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RLV-Return Mode "In-Air-Capturing" and Definition of its Development Roadmap

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An innovative approach for the return of reusable space transportation vehicles has been proposed: 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 project FALCon (Formation flight for in-Air Launcher 1st stage Capturing demonstration) funded by EC in Horizon 2020 is progressing this advanced technology. A dedicated session at the EUCASS 2022 is organized with a total of 6 technical presentations.

This paper serves as an introduction into the topic, summarizes system aspects of the launcher performance improvement and explains the structure of the FALCon-project.

Main part of the paper is the definition of the next steps for the technical development roadmap. This activity has been organized in cooperation with the European stakeholders from industry, agencies and research organizations. The outcome and results of two dedicated workshops and additional splinter meetings are summarized. The iterated technology development roadmaps considering the recommendations from the splinter meetings are presented.

Abbreviations

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
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

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.

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 [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 conventional sailplanes.

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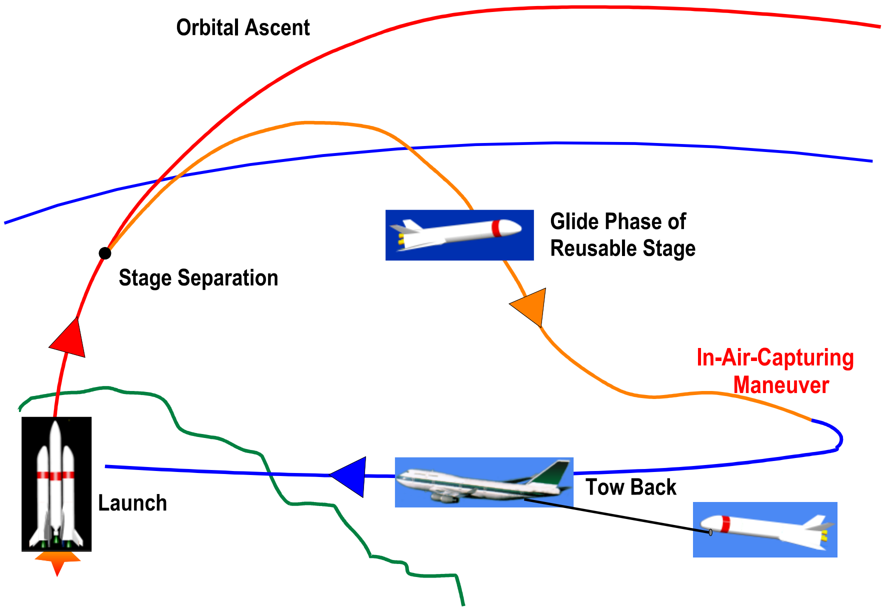

Figure 1: Schematic of the innovative "in-air-capturing"

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. The first proposal was made by the Russian launcher company Khrunichev [5] and more recently by the American company ULA for its Vulcan launcher. The ULA proposal intends recovering not more than the first stage's engine bay instead of a full stage [6, 7] which is driven by the mass constraints of a parachute and helicopter-based MAR as already explained in [5]. Currently, reusability of any Vulcan component seems to have lost priority in the development program.

In April 2020, the NZ-based company Rocket Lab has successfully performed a drop test and helicopter recovery of its Electron micro-launcher first stage. The company has announced their intention to recover the first stages using mid-air retrieval [8]. Such capture of a first stage involved in a launcher mission to space has been achieved for the first time with Electron flight #26 on May, 2nd 2022. As this stage was released by the helicopter shortly after and splashed down to the ocean, the full recovery for subsequent operational use is still to be demonstrated.

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. For this reason, probably, ULA switched to partial recovery of the engine bay only of the relatively large Vulcan first stage. A brief historic review of MAR in spaceflight history is included in [20].

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. The DARPA funded program X-61A Gremlin achieved in October 2021 a spectacular successful in-air recovery of X-61 UAV by C-130 cargo aircraft [9]. The interest lies with deployment and later recovery of a large number of small swarming drones.

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:

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

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 [22]) 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 [22]. As mission and stage number are

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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 [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. 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.

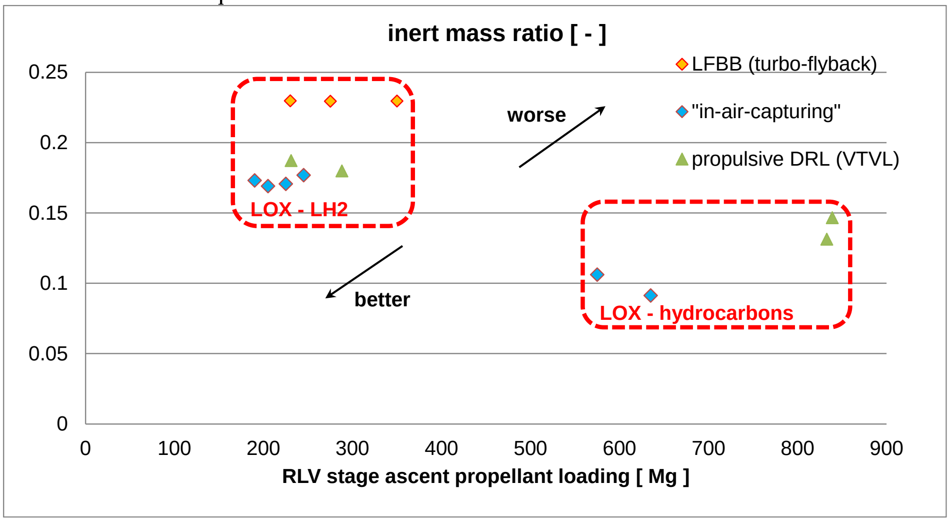

Figure 2: Inert mass ratio depending on RLV-return modes and ascent propellant loading, GTO-mission TSTO (LOX-LH2 and LOX-hydrocarbons)

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 has been presented in [15]. The turbofan-powered LFBB mode requires a significantly heavier and larger stage compared to an IAC-mode RLV. 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 [15].

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 [22]. 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. However, inflatable devices like ballute could be even more beneficial for small launchers than winged concepts, offering good performance while keeping the re-entry loads within reasonable limits [22]. In case of small launchers, using vertical landing might lead to a performance penalty too high to be economically and technically viable. Simple parachute methods with late deployment in the subsonics as obviously intended for Electron have the lowest mass impact [22] but experience heatloads during reentry in excess of SpaceX' Falcon9. Thus, suitability of this approach even for small launcher applications with delicate liquid engines is still to be demonstrated.

1.2 Cost assessment

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: a relatively large-size capturing aircraft – depending on the size of the RLV. Used, refurbished and modified airliners like the Airbus A340 shown in Figure 3 are sufficient for the task of towing large winged RLV.

The stage dry mass of an RLV to be recovered by "in-air-capturing"-method, usually correlated with development and production costs, is reduced by 37% compared to the reference LFBB-configuration [15]. Even when considering 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.

An extensive study on operational scenarios of various RLV concept recovery methods has been performed at DLR [16]. 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

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indicate that both recovery modes DRL and IAC have similar operation expenses of approximately 500 k€ per flight [16, 17, 22].

Using IAC for small-sat launchers should make use of smaller and cheaper turboprop aircraft as recently investigated by DLR [22]. The recovery costs could be reasonably low at 150000 US$ per flight. The share of recovery costs using a smaller turboprop aircraft to total launch costs (5 million US$ for Electron) is 3% and thus comparable to the heavy-lift scenario [22].

2 How “in-air-capturing” (IAC) works

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.

At around 20 km altitude the reusable stage decelerates to subsonic velocity and rapidly loses altitude in a gliding flight path. At this location the RLV is awaited by an adequately equipped capturing aircraft. 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. 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” (see section 2.2). 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 [3, 15, 18, 21]. 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.

2.1 “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

2.2 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 [3, 4]. 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 and simply advances towards 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 (Figure 4). With an ACCD release initiated at e.g. 230 m distance between the two crafts both in parallel descent, the whole maneuver can take about 14 s in the nominal simulated case and without wake turbulence according to the simplified early simulations. All loads at controlled contact remain then below 3 g and the final relative velocity is at 5 m/s [3, 10].

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 in early studies [3, 4] and aerodynamic data sets have been generated (Figure 5 and [19]) to be used by intended 6DOF-simulations briefly summarized in the following section 2.3. An engineering model of the aerodynamic data set has been established which is a superposition of limited CFD-calculations to generate an extended database with asymmetric flap deflections [25]. This approach is found to be sufficiently accurate and in good balance to required computation time [25].

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Figure 3: Rendering of Airbus A340-600 large capturing aircraft towing the ACCD (small white dot in the center) which is approaching the RLV-stage in the back, A340-600 picture © AIRBUS S.A.S. 2010

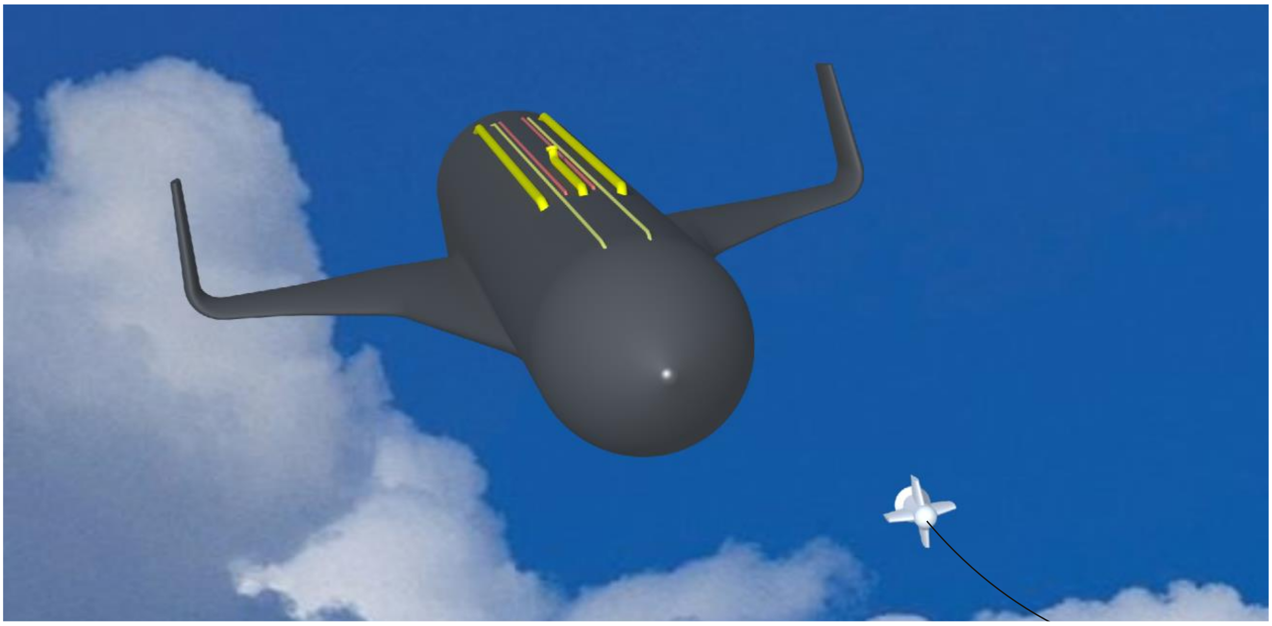

Figure 4: Rendering of ACCD cautiously approaching the RLV-stage shortly before contact

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 [4, 13, 20]) and has been subsequently mechanically sized supported by Finite-Element stress and deformation analyses [4, 11, 12].

The towing 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 has been estimated in early analysis to be sufficient for up to 200 kN load [3]. Actually, the rope dynamics are an important factor to be considered and a parametric numerical model has been established in the FAL-Con-project [21, 24].

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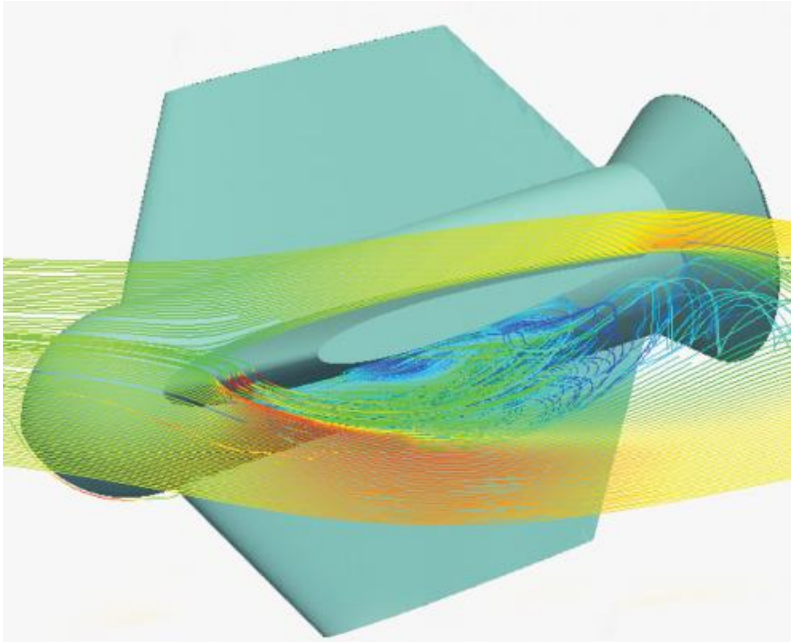

Figure 5: CFD simulation by VKI of the full-scale Aerodynamically Controlled Coupling Device (ACCD)

Preliminary technical requirements of the tow-aircraft were already derived in [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 (Figure 3) or Boeing-747-class jet, which have been produced in large numbers. Meanwhile, a vast quantity of these airplanes is available at an affordable price, since many of them have now been retired from commercial airline service.

DLR performed a study on different RLV recovery options including technical feasibility assessment [13]. To ensure that the aircraft and stage could operate in the towing configuration, the flight envelope was computed for the A340-600 with four Rolls-Royce Trent 500 turbofans connected to a winged RLV stage of approximately 70 tons return mass [20] (see alternative example B747-400 in [13]). This static analysis is complemented by dynamic simulation of the pull-up maneuver of both vehicles right after capturing confirming the generous margins even for significant larger RLV-stages than 70 tons [21, 26].

2.3 Simulated approach, capturing and towing 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 around 0.5. 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.

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 preliminary defined and are described in [18, 20]. One critical aspect to ensure such a formation is that the aerodynamic performance of both the RLV and towing aircraft should be matched as far as feasible. The initial goal is set to maintain a minimum of 60 s of formation to allow the capturing device to attempt the capture of RLV.

Plotted data of early flight simulations for the approach maneuver have been presented in [3, 15]. Simulations of the RLV-approach (3DOF) indicated that a minimum distance below 200 m between RLV and aircraft can be maintained for up to two minutes [3, 15] when the aircraft is assumed following a constant glide angle compatible with the target L/D of the RLV.

However, 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,

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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. The reference RLV is assumed to be non-cooperative at an altitude of 9170 m with a velocity of 197 m/s at the start of the dive simulations. Reference 18 shows the effect on formation time for 500 combinations of initial altitude and initial velocity of the towing aircraft (reference A340-600 as in Figure 3). It can be observed that the longest formations 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 [18, 21]. The refined modeling of a real reference aircraft (A340-600) and its constraints in L/D, initial weight, idle thrust reduces the achievable formation duration compared to ideal assumptions of the past [3, 15]. However, the time in close formation is found longer than 60 s in many cases which provides still good margin for a successful maneuver [18, 21].

The approach, capturing and towing maneuver of full-scale launcher stages is 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. A stepwise refinement of numerical models is increasing the realism of the simulations. Latest results on full-scale “in-air-capturing” simulations of an RLV performed in the FALCon-project are presented in the references [24, 26].

3 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 [13, 15], 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, a Horizon 2020 project with the name FAL-Con (**F**ormation flight for in-**A**ir **L**auncher 1st stage **C**apturing dem**on**stration) has been kicked-off in March 2019. Now scheduled to finish after 45 months in November 2022 and with total funding of 2.6 M€, the FALCon project addresses 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)

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	Insitut 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

3.1 Flight testing preparation

The experimental test and validation processes in FALCon are the key objectives of the project [27]. Half of all the workpackages are dedicated to this goal. The to be captured RLV-stage demonstrator has been purpose-designed while DLR introduced a tow aircraft for FALCon (Figure 6). Both UAV are based on commercially available kits but modified for the tasks in the FALCon-project [23]. The coupling unit will be an upgraded version of the device developed and used in the previous AKIRA project [13, 15]. An integrated communication and data fusion strategy is 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 [28]. 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 [29]. The hardware including on-board

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computers must be lightweight for not influencing the flight performance but powerful enough to run the state machine and the formation algorithms.

Figure 6: DLR UAV *APUS*

Embention is in charge of preparing the RLV scale model aircraft that will be used in the simulation of the in-air capturing maneuver. A vehicle geometry not necessarily typical for a winged RLV stage is chosen on the Rapier-kit jet plane (Figure 7). The so-called RLVD reaches a total length of 4.4 m and overall span of 2.6 m [23]. Note the unusual shape of the nose section prepared for the integration of the LIDAR sensor on top. This 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 parameters values are typical for winged RLV-launcher stages. Control surfaces are elevons, flaperons and rudders [23].

Figure 7: RLV scale model *RLVD* of Embention

The planned joint flight tests with the RLVD, TAD and ACCD will be realized at the National Research Center for Unmanned Aircraft (NRCUA) at Cochstedt, Germany, which is operated by DLR [23]. The maneuver will 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 follow a straight path of -10° glide path angle that the test will cover a distance on ground of approx. 3100 m [23]. Recently, both flight vehicles (APUS and RLVD) have finished the SORA authorization process. With the permission for UAV flight operations, the intended flight tests will conclude the project in summer 2022.

3.2 Simulations for experiment and full-scale application

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 have a close interaction and fruitful exchange of requirements, methods and

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procedures. Experiment simulation is supported by windtunnel tests in subsonics at VKI. Recovery simulations of full-scale RLV first stages is supported by CFD calculations of the flow field around the three full-scale vehicles/objects in formation flight conditions and the dynamic modeling of all these vehicles including the flexible dynamics of the towing rope [24].

The aerodynamic parameters are among the essential inputs required by the flight dynamic models, and were previously based on low fidelity aerodynamic tables [15]. The von Karman Institute (VKI) in cooperation with DLR revised this aerodynamic database so that sufficiently accurate aerodynamic tables can be used to compute the forces and moments acting on the ACCD [24, 25, 30]. The wake generated by the A340 aircraft with deployed gear has been calculated using RANS methods [18, 19, 24, 31] and a significant downwash (vertical) component at higher angles of attacks is observed [24]. A short summary of latest results from simulation of full-scale "in-air-capturing" is provided in the above section 2.3 starting on page 6.

Further, wind tunnel tests have been completed to precisely measure the aerodynamic performance of the subscale coupling unit in its original size. As a result, a more refined simulation of the "in-air-capturing" technology with subscale vehicles can be performed in preparation to the flight demonstrations. A sensor fusion algorithm is developed, which fuses all available measurements into one state and weighs them according to their quality. [29] The sensor measurements are subject to noise and delay and arrive at different time intervals and with different sample rates. As a consequence, the standard equations of the Extended Kalman filter has been slightly adapted [29].

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. Reference 29 shows an overview of all components of the applied modular simulation framework. 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 image shows the APUS flying in front of the RLVD building up the formation in the area of the NRCUA in Cochstedt.

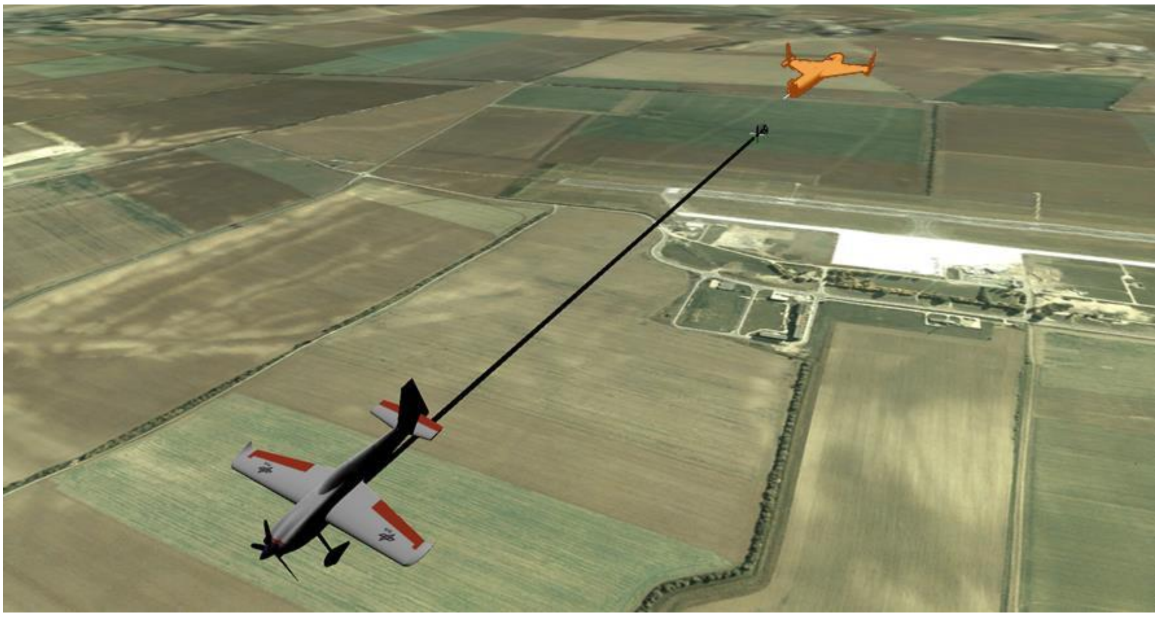

Figure 8: Visualization of the lab-scale experiment simulation [29]

4 Technical development roadmap towards future implementation

The development roadmap for "in-air-capturing" is defined in cooperation with the European stakeholders e.g. ESA, CNES, ONERA, CIRA, VKI, DLR, universities and industrial partners. This process considers the classical Technology Readiness Level (TRL) definition (e.g. [14]). 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." [14] Exactly this methodology is implemented in FALCon for the establishment of the "in-air-capturing" roadmap.

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Starting point of all activities concerning “in-air-capturing” is the already achieved technology development status from DLR’s AKIRA-project [13, 15]. Results on IAC from this previous activity have been made available to FALCon-project partners. Completion of AKIRA finished also PDA Phase 1 and approached a TRL of 4. The Horizon2020 FALCon-project initiated PDA Phase 2, consolidates the TRL of 4 and is planned to bring some relevant technologies close to a TRL of 5 and IRL close to 1 by modeling all relevant maneuvers with sufficient accuracy.

4.1 Dedicated workshops with European aerospace stakeholders

A special activity in FALCon is 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. The 1st roadmap development workshop "in-air-capturing" was scheduled in Paris in March 2020, exactly at the time when the spread of Corona-Virus (Sars-CoV-2) and CoViD-19 cases and related regulations by authorities made all professional events of this type impossible. Due to the highly dynamic situation developing in Europe with most of the international travel options being annulled, the workshop scheduled March 26th/27th 2020 as an in-person event had to be cancelled.

As the situation did not sufficiently improve by end of 2020, the 1st roadmap workshop on "in-air-capturing" development had to be organized as a “virtual” online conference on February, 10th 2021. This event had been planned for reduced duration of 3 hours, understood as more adequate for an online meeting.

In the first part of 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. Afterwards, the current status of on-going simulations, experiments and lab-scale flight demonstration in the FALCon project have been presented and complemented by an outlook on the next steps in the H2020-project. 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 4.3). A relatively short session for Q&A was included on February, 10th at the end of the event.

Participants from the following organizations were registered and actually participating at least partially in the three and a half hours online-event: ASTOS (DE, RO), CIRA (IT), CNES (FR), Dassault (FR), Deimos (ES), DLR (research and space agency) (DE), European Commission (REA), Embention (ES), ESA HQ Paris, ESA-ESTEC, GTD (ES), Lockheed Martin (UK), ONERA (FR), Pangea (ES), REL (UK), RFA (DE), S2T (DE), VKI (BE).

The discussions and feedback scheduled for the 2nd day of the cancelled Paris workshop has been 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 discussion with Airbus Flight Testing in Toulouse on the feasibility of A340-600 modifications to allow as the capturing and towing aircraft was already held in July 2020.

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. Participants from the following organizations were registered in the five hours hybrid event: ASTOS (RO), CIRA (IT), CNES (FR), Dassault (FR), DLR (DE), ESA-ESTEC, ONERA (FR), REL (UK), Supaero (FR), VKI (BE).

4.2 Areas of technology development and demonstration needs

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

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- 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

As described in section 2.2, three aerospace vehicles are planned to be used in the IAC procedure:

- winged RLV stage,
- towing aircraft and
- a capturing device or ACCD

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.

4.3 Proposed technology development roadmaps

The subsequently presented technical maturation plans are structured along the main technical areas requiring major development work as listed in section 4.2. Propulsion and electrical systems are not considered because almost no development effort seems to be necessary.
Note, the placement of the box "FALCon project" in all figures of this section shows the time but not necessarily the TRL position reached in FALCon. The center of each box is located close to the intended TRL and its width represents approximately the time extension of the activity.

4.3.1 Aerodynamics

The most important technology development activities in the field of aerodynamics are presented in Figure 9. Major activities of the future will have to focus on the formation flight of different vehicles in close proximity and perturbed wake flow conditions.

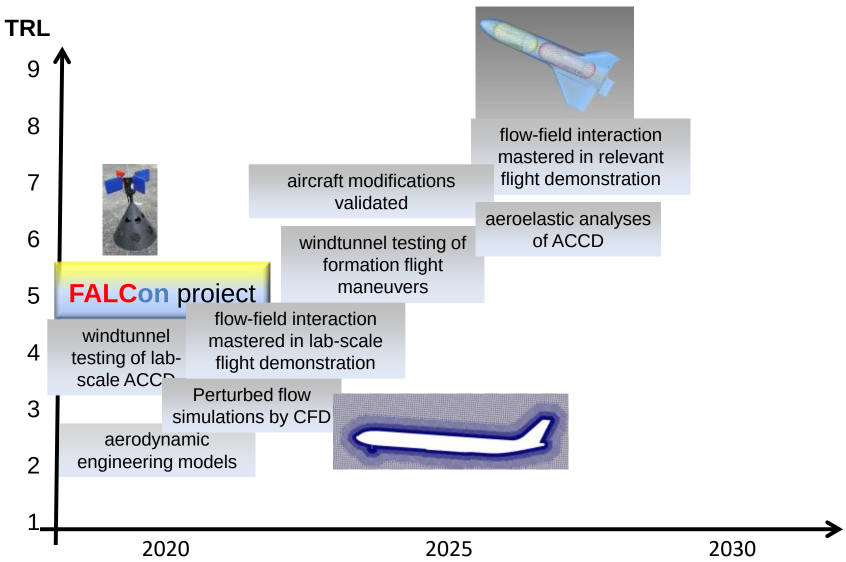

Figure 9: Development Roadmap proposed for aerodynamic technologies

4.3.2 Structures and Mechanics

The most important technology development activities in the field of structures and mechanics are presented in Figure 10. Major activities of the future will have to focus on component and mechanisms development and ground testing considering structural dynamic behavior.

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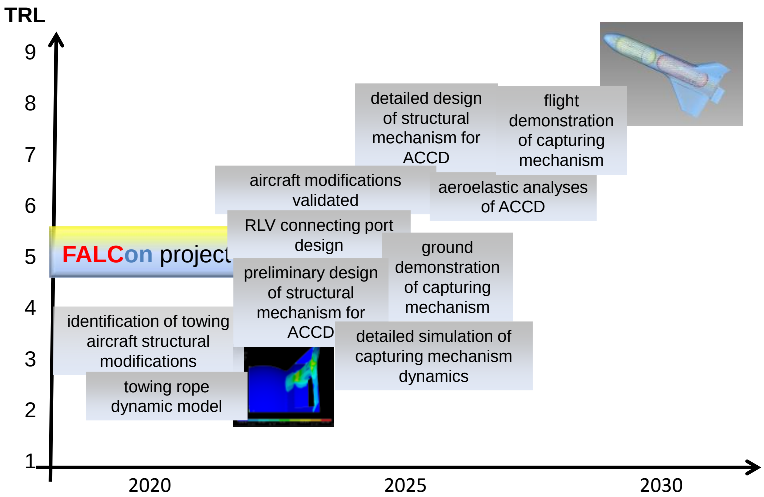

Figure 10: Development Roadmap proposed for structures and mechanics

4.3.3 GNC

The most important technology development activities in the field of GNC are quite extensive, both in numerical simulation of future full-scale operational types and flight testing of subscale size. Therefore, these are presented in two separate plots in Figure 11 and Figure 12.

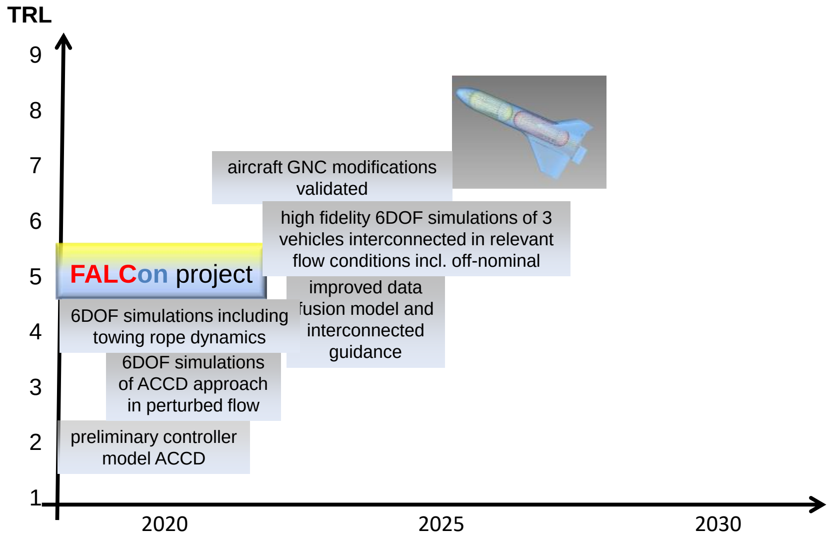

Figure 11: Development Roadmap proposed for GNC simulation (full-scale)

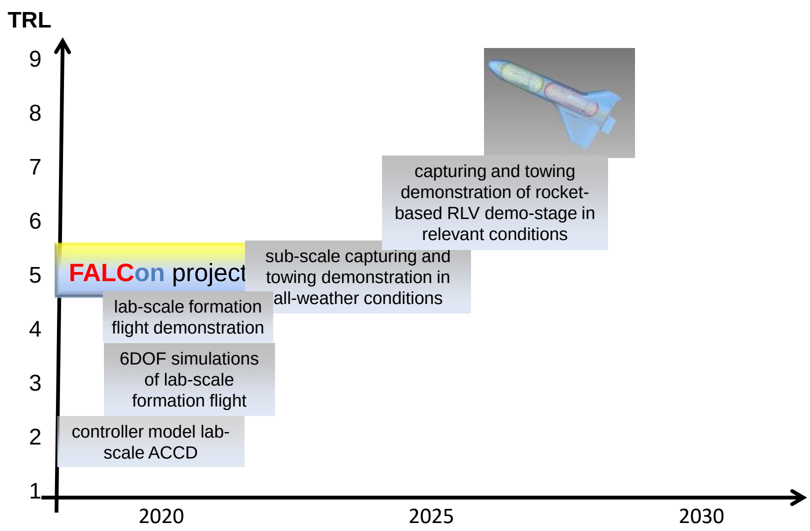

Figure 12: Development Roadmap proposed for (subscale) flight testing

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Major activities of the future will have to focus on suitable data fusion and connected guidance and high-fidelity simulations of the In-Air-Capturing process of an RLV stage, including simulations of relevant off-nominal behavior. The next step in flight demonstration will introduce larger scale vehicles performing the full procedure of approach, capturing, towing in all-weather, day & night conditions. The final flight demonstration step at the end of the 2020s is the multiple successful capturing and towing of a returning hypersonic RLV demonstrator. Future flight testing should be performed over the sea for ground risk mitigation.

A critical point for the subscale flight testing becoming more apparent in the discussions in 2021 was the fact that the right size of UAV required for the next demonstration steps are not readily available in Europe.

4.3.4 Software, IT

The most important technology development activities in the field of software and IT are mostly related to object recognition, perception and data fusion. An overview is presented in Figure 13. Major activities of the future will have to focus on suitable data fusion and perception techniques which are connected guidance and potentially to an autonomous artificial neural network for vehicle GNC.

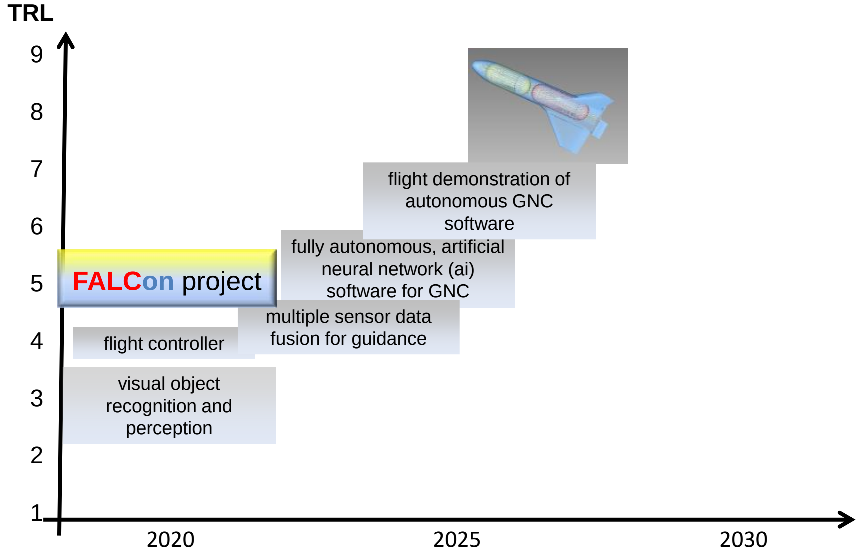

Figure 13: Development Roadmap proposed for software and IT

4.3.5 Integration readiness

An IRL-centric view on "In-Air-Capturing" development is presented in Figure 14. The FALCon-project should run system simulations of the maneuver at full-scale, 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.

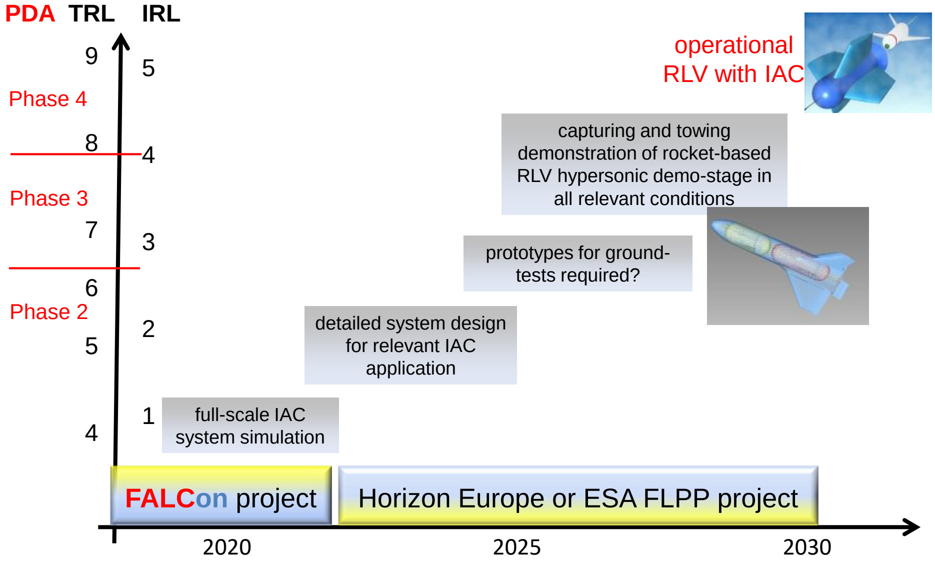

Figure 14: Development Roadmap proposed for "In-Air-Capturing" Integration Readiness

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4.3.6 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 technology development roadmap on system level. Figure 15 shows which system demonstration milestones need to be achieved in the coming 5 to 8 years. After successful lab-scale demonstration in FALCon another subscale demonstrator will be needed for increased scale, increased speed capturing and towing in all relevant weather conditions and in day- and night-time. Operational, certification and legal issues are to be addressed in the second half of the decade when a consolidated scenario has been established.

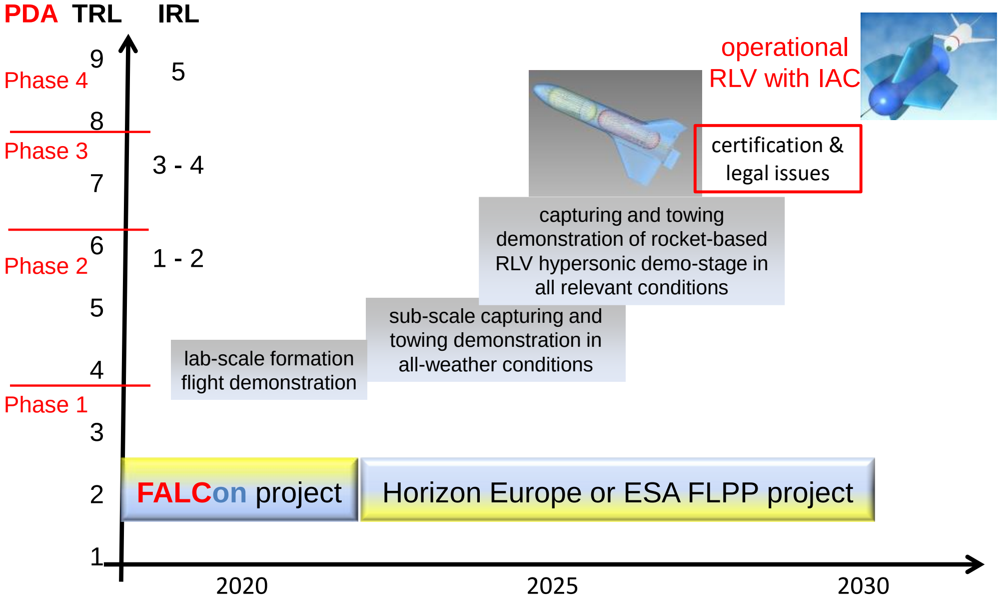

Figure 15: Development Roadmap major system demonstrations

The development roadmap shown in Figure 15 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 [22] and the promising results are to be discussed with European stakeholders. Those applications would probably need an adapted development of the major system demonstrations.

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 RLV-types and separation conditions. The functionality of the procedure and its high-level requirements are explained. Latest simulation results of the full-scale application are summarized which are presented in more detail in additional EUCASS2022-papers.

The European research project FALCon within Horizon 2020 is progressing the "in-air-capturing"-technology by performing lab-scale flight experiments to bring the TRL beyond 4 at the end of this year. The required UAV are now ready for testing in Cochstedt and the complex European authorization process is finalized. The flight experiments are supported by refined simulations of the planned formation flight maneuver with subscale vehicles. 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 for ensuring the safety of persons on ground.

Beyond the promising performance of the advanced RLV-recovery method and significant progress already achieved in its technical analyses, the remaining open points and the required next development steps are systematically analyzed in FALCon. Two European-wide workshops and several dedicated splinter meetings have been organized in this context with a broad participation from aerospace research, agencies and related industry.

The technical maturation plans are presented, structured along the main technical areas requiring major development, namely aerodynamics, structure & mechanical systems, GNC and software, IT, communications. The fields of

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propulsion and electrical systems are identified as not requiring any maturation dedicated to the "in-air-capturing"-process. 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 implemented in a completely new, partially reusable European launch vehicle to be operational around 2035.

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. Its realization is now mainly subject to political courage or clearly success-oriented entrepreneur's decision.

Acknowledgements

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