Readiness Level
TSTO	Two-Stage-To-Orbit
TVC	Thrust Vector Control
UAV	Unmanned Aerial Vehicle

1. Introduction

Independent access to space has been a key target for Europe since decades. For more than 40 years the Ariane family of launchers has assured this goal successfully. During these years, Ariane was able to capture a significant share of the accessible worldwide launch market and supported by this income, the European institutional missions could be kept affordable. However, the geopolitical and technological landscape is rapidly changing. In recent years, the share of Europe of all launches is dramatically reduced. The private US-company SpaceX now has a dominant role in the number of launches using its partially reusable Falcon(9/H) rocket (share 2022: 34% of all successful flights worldwide vs. Europe's total share only 2.2%, see e.g. [1]).

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. It has been proposed to copy the Falcon 9 architecture for a future European launcher available after Ariane 6 in the mid-2030s. However, the Falcon 9 now has reached its final design iteration and a much more ambitious system, the Starship, is in early flight testing by SpaceX and could be operational well before 2030.

A completely different and innovative approach for the return of RLV-stages with better performance offers the patented "In-air-capturing" (IAC) [2]: 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 [3]. 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.

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Differently, within the in-air-capturing method, the reusable stage is awaited by an adequately equipped capturing aircraft (most likely fully automatic and potentially 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 of several thousand meters [4]. 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 conventional sailplanes.

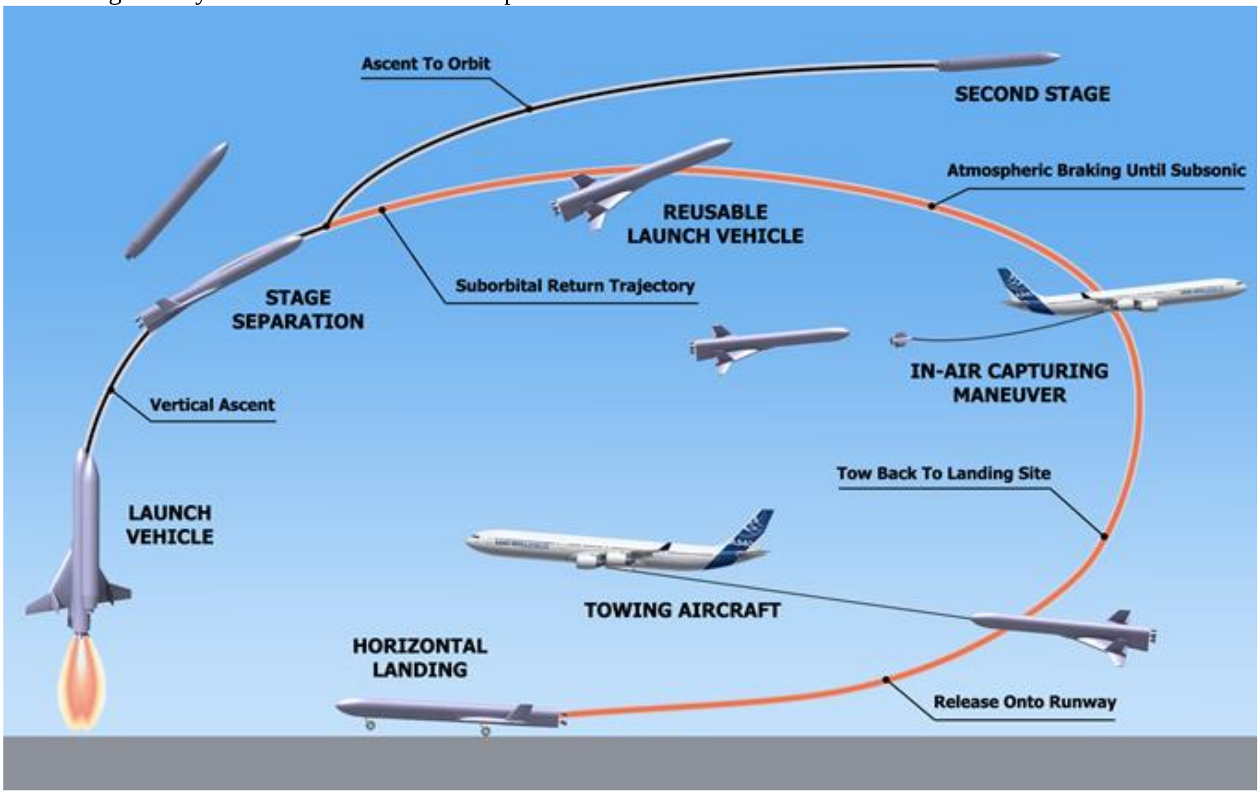

Figure 1: Schematic of the “in-air-capturing” mission cycle

After DLR had patented the “in-air-capturing”-method (IAC) for future RLVs, similar approaches have been proposed. However, those named *mid-air retrieval* (MAR) or *mid-air capturing* are relying on parachute or parafoil as lifting devices for the reusable parts and helicopters as capturing aircraft. A brief historic review of MAR in spaceflight history is included in [6].

The NZ-based company Rocket Lab has successfully performed capture of a first stage involved in a launcher mission to space for the first time with Electron flight #26 on May, 2nd 2022. This stage was released by the helicopter shortly after and splashed down to the ocean.

Obviously, the size and mass of the stages to be captured by MAR are much more restricted than for IAC due to mass limitations of parachutes and helicopters. A significant operating cost disadvantage of the MAR as proposed is related to the limited flight range of helicopters, which usually makes the use of additional ships as landing platforms indispensable. For this reason, probably, ULA and Rocket Lab favor now the direct splash-down of their stages into the sea with subsequent recovery by ships. However, the mechanical loads upon impact with the water surface are critically high and contamination of sensitive parts of the launcher with seawater could be a cause for concern. The practical interest of such recovery of RLV for subsequent operational use is still to be demonstrated.

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 affected. 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:

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

The higher the inert mass ratio of a stage, the lower is its acceleration performance if propellant type and engine performance are unchanged. Figure 2 shows a comparison of the inert mass ratio for generic TSTO-launchers (design assumptions described in [21]) and different return modes of the reusable first stage. All launchers have been sized for 7.5 tons GTO payload with a variation in separation Mach-number of the RLV [21]. As mission and stage number are identical, the inert mass ratio can be presented as function of the total ascent propellant loading. The propellant combinations LOX-LH2 and LOX-hydrocarbons (methane and RP) are placed in clearly separated areas. In all presented cases the IAC-stages have a performance advantage not only when compared to the LFBB with turbojet flyback (as already claimed in the past, see [3 - 5]) 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. Approximately 1 km/s additional Δv is required for the propulsive deceleration and landing maneuvers. Thus, the RLV's increase in ascent propellant loading in case of DRL- compared to IAC-mode is becoming more significant for the hydrocarbon fuels because of their lower Isp resulting in a less favorable exponent in the rocket equation.

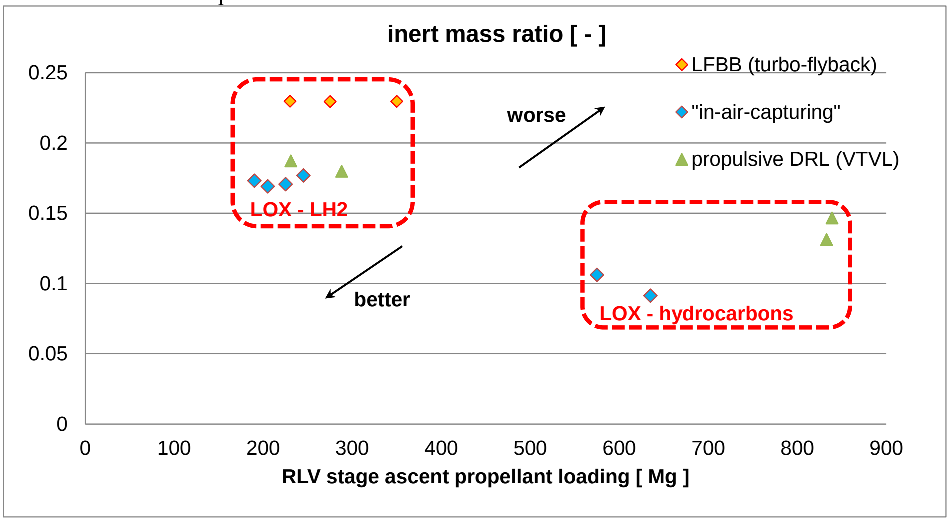

Figure 2: Inert mass ratio depending on RLV-return modes and ascent propellant loading, GTO-mission TSTO (LOX-LH2 and LOX-hydrocarbons)

One of the main advantages of IAC comes from the fact that the recovery method can be applied to wide range of winged launch systems. Similar to the comparison of different return methods for heavy-class launchers, a comparison has been performed for superlight launchers in the payload class of up to 1000 kg to LEO [21]. Horizontal landing with some kind of In-Air-Capturing or Mid-Air-Retrieval offers quite low performance losses, even lower than the DRL, similar to the results of heavy-class launchers.

1.2 Economic Interest Analysis

Looking from the launcher performance perspective the idea of RLV-stage "in-air-capturing" has similarities with the DRL-mode, however, initially not landing on ground but "landing" in the air. Thus, additional infrastructure is required: the capturing aircraft adequate to the size of the RLV. Based on the size of the RLV-stage to be captured, a suitably sized aircraft must be selected.

Economic viability and the possibility to decrease the launch costs is the main rational behind reusability. Therefore, within the FALCon project a preliminary cost estimation and an analysis of economic viability has been carried out with regard to operational cost including main hardware elements. An extensive study on operational scenarios of various RLV concept recovery methods has been performed at DLR [9]. This investigation includes the autonomous return flight options LFBB and RTLS as well as the down-range recovery on a sea-going platform (DRL) and "in-air-capturing" by large towing aircraft. All direct costs including personnel, port- or air-traffic-control-fees, and depreciation of the drone ship or the aircraft have been taken into account and have been estimated based on publicly available data of similar vehicles. The preliminary results of the study indicate that both recovery modes DRL and IAC have similar operation expenses of approximately 500 k€ per flight [9, 10, 21]. Using IAC for small-sat launchers should make use of smaller and cheaper turboprop aircraft and recovery costs could be reasonably low at 150000 US$ per flight [21].

It is important to note that RLV-recovery costs represent only a minor portion of overall launch costs. Another factor is hardware refurbishment after each flight, for which limited experience is available today because of the low number

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of operational RLV to date. The short turn-around times meanwhile realized by SpaceX with their Falcon 9 first stages indicate that the refurbishment effort is limited. Comparing the mechanical and thermal loads of horizontal landing vehicles with those utilizing propulsive deceleration and vertical landing, it is to be expected that refurbishment costs for VTHL implementing IAC are likely to be lower than for VTVL since VTHL rocket engines do not require multiple ignitions during a mission and, further, the winged stage is not flying into its own exhaust plume during re-entry. Both phenomena are creating additional loads on the VTVL-hardware which usually impact the number of safe reuses or the effort for refurbishment after each flight.

If the efforts for recovery and refurbishment operations are coming close for all investigated RLV-return-methods, then the size and weight of the launcher stages are the dominant cost factors. The comparison of different return modes of the first stage RLV all sized for the same mission as shown in Figure 2 can serve as input for RC and NRC-costs estimations. The ascent propellant loading is between 15% and 32% less for the IAC-mode compared to VTVL in DRL-mode resulting in significantly smaller and lighter stages. Depending on the architecture and the operational scenario this improvement can allow cost reductions between 10% and 25% for IAC compared to the vertical landing method downrange on a ship as operated by SpaceX [11].

Accurate numbers on the cost-saving would require the selection of a specific launcher system and its mission and application scenario. However, it is safe to state that for an Ariane 6 class partially reusable launcher the reduction in cost per flight could be several million € and over the total life-cycle the saving potential could be well beyond a billion € [11].

1.3 “In-Air-Capturing” procedure high-level requirements

Based on previous analyses on the “In-Air-Capturing”-procedure, the following high-level requirements can be derived which should guide the technology development:

- **R1:** capturing of winged RLV-stages in subsonic flight in altitudes below 10000 m in areas downrange of the launch site
- **R2:** subsequently towing of winged RLV-stages in subsonic flight back to a release area close to the launch site
- **R3:** cost efficient operations making use of modified, existing, subsonic aircraft capable of towing the winged RLV-stage
- **R4:** safe operations of IAC with capturing success-rate > 99.9% (tbc) with minimum environmental impact and risk of third-party damage less than nominal space launcher operation

1.4 Potential “in-air-capturing” hardware

The most promising capturing technique is using an aerodynamically controlled capturing device (ACCD), showing the best performance and lowest risk [4, 5]. Thus, three flight vehicles are involved in the “in-air-capturing”-process: the winged RLV, the towing airplane and the ACCD which all need to operate in a closely coordinated way.

The ACCD is to be released and then towed by the airplane as in the artist impression in Figure 3. This device contains the connecting mechanism, avionics and simply advances towards the stage by its own drag and lift. Actuators control the ACCD’s orientation and the approaching velocity might be further controlled by braking of the towing rope from inside the aircraft for smooth close-in (Figure 3, right). Aerodynamic controllability and at the same time sufficient maneuverability of the ACCD during the subsonic capturing process are required. This device is in focus of the most challenging research and development needs for the “in-air-capturing”-technology.

Figure 3: Renderings of Airbus A340-600 large capturing aircraft towing the ACCD (small white dot in the center of left picture) and at right close-up of ACCD cautiously approaching the RLV-stage shortly before contact (A340-600 picture © AIRBUS S.A.S. 2010)

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2 Progress in H2020 research project FALCon

DLR started the first step beyond pure simulation of "in-air-capturing" up to lab-scale flight experiments in its internal project AKIRA [7, 8], targeting a TRL between 3 and 4. The project was initiated in early 2017 and finished end of 2019. In order to accelerate the development of "in-air-capturing"-technology, the Horizon 2020 project with the name FALCon (**F**ormation flight for in-**A**ir **L**auncher 1st stage **C**apturing dem**on**stration) has been kicked-off in March 2019 [7] and was finished after 45 months in November 2022. With total funding of 2.6 M€, the FALCon project addressed three key areas:

- "in-air-capturing"-Simulation (subscale and full-scale)
- "in-air-capturing"-Experimental Flight Demonstration
- "in-air-capturing"-Development Roadmap and economic benefit assessment

Table 1 gives a list of the partners involved in FALCon. Three of them are from the aerospace and mechanical research area (DLR, VKI and IMech-BAS) while the other four are European SME.

Table 1: List of FALCon project partners

Participant No	Participant organization name	Country
1 (Coordinator)	Deutsches Zentrum für Luft- und Raumfahrt (DLR)	Germany
2	Institut von Karman de Dynamique des Fluides (IVKDF, VKI)	Belgium
3	Drone Rescue Systems GmbH	Austria
4	Soft2tec GmbH (S2T)	Germany
5	Astos Solutions SRL (ASTOS)	Romania
6	Institute of Mechanics, Bulgarian Academy of Sciences (IMech-BAS)	Bulgaria
7	Embention	Spain

At 9th EUCASS-conference in Lille a dedicated session on FALCon had been organized and, in several papers, major aspects of the research status in summer 2022 were presented. (See references [14 - 19].) A VKI Lecture Series on RLV and "in-air-capturing" was held in April of 2022 addressing the fundamentals of the technology (ref. [6, 20 - 25]). This section cannot provide the same level of detailed results as in the previous publications but is briefly summarizing the final status at the project's end in November 2022.

Adequate simulation of the "in-air-capturing"-process was one key-element to increase its TRL in FALCon. This has been addressed in two workpackages which have a close interaction and fruitful exchange of requirements, methods and procedures. The following two subsections summarize the progress achieved for a full-scale, operational size and for the lab-scale experiment.

2.1 Simulations for full-scale application

The reference test case for full scale simulations in FALCon was a heavy-lift, high-performance launcher with a winged RLV booster with 80 tons return (empty) mass. This DLR-pre-defined winged stage can reach a trimmed subsonic L/D ratio up to 6. For this heavy RLV-class, the Airbus A340-600 (Figure 3) is considered suitable as towing aircraft because of its availability in relatively large numbers at very affordable prices as it is now leaving active airline fleets. Still this aircraft is fully capable of performing its capturing and towing mission with minor modifications. 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 [4].

A schematic of the reusable stage's full operational cycle has been shown already in Figure 1. The maneuvers involved in the IAC process can be divided into six phases as shown in Figure 4. 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. At around 20 km altitude the reusable stage decelerates to subsonic velocity and rapidly loses altitude in a gliding flight path. The RLV and the capturing aircraft 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 (Figure 4 a), actively controlled by aerodynamic braking. Any direct contact between the two large vehicles is to be strictly avoided and they are always kept at a certain safety distance. The connection is established via a small flight vehicle called "ACCD" (Figure 4 c). The time window to successfully perform the capturing process is dependent on the performed flight strategy of both vehicles and can be extended up to more than one minute. The entire maneuver is fully subsonic in a typical altitude range from around 8000 m to 5000 m [4, 8, 11, 14]. After successfully connecting both vehicles, the winged reusable stage is towed by the large carrier aircraft back to the launch site (Figure 4 e). Close to the airfield, the stage is released from its towing aircraft and autonomously glides back to Earth like a sailplane (Figure 4 f).

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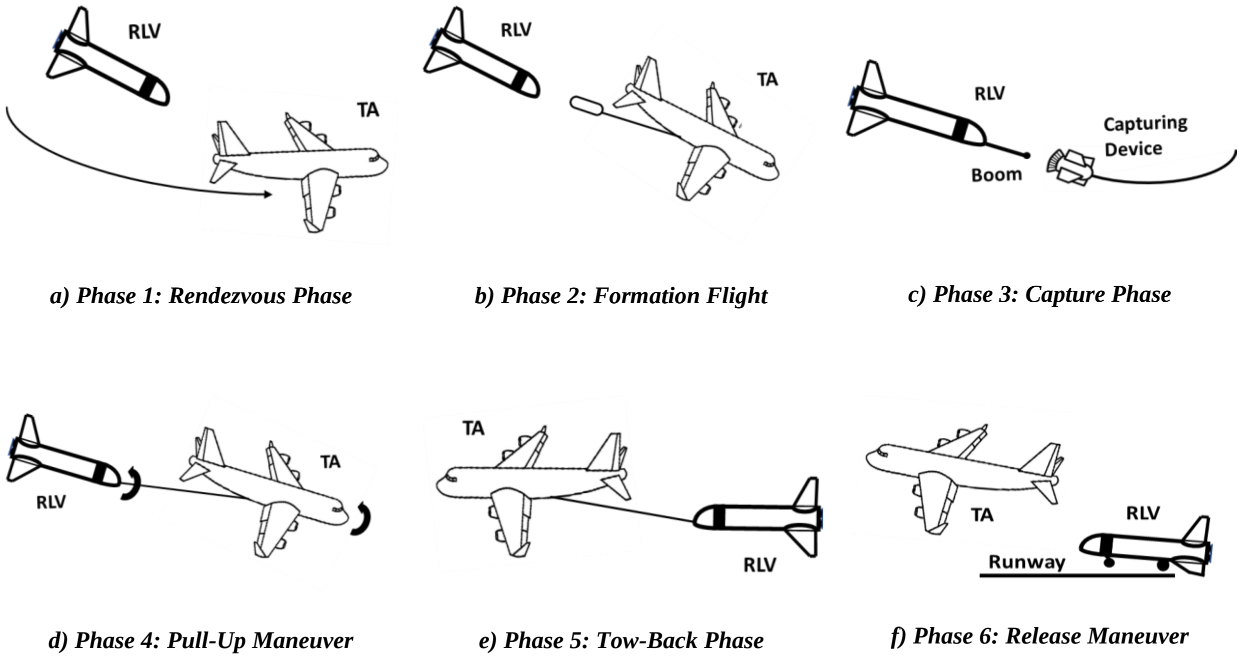

a) Phase 1: Rendezvous Phase *b) Phase 2: Formation Flight* *c) Phase 3: Capture Phase*

d) Phase 4: Pull-Up Maneuver *e) Phase 5: Tow-Back Phase* *f) Phase 6: Release Maneuver*

Figure 4: Phases of In-Air Capturing [15]

The parallel formation for IAC requires both the participating vehicles to be in a gliding flight with similar altitudes, velocities and flight path angles separated by a safe distance. The criteria or constraints for formation have been preliminarily defined and are described in [6, 12]. A crucial aspect ensuring such a formation is that the aerodynamic performance of both the RLV and towing aircraft should be matched as far as feasible. A real airplane might adapt its L/D to the target value but this would usually not coincide with the required conditions to keep it on a desired constant flight path and within acceptable speed range. An important factor is the generated lift-to-weight-ratio. Another factor on the dynamics is the remaining minimum idle thrust of the turbofan engines. Nevertheless, a certain “box” in velocity, altitude and flight path angle can be found in which both vehicles, the capturing airplane and the RLV-stage are flown sufficiently close to each other that capturing and connecting can be achieved.

A Monte Carlo study has been performed to identify which initial conditions would provide the longest formation times. Reference 12 presents the effect on formation time for 500 combinations of initial altitude and initial velocity of the towing aircraft. The longest formation times are obtained when the aircraft dives from initial altitudes between 7500 m and 8500 m.

The selected flight strategy and the applied control algorithms show in simulations a robust behavior of the capturing aircraft and reusable stage to approach each other [12, 14]. The consideration of a real reference aircraft (A340-600) and its constraints in L/D, initial weight, idle thrust limit the achievable formation duration However, the time in close formation is found longer than 60 s in many cases which provides still good margin for a successful maneuver [12, 14].

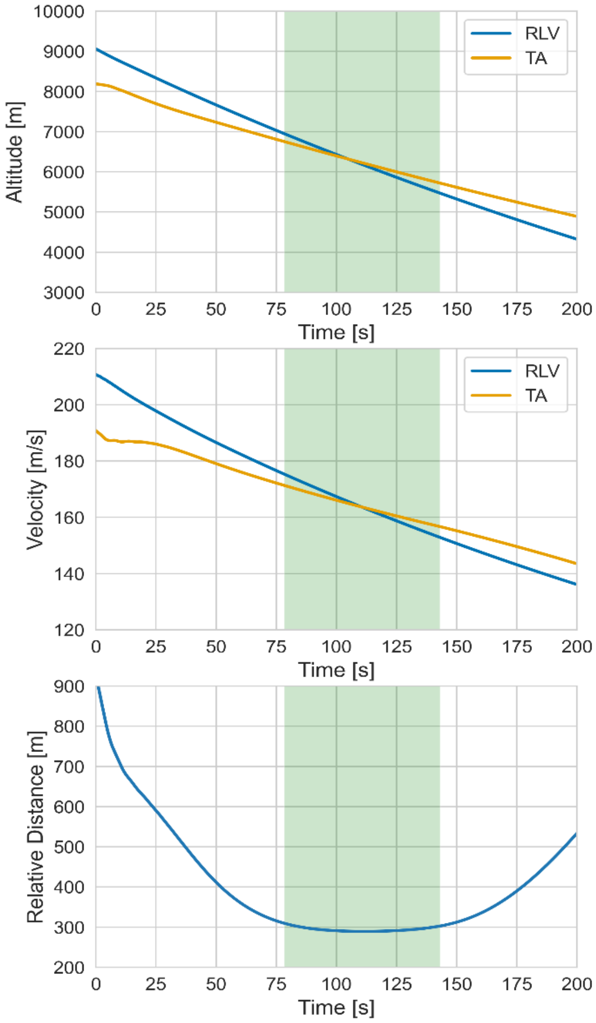

Figure 5: Rendezvous and formation flight trajectory simulation between towing aircraft (TA) and RLV

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To ensure that the aircraft and stage could operate in the towing configuration, the flight envelope was first assessed by static analyses [6, 7] and subsequently complemented by dynamic simulation of the pull-up maneuver right after capturing (Figure 4 d) of both vehicles executed by the A340-600 with four Rolls-Royce Trent 500 turbofans, confirming the generous margins even for significant larger RLV-stages than 70 tons [14, 17].

In order to quickly span the gap between TA and RLV, the highly agile and maneuverable Aerodynamically Controlled Capturing Device (ACCD) is needed. The nose is connected to the TA via rope and the back of the device contains a capturing mechanism that locks on to the RLV on contact. A preliminary configuration has been defined in early studies [4, 5] and the von Karman Institute (VKI) in cooperation with DLR established an aerodynamic database so that sufficiently accurate aerodynamic tables can be used to compute the forces and moments acting on the ACCD with acceptable required calculation time [15, 16, 25].

The capturing mechanism inside the ACCD is a critical part which has been preliminarily designed 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. The preliminary design of such a capturing mechanism has been developed (see drawing of internal parts in [5, 6, 7]) and has been subsequently mechanically sized supported by Finite-Element stress and deformation analyses [5].

The approach-, capturing- and towing-maneuvers of full-scale launcher stages are quite complex. Beyond the dynamics of all involved hardware, the turbulent wake field of the towing aircraft and sophisticated control algorithms are to be considered in the simulations. The wake generated by the A340 aircraft with deployed gear (for adjusting L/D) has been calculated using RANS methods [13, 15, 19] and a significant downwash (vertical) component at higher angles of attacks is observed [15]. Figure 6 shows the vortex formation behind the ACCD when approaching the nose section of the RLV. The rope dynamics are an important factor to be considered and a parametric numerical model has been established in the FALCon-project [15, 20].

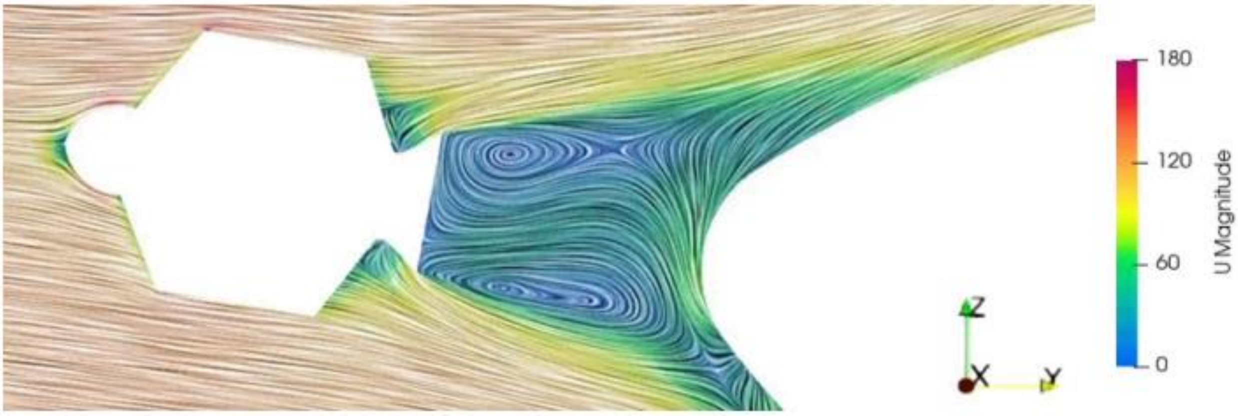

Figure 6: Close view of vortex formation behind the ACCD in coupled case with RLV nose [27]

A stepwise refinement of numerical models is constantly increasing the realism of the simulations. Recent results on full-scale "in-air-capturing" simulations of an RLV performed in the FALCon-project are presented in the references [15, 17, 19, 26, 27].

2.2 Simulations and tests for flight experiment

For validation of the developed algorithms before going into flight tests, a simulation of the overall maneuver with all components implemented and connected is mandatory to reduce the risk of damaging the demonstrators and even more important for ensuring the safety of persons on ground. Another objective has been tuning and integration of control parameters of controllers with code generated in simulation directly fed into the experimental flight demonstrators. The simulation environment has been built up modularly to simplify substitution of subsystems. For each experimental vehicle three flight dynamic models with different levels of fidelity were created. Two of these models have been nonlinear and the third been linear. The nonlinear model has been used to parametrize the flight control systems of the vehicles.

In FALCon, a windtunnel test campaign has been carried out to precisely measure all forces and moments experienced by the subscale coupling unit in its original size, covering a representative range of flight velocities (80 to 180 km/h). A windtunnel model of the experimental ACCD was manufactured for mounting onto the aerodynamic balance of the VKI L1-B windtunnel. CFD simulations featuring the ACCD in the windtunnel configurations were first compared with the experiments, yielding a satisfactory validation. Corresponding cases were run in realistic flight conditions without windtunnel effects. Additionally, CFD was used to extend the configurations to cases that could not be tested

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in the tunnel, featuring all four control surfaces at various deflection angles, roll, etc. This enabled to complement the aerodynamic inputs needed by the controller developed by DLR. The generated CFD test matrix includes complex asymmetric scenarios providing extra insight into the 3D flow field (Figure 7).

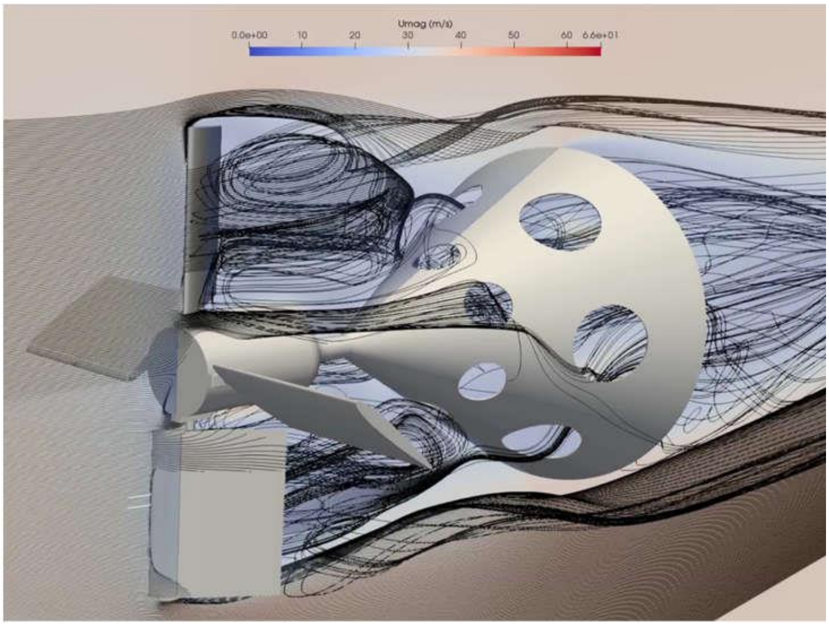

Figure 7: 3D flow field of experimental ACCD generated by CFD

As a baseline the simulation framework from previous DLR internal projects on UAV was utilized, which then was gradually expanded to meet the requirements of the FALCon-experiment. It consists of classic 6DoF flight mechanics, which takes the following forces into account: drag generated by the stabilizing cone, lift caused by the control surfaces and rudder deflection as well as an external force induced by the towing rope. Reference 24 shows an overview of all components of the applied modular simulation framework.

A sensor fusion algorithm is developed, which fuses all available measurements into one state and weighs them according to their quality. [24] The environmental perception system of the ACCD was designed to use a LIDAR laser scanner and an infrared camera to determine the position of the ACCD with respect to the nose tip of the RLVD. Both models, for LIDAR and IR camera, must calculate a relative position estimate that is based on the absolute position difference and contains the uncertainties with their respective characteristics. The sensor measurements are subject to noise and delay and arrive at different time intervals and with different sample rates. A generation routine for artificial images includes the expected noise of the image sensor and lens characteristics. The same algorithm is used in the simulator as run on the actual camera. The flight mechanical models also include motor & actuator dynamics. Since the control surfaces of the demonstrators are actuated by servos, the dynamics are approximated as PT2 transfer functions given that they include a feedback loop with a position encoder. The motor dynamics include parameters and characteristics from the respective engine data sheet. The environment model for each aircraft consists of an ISA-model, a WGS84 ellipsoid gravity model. In addition, a rope module was developed consisting of a 2D massless spring damper model. [24]

To get a better understanding of the position and orientation of each demonstrator and for debugging purposes, a visualization has been implemented (Figure 8). The images from video show the APUS flying in front of the RLVD building up the formation in the area of the National Research Center for Unmanned Aircraft (NRCUA) in Cochstedt and subsequently when connection is established (right).

Figure 8: Visualization of the lab-scale flight experiment simulation (https://www.youtube.com/watch?v=Q-DtsKuAy2k)

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2.3 Flight testing preparation

The experimental test and validation processes in FALCon was one of the key objectives of the project [18]. Both UAV are based on commercially available kits but were modified for the tasks in the FALCon-project [22]. The towing aircraft demonstrator (TAD) or *APUS* is a scaled replica Zivko Edge v540, an aero-artistic airplane (Figure 9). Some modifications were applied in FALCon: change of the aircraft engine to fulfil the required operation velocity, controlled shift in the center of gravity (CoG), adaption of the flight controller hardware. and additional extensions to enable safe BVLOS operations.

Figure 9: DLR UAV *APUS* intended to be used as towing aircraft demonstrator (TAD)

Embention has been in charge of preparing the RLV scale model aircraft. A vehicle geometry not necessarily typical for a winged RLV stage is chosen on the Rapier-kit jet plane (Figure 10). The so-called RLVD reaches a total length of 4.4 m and overall span of 2.6 m [22]. Note the unusual shape of the nose section prepared for the integration of the LIDAR sensor on top and how this integration had been realized. This nose geometry is producing additional aerodynamic drag. Thus, the subsonic trimmed L/D is approximately 7 and CoG is far aft because of the jet engine placed in the back. Both parameter values are typical for winged RLV-launcher stages. Control surfaces are elevons, flaperons and rudders [22].

Figure 10: RLV scale model *RLVD* of Embention with sensor head integration shown in figures on the right

The coupling unit was built as an upgrade of the device developed and used in the previous AKIRA project [7, 8]. The original ACCD was completely built with carbon composite materials. Flight tests showed that this kind of construction being highly stable but also brittle. As a consequence, several parts of the ACCD crack already during a nominal landing. Therefore, a new design and building process had been developed to reduce the necessary maintenance effort. The new ACCD designed during the FALCon project (Figure 11 left) is built by rapid prototyping using Polyactida (PLA) as base material.

An integrated communication and data fusion strategy has been developed in FALCon. A sensor package had to be integrated into the flight experiment with an infrared camera system on the RLVD in combination with optical markers on the coupling unit [23]. The ACCD is equipped with LEDs forming a specific pattern which is recorded using an IR sensitive camera located in the nose of the RLVD [24] (Figure 11 right).

All hardware components were integrated in to the RLVD at Embention, Spain (Figure 10 right). However, the planned final function test was, unfortunately, not possible within project duration, because flight tests became impossible after the TAD was damaged in a test anomaly as explained below.

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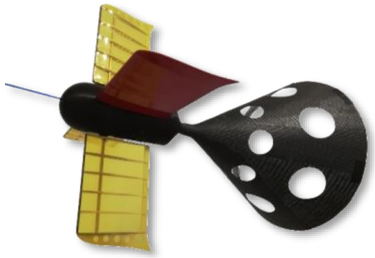


Figure 11: Coupling unit or experimental ACCD (left) and LED pattern, visible in the cone of the ACCD in static camera tests (right)

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. The camera included a processing unit for on-board evaluation of the images using a dual core Cortex A9 CPU and a matching GPU for offloading pixel-based processing from the CPU.

The joint flight tests with the RLVD, TAD and ACCD were planned to be realized at the National Research Center for Unmanned Aircraft (NRCUA) at Cochstedt, Germany, which is operated by DLR [22]. The maneuver was to be implemented in an altitude range between approx. 655 m and 100 m above ground level, with a velocity of approximately 42 m/s (150 km/h). The non-propulsive RLVD should have followed a straight path of -10° glide path angle with the test covering a distance on ground of approx. 3100 m [22].

In order to be able to execute the flight experiment, both vehicles must first have received flight authorization. A significant effort had to be spent in FALCon on this task obtaining such flight permits. This action was requested for each vehicle and managing organization separately. DLR applied to Germany's LBA for the TAD and Embention applied to Spain's AESA for the RLVD and then asking for LBA approval operating the RLVD in Germany based on *Easy Access Rules for Unmanned Aircraft Systems*.

After many iterations with AESA, Embention was granted in June 2022 with the flight authorization for the RLVD covering operation in a generic scenario as specified in the ConOps, SAIL II, BVLOS and flight over sparsely populated area and maximum altitude of 1218 m. After many additional iterations with LBA, Embention was granted with the flight authorization for the RLVD also in Germany.

To reach the flight clearance of TAD (APUS), DLR requested the authorization to the LBA by means of delivering a similar data pack as for the RLVD. After many iterations, DLR was granted in September 2022 with a flight permit with the characteristics SAIL II, BVLOS, flight over sparsely populated area and maximum altitude of initially 220 m.

The flight authorization process of both vehicles (APUS and RLVD) including preparation has consumed roughly 18 to 20 months. This period of time was longer than originally expected and this is partly due to the general complications arising from the restrictions of the "corona crisis", but also significantly to the introduction of a new "SORA process" for which there was no previous experience, either on the part of the applicants or the competent authorities.

2.4 Flight testing performed

With the permission for UAV flight operations, the initial flight tests of RLVD including sensor head started in Spain in summer 2022. Planning for the formation flight training and subsequent demonstration of the ACCD coupling with the RLVD was completed and targeted for October 2022 in Cochstedt. Mid-September the APUS was ready for its first solo flight after approximately 17 months. Right after take-off on September, 21st during the first climb, the emergency parachute rescue system was deployed automatically. Due to the drag of the parachute and the engine automatically shut-off, the APUS was not possible to be retarded at its low altitude of 70 meters and the aircraft experienced a hard landing off the landing strip. The mishap was in no way related to the intended experiment and the APUS flight condition and attitude did not require any emergency action at the time right after take-off. The cause of the anomaly could be fast revealed using the log-file of the rescue-system. It turned out that during maintenance procedures at the manufacturer the parachute system had been erroneously set to automatic mode of a wrong configuration designed for different vehicles and triggered by events not at all critical for the APUS high-performance artistic airplane.

Unfortunately, the airframe had suffered some major damage, requiring several months of repairs and overhauls. These actions in autumn of 2022 prevented any further flight tests of APUS within the FALCon-project. This situation did not only exclude continuation of the formation and coupling demonstrations but had also a negative impact on the intended flight validation of the flight perception hard- and software. Any transfer of the hardware to the RLVD was

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impossible by the specific design of the connection. One of the lessons learned during the project was that a certain redundancy should be available on system level and to keep this affordable, it might be better to have the same aircraft type in both roles as towing aircraft and RLV-stage demonstrator. This would have the additional advantage of reducing the effort for gaining the flight authorization.

At the end of the FALCon-project the RLVD has been used solo in Spain for demonstration of the flight path required for the formation and coupling maneuver in order to gather all data necessary with variations of the descent flight path angle required by DLR for performing the experiment simulation. The manoeuvre was set as similar as possible to the one for the joint flight tests initially planned for Cochstedt. The maneuver started during a turn and then moved to a 0º roll position, and the control loops were aiming to acquire the target descent angle and speed. At this moment the jet engine was also set to idle, losing most of its thrust in order to simulate an aircraft without engine like an unpowered reusable rocket stage. After a convergence period of around 10 seconds with a little overshoot, the target speed and path has been acquired, remaining within acceptable margins of error for the rest of the descent. Once the lower altitude bound was reached (150-200 m AGL) the formation flight test was finished, the jet engine thrust raised and the aircraft went to a loitering position waiting for the next input.

During this flight campaign a total of three nominal descents were executed with a good degree of repeatability, reliability and adaptability. Also, the initial design, planification and simulations were evaluated as solid and accurate, allowing for a very smooth transition into the flight test with little to no incidents, changes or deviations from the original design needed to fulfil the required performances.

2.5 Technical development roadmap definition for future implementation

The development roadmap for “in-air-capturing” has been defined in cooperation with the European stakeholders e.g. ESA, CNES, ONERA, CIRA, VKI, DLR, universities and industrial partners. This process considered the classical Technology Readiness Level (TRL) definition (e.g. [30]). 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.” [30] Exactly this methodology has also been implemented in FALCon for the establishment of the “in-air-capturing” roadmap.

Starting point of all activities concerning “in-air-capturing” was the already achieved technology development status from DLR’s AKIRA-project [7, 8]. Results on IAC from this previous activity had been made available to FALCon-project partners. The Horizon2020 FALCon-project initiated PDA Phase 2, with the aim of consolidating the TRL of 4 and IRL close to 1 by modeling all relevant maneuvers with sufficient accuracy.

As an aerospace system, the following technology areas are of potential relevance in the development and demonstration of the “In-Air-Capturing”-technology for the recovery of winged RLV-stages:

- Aerodynamics
- Structure & Mechanical Systems
- Propulsion
- GNC
- Software, IT, communication
- Electrical system

An operational system would have a potential impact on the following areas:

- Operations in flight & on ground
- Certification & Qualification
- Manufacturing
- Safety and legal issues
- Environmental issues
- Economics

The three aerospace vehicles, winged RLV stage, towing aircraft and capturing device or ACCD are planned to be used in the IAC procedure. Each of these vehicles might require new and innovative technologies but, in many cases, existing, of-the-shelf components and technology are probably fully sufficient. However, even if many components and hardware already exist, the successful interaction and interconnection of all these components in a new application with time-and safety-critical operations raises some developmental challenges.

A special activity in FALCon was the organization of several dedicated meetings and workshops with the stakeholders to bring the aerospace community together for review and coordination of the proposed roadmap. Unfortunately, this activity was severely affected by the impact of the “Corona-crisis” making all professional in-person events impossible.

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The 1st roadmap workshop on "in-air-capturing" development had to be organized as a “virtual” online conference on February, 10th 2021. In the this workshop the "in-air-capturing" method was explained to the European stakeholders and its superior calculated performance as an RLV-recovery method was demonstrated and the status of ongoing simulations, experiments and lab-scale flight demonstration in the FALCon project was presented. Further, the workshop described a first proposal for the following technology maturation steps after H2020 in the form of dedicated technology development roadmaps (see following section 2.6). A relatively short session for Q&A was included on February, 10th at the end of the event.

The discussions and feedback had to be moved to separate, dedicated splinter group meetings in a bilateral or multilateral form with all interested partners. These splinter workshops were held in order to appropriately address some of the open questions with regards to In-Air-Capturing and the development roadmap. These in total six meetings were focused on several subtopics and challenges related to IAC:

- System
- Avionics/GNC
- System dedicated to Microlauncher
- Operations
- Flight Testing
- Towing Aircraft Modifications

For those meetings, a group of experts on the respective field, not only limited to FALCon internal personnel but specifically including external experts, were invited to discuss the respective topics. The dedicated workshops were all happening by online teleconference between March 2021 and January 2022.

The 2nd technology development roadmap workshop consolidating all previous results with the interested stakeholders was organized on April, 28th 2022, right after the VKI-lecture series on “in-air-capturing”-technologies.

2.6 Proposed technology development roadmaps

The technical maturation plans are structured along the main technical areas requiring major development work as previously listed. Propulsion and electrical systems were not considered because almost no development effort seems to be necessary. A complete overview on the roadmaps has been presented in [14] and the final update in FALCon is available in [11].

2.6.1 Integration readiness

An IRL-centric view on “In-Air-Capturing” development is presented in Figure 12. The FALCon-project has run system simulations of the maneuver at full-scale, almost reaching the lowest IRL of 1 at the end of the project. The next step will see a detailed system design of all mechanical and electrical systems needed for IAC. The question if any mechanical or sensor prototypes are required for ground testing is to be evaluated.

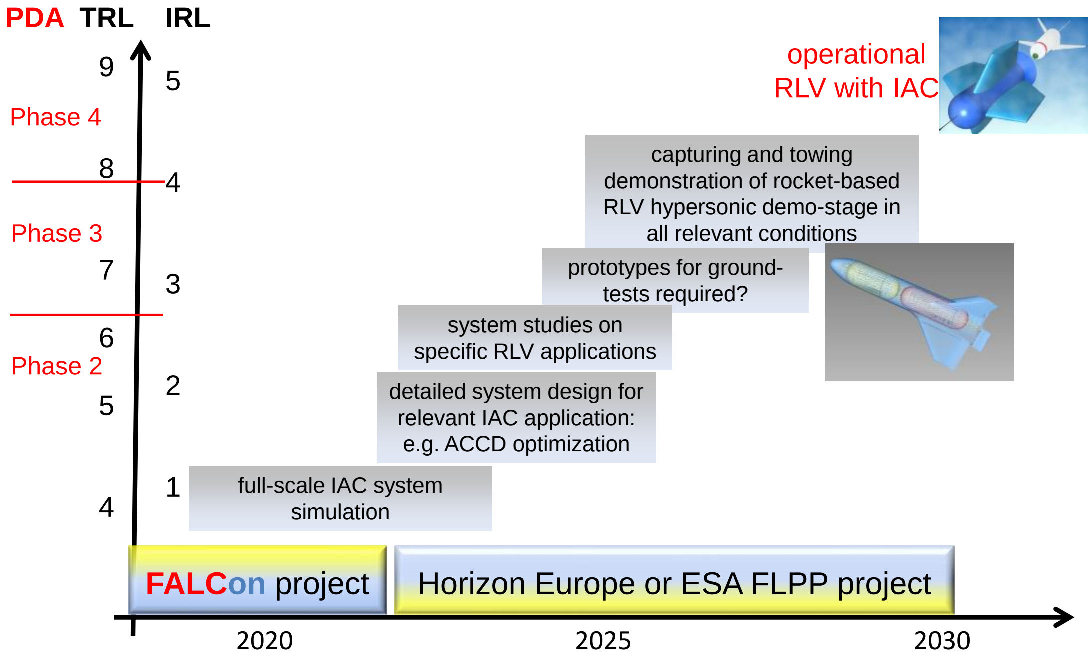

Figure 12: Development Roadmap proposed for “In-Air-Capturing” Integration Readiness

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2.6.2 Development Roadmap proposed in FALCon

A realistic Initial Operational Capability (IOC) target date for a completely new, partially reusable European launch vehicle is probably around 2035. Further assuming at least 5 years for development and qualification of the RLV, a TRL of 6 should have been achieved in 2029 by capturing and towing a representative hypersonic flight demonstrator. A TRL between 5 and 6 is usually accepted at the start of industrial development. As the IAC has a major impact on the overall launch system architecture, the TRL-requirement is set to 6.

This TRL with target date 2029 is used as the baseline of the updated technology development roadmap. Recent delays in the development of Ariane 6 could push the IOC of a next generation launcher with reusable first stage further to the right. The baseline target date is kept unchanged to the previous roadmap [14] but it should be kept in mind that some additional time margins might become available. Figure 13 shows which system demonstration milestones need to be achieved in the coming 5 to 8 years. After successful lab-scale demonstration another subscale demonstrator will be needed for increased scale, increased speed capturing and towing in all relevant weather conditions and during day- and night-time. Assuming funding is available without major delays, the lab-scale demonstration can be completed in 2023 and the subscale flight testing in 2026.

The option of linking “in-air-capturing” technology with recovery of the potential successor of DLR’s hypersonic demonstrator ReFEx should be investigated. Operational, certification and legal issues as well as an environmental compatibility assessment are to be addressed in the second half of the decade when a consolidated scenario has been established.

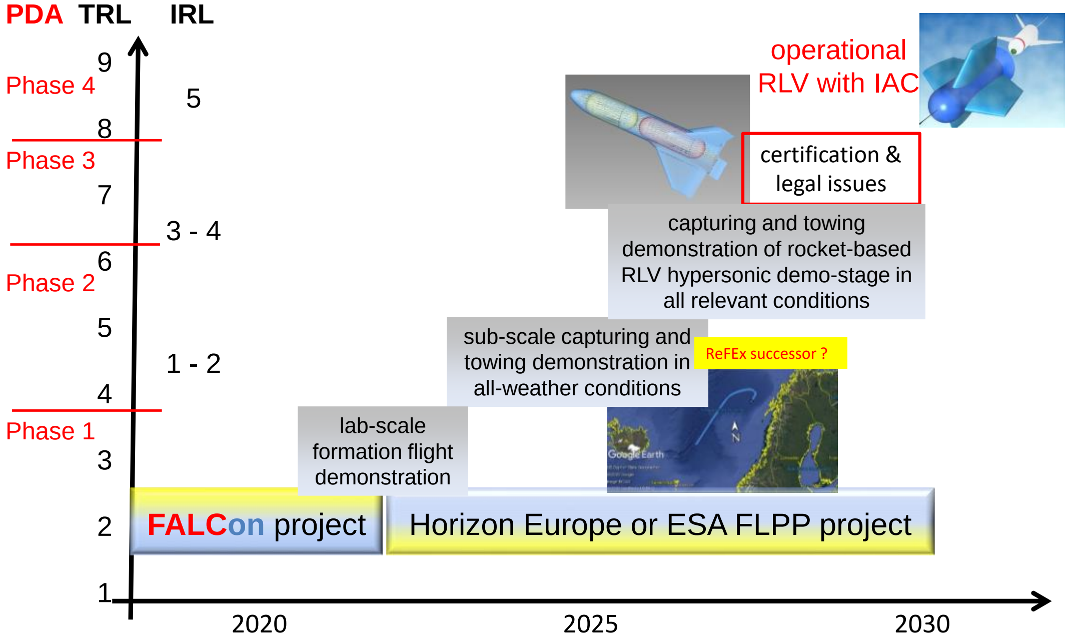

Figure 13: Development Roadmap major system demonstrations

The development roadmap shown in Figure 13 is oriented on a large-scale launcher and its RLV lower stage. Alternate operational scenarios of the “In-Air-Capturing” technology on potential micro-launchers or capturing reentry configurations are under investigation [21] and the promising results are to be discussed with European stakeholders. Those applications would probably need an adapted development of the major system demonstrations.

2.7 Proposed next step actions and development cost assessment “In-Air-Capturing”

Based on the technology maturation plans defined the immediate next steps after FALCon can be identified. Considering a time frame up to roughly 2026, mainly the following actions should be addressed:

- extensive perturbed flow analyses in different scales
- preliminary design of structural mechanism in ACCD and RLV-connecting port
- avionic component pre-selection for different full-scale applications
- improved data fusion model and interconnected guidance
- finalizing lab-scale flight demonstration
- sub-scale capturing and towing demonstrations (up to 250 km/h, up to 6000 m) flying in all relevant weather conditions during day and night
- full-scale simulations with refined models of the subsystems in nominal and off-nominal conditions
- systematic system studies on different launcher applications

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- environmental compatibility assessment, refined cost-benefit analysis, operational, certification and legal issues to be addressed

Using the technology development roadmaps for "in-air-capturing" a *rough* estimation of the investment needed to bring this advanced technology up to the industrial phase of launcher system development could be performed. The efforts are estimated for three phases subsequently following the FALCon-project:

- up to TRL5 / IRL1: **10 M€** (for above actions)
- up to TRL6 / IRL2: **40 M€** (+ hypersonic rocket demonstrator 30 M€ to 150 M€)
- up to TRL8, qualification: **100 M€** (+ launcher development)

These costs are to be accumulated and are all based on e.c. 2022.

Figure 14 shows the technology development effort of the phases split by major elements with the assumption of a hypersonic demonstrator flight costing 30 M€ alone. Actually, the latter is strongly dependent on the size and demonstration purposes and its reusability. The 30 M€ is at the lower end and might be the ReFEx-successor as mentioned above and shown in Figure 13. Using an operational mini-launcher's first stage for recovery at the end of a commercial mission might reduce this cost item and a larger, autonomous, rocket-powered demonstrator might go up to 150 M€ or beyond. The right column shows the development costs from TRL 6 to TRL8 with qualification before first launch only for "in-air-capturing"-related activities. The launch vehicle and ground infrastructure costs of the system are specific to the chosen design architecture and, thus, are not included.

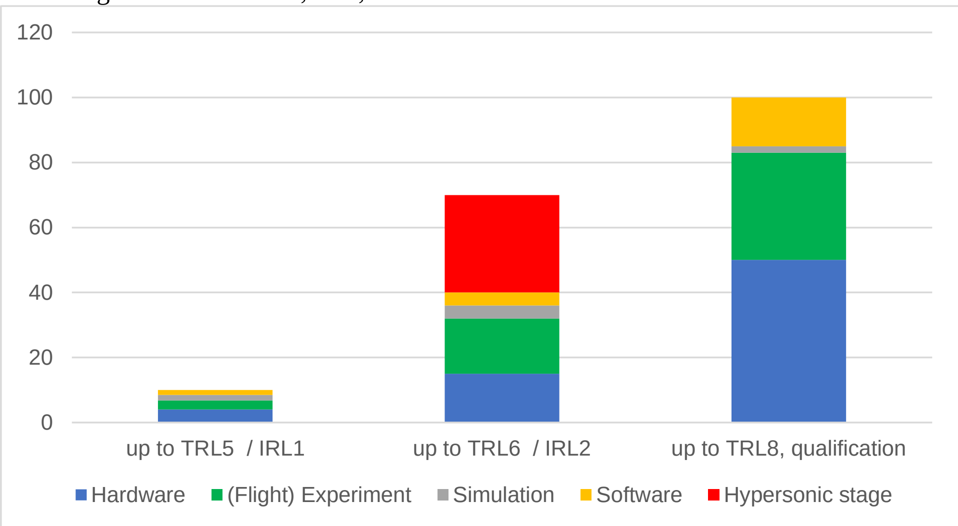

Figure 14: Technology development effort ROM [M€] (e.c. 2022) for "In-Air-Capturing"

2.8 Technology transfer options

Beyond the spaceflight related synergies also aeronautical applications have been identified with many technological similarities to the automatic approach and formation flight maneuver of IAC. One of the examples is the DARPA funded program X-61A Gremlin which achieved in October 2021 a spectacular successful in-air recovery of X-61 UAV by C-130 cargo aircraft [30]. The interest lies with deployment and later recovery of a large number of small swarming drones.

This year the US-company Magpie Aviation claimed to have achieved the "World's first automated aerotowing connections" [32] with having a civil aeronautical application in mind. Obviously, several technological synergies exist to the "in-air-capturing" of RLV-stages which is currently under exploration.

3 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 RLV-types and separation conditions. The functionality of the procedure and its high-level requirements are explained. Operational costs are found very similar to VTVL-stages. Thus, size of the reusable stages become driving factors for overall cost assessment. Depending on the architecture and the operational scenario this improvement can allow cost reductions between 10% and 25% for IAC compared to the vertical RLV-landing method used by non-European competitors.

The European Horizon 2020 research project FALCon has been progressing the "in-air-capturing"-technology in several areas which the paper summarizes. Two UAV and an automatic coupling unit were prepared for testing with the complex European authorization process been successfully concluded. The intended formation flight and autonomous

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coupling could not be tried within the project after an in-flight anomaly damaged the towing aircraft demonstrator in an incident not related to the planned experiment. Nevertheless, nominal unpowered descents were executed several times with the RLV demonstrator alone with a good degree of repeatability, and reliability showing good agreement with the simulation models.

Significant progress was reached by performing sophisticated full-scale- and lab-scale-flight experiment simulations. The flight experiments were supported by refined simulations of the planned formation flight maneuver with subscale vehicles. Several sensor models were included and validated as far as data became available. The simulation of the full-scale launcher application made significant progress and major results are summarized. A close formation flight duration of more than 60 s is possible and the pull-up of a winged RLV-stage with at least 80 tons dry mass was demonstrated.

The technical maturation plans in-air-capturing"-technology have been defined and discussed with broad participation from European aerospace research, agencies and related industry. The derived technical development roadmaps can reach a TRL of 6 by the end of the decade and thus allow the advanced RLV-recovery-technology to be implemented in a completely new, partially reusable European launch vehicle to be operational around 2035. The next development steps are identified and the estimated investment of 10 M€ required is found affordable in comparison with alternative RLV-technology demonstrations.

From the technology perspective "in-air-capturing" can be made ready for use as the best RLV-recovery method providing Europe once again with one of the most advanced launcher systems.

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