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Analysis of Novel Concepts for the Return of Upper Rocket Stages

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Abstract
A general shift to non-destructive controlled re-entry for any kind of launcher element that reaches an orbit after use without dead-end and possibly contaminating disposal in the environment could increase not only economic, but environmental sustainability in the space sector. This paper provides a review on launcher related space debris and deployable concepts are discussed as a cost-effective, integrable technology for a "design to not demise". A gap analysis of existing deployable recovery concepts is presented as well as research approaches for the application of rigidly deployable systems for cost efficient orbital stage recovery.

1. Introduction

According to the Space Environment Report 2022 of the European Space Agency (ESA), the Kessler effect [1], that could make space inaccessible for many generations, can already be seen today, as the number of objects in orbit is already multiplying by itself in the absence of further launches [2]. Upper stages represent a significant share of total debris and as due to their size, they have a high potential for collisions and generating additional debris [3]. In Europe, ESAs approach for reducing the collision risk is, among others, to perform active debris removal. However, this may only be effective when actually removing hundreds of orbital stages [4]. Therefore, in addition, a quick removal of orbital stages to be launched in the future from crowded orbit regimes such as Low Earth Orbit (LEO) at end-of-life is of crucial importance for the future of the space industry.
But in addition to the risk to future missions from uncontrolled anthropogenic space objects, the issues of sustainability and ecological footprint are also coming into focus, i.e. in particular the impact on the environment and climate from future and increased space activities. It is common practice in spaceflight to let spent satellites and rocket stages burn up in the Earth's atmosphere or fall into the ocean without being recovered. As space activities grow into a mass-produced industry, this is neither economically nor ecologically sustainable in the long term. Also, the particles produced during re-entry promote or could promote climate change, especially in view of increased space activities in the near future. In Europe, ESA has therefore been pursuing the development of new standards and technologies for the long-term realisation of a sustainable space industry with minimal environmental impact as part of the Clean Space Initiative since 2012 (see, e.g., Ref. [5]).
The realisation of spent launch vehicle removal represents a crucial hurdle in the development of a sustainable space industry. Both, removing existing upper stages and preventing the placement of further upper stages in orbit would have a correspondingly effective impact on reducing or avoiding space debris. The recycling or reuse of spent orbital stages could make spaceflight more sustainable. This requires orbital stage recovery. Research into the return of rocket stages has been going on since the early days of spaceflight, such as Convair in 1957 with a reusable single stage to orbit (SSTO) [6] or the NASA in the 1970s with the Space Shuttle [7], primarily with the aim of reducing launch costs and increasing launch rates. While reusable first stages such as the Falcon 9 first-stage boosters are now an increasingly common part of the space industry, there are as yet no established comparable solutions for the return of stages that reached an orbit. The recovery of large structures from Earth orbit is a challenge and usually associated with high costs due to the high velocities during re-entry. Novel concepts for particularly mass-efficient deployable and at the same time robust structures, made possible by advances in materials research, could enable cost-efficient orbital stage recovery. This in turn would allow at least partial reuse of expensive components and prevent recyclable materials

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from being disposed of in the environment. Therefore, as a first step, a literature review on orbital stage return was done, summarised below. Firs an overview of the characteristics and related challenges of orbital stage recovery and the state of the art of novel deployable recovery concepts is given based on a literature review. In the end, current technology and research gaps are presented as well as new research approaches.

2. Quantification and current strategies

This section summarises the quantitative situations of orbital stage debris in Earth orbit and goes into detail on the problems with current disposal strategies.

2.1 Quantification

Launcher systems that bring payload into an Earth orbit are made of one or more propulsive segments, that are separated from the remaining segment, or stages, one after another on different altitudes at different velocities. If a rocket stage reaches the first cosmic velocity of 7.9 km/s, it has orbital velocity. After releasing the payload, these stages are considered space debris. The payload is brought into the target orbit by the upper stage of a rocket, but lower stages of some launcher systems themselves already reach orbital velocity. To cover the total amount of launcher stage induced debris, all these stages will be referred to as orbital stages. Currently, orbital rocket stages are not yet being recovered after use. With correspondingly low orbital altitudes, orbital stages are being left until natural decay due to residual atmosphere induced drag or perform a de-orbit manoeuvre, followed by re-entry and falling into the ocean or on land. According to the Space Environment Report 2022 of ESA [2], in July 2022 there were about 36,500 objects larger than 10 cm in Earth orbit, created since the official beginning of space industry in 1957 [8]. The number of orbital rocket launches is estimated to grow by 15% p.a. or more in the coming years, not yet taking space tourism activities into account. With a projected further increase in space activities by a factor of 5-10 over the next decade, launches will increase accordingly. Of all catalogued Earth orbiting objects, rocket bodies represent about 8% as shown in Figure 1, although there are estimations up to 11 %. This does not include fragmentation parts of upper stages. Rocket bodies are the source of 35% of the total breakup debris [3, 2]. Figure 2 shows the history of the total number of rocket bodies launched into orbit since the beginning of space flight. In addition, this data show that about two-thirds of the orbital stages ever launched have been deorbited, and a second curve emerges showing the increase in longer-term or permanent orbital rocket bodies. However, above a perigee height of 300 km about 70 % of all orbital stages have not yet been deorbited. The underlying data were taken from the standard catalogue for space objects that contains all artificial objects in the orbits of Earth and those that left Earth's orbit, provided by J. McDowell [9]. According to these data, about 78 % of the deorbited orbital stages re-entered within their launch year or the following year. The differentiation by orbit, namely altitude and inclination, plays a decisive role in terms of criticality for debris growth. Therefore, Figure 3 and 4 show an evaluation of the data with regard to the quantity distribution of orbital rocket stages in the LEO regime over perigee altitude and inclination. The data for all orbital stages ever launched in Figure 3 show a compression at a perigee below 1000 km and one significant peak for an orbit inclination at about 52° within a perigee altitude between 170 and 210 km. A comparison with Figure 4 shows that this and some other orbital regions have relatively small amounts of orbital stages in the long term, despite a high launch frequency. A clear maximum in non-deorbited orbital stages is seen at an inclination of about 83° between a perigee altitude of 945 and 970 km. This is consistent with evaluations by Surrey Satellite Technology Limited [4]. From this evaluation it also appears that disused upper stages have significantly high values when considering the product of mass and probability of collision of each debris object, an arbitrarily chosen measure of the effective influence of an object on debris development. The origin of objects with high effective impact is primarily in upper stages of launchers of the Commonwealth of Independent States (CIS) and secondarily in upper stages of launchers of the United States (US). From Figure 4, it can be seen that orbital stages primarily cluster below a perigee height of 1500 km at inclinations just below 100°, at about 83°, at about 75° and at about 63°.

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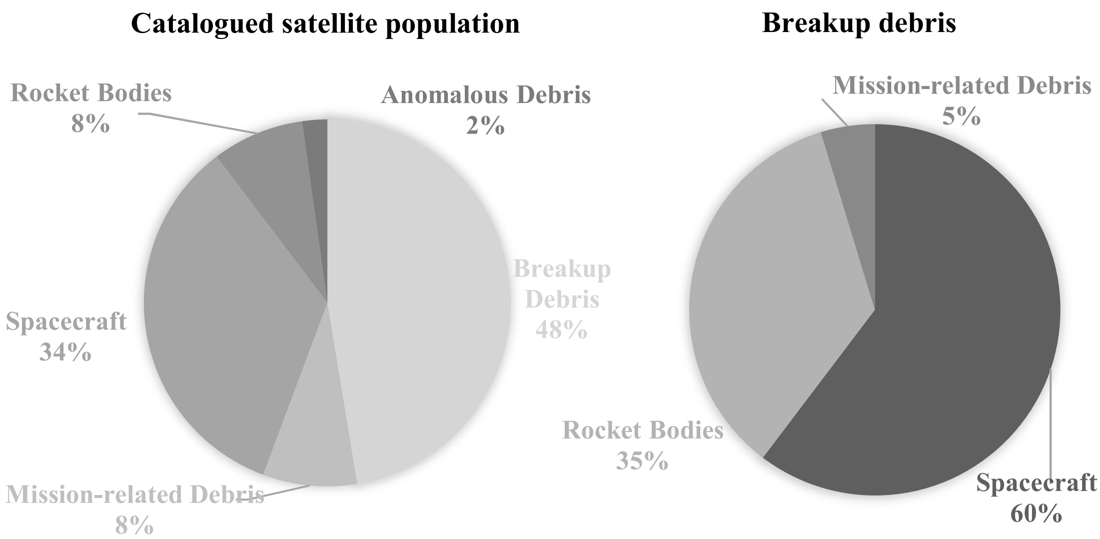

Figure 1: Left: Relative segments of the catalogued in-orbit Earth satellite population. Right: Sources of all catalogued satellite breakup debris by satellite type. [3]

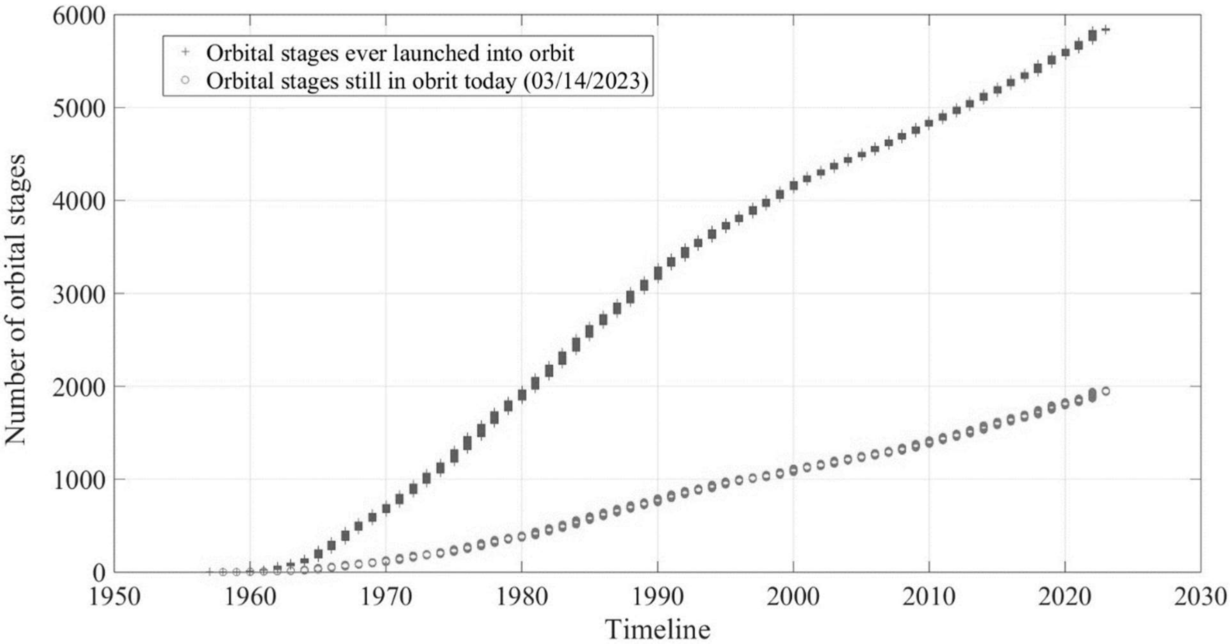

Figure 2: History of the number of upper stages ever launched into Earth orbit since the beginning of spaceflight and upper stages still in orbit today [9].

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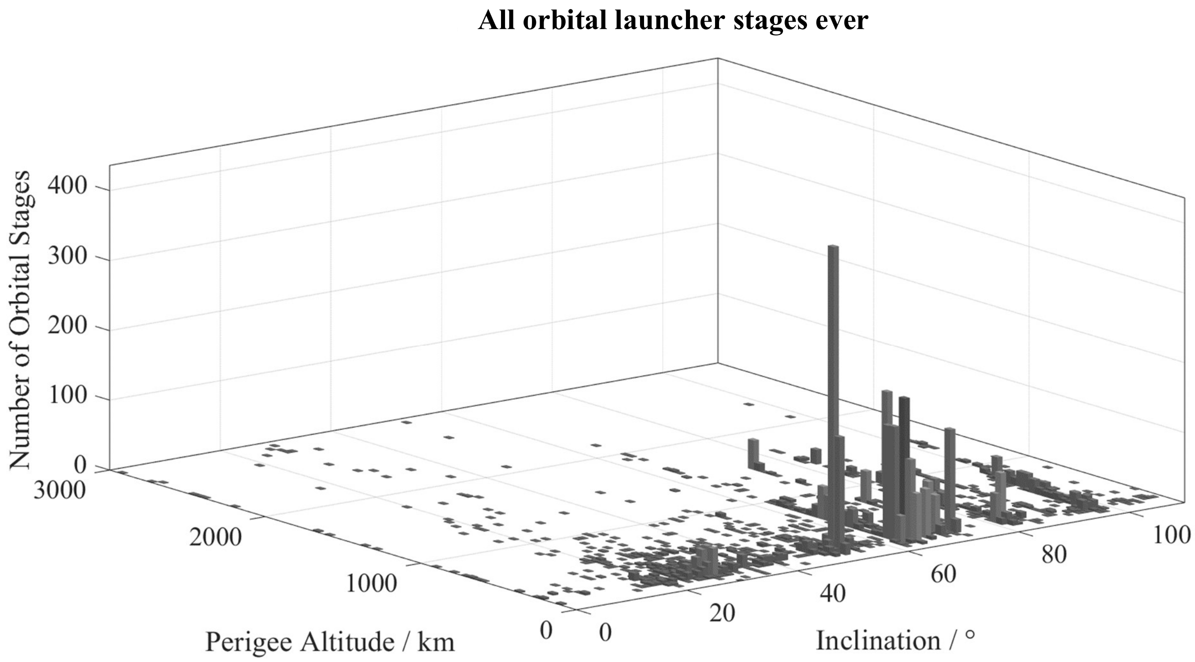

Figure 3: Distribution of the number of orbital rocket stages that have reached an Earth orbit since the beginning of spaceflight (as of 03/14/2023) over their respective orbital inclination and perigee altitude. The representation is limited to a perigee altitude of up to 3000 km and an inclination between 0° and 110° [9].

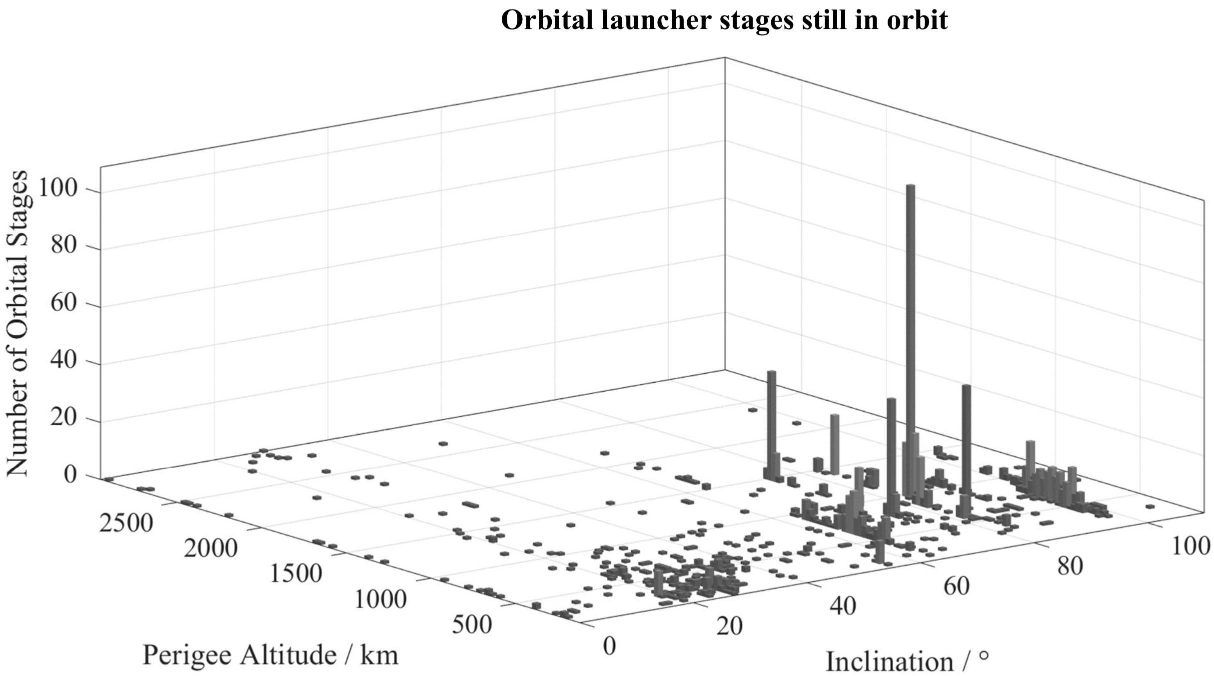

Figure 4: Distribution of the number of orbital rocket stages that have reached Earth orbit since the beginning of spaceflight and are still in orbit today (as of 03/14/2023), over their respective orbital inclination and perigee altitude. The representation is limited to a perigee altitude of up to 3000 km and an inclination between 0° and 110° [9].

2.2 Current disposal strategies

As mentioned, removing orbital rocket stages from certain locations such as LEO is crucial to prevent space debris from affecting future space activities. According to international space agreements such as the "UN Space Debris Mitigation Guidelines" [10], space operations today shall respect a panel of space debris requirements which are applicable to launcher elements. According to these requirements, an object whose orbit passes the LEO region must

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Figure 5: Left: Carbon-fibre-wrapped pressure tank of a Falcon 9 upper stage recovered after uncontrolled re-entry on Java [11] Right: Debris possibly associated with this space debris was found after the CZ-5B re-entry over Indonesia in early August 2022. 3 Debris found by locals in Sanggau regency (near the Indonesian-Malaysian border) [12]

vacate within 25 years, or, in the future, even 5 years. ESAs goal in general is to reduce the number of orbiting debris to zero. In case of upper stages, as a first approach, their design should be adapted so that no components without thrusting capabilities such as payload adapter and fairings are decoupled from the propulsion stage when orbiting. In addition to this, ESA is investing in in research and comprehensive realisation of “design for demise” [13] as a mandatory measure for all objects that perform uncontrolled re-entry. However, large space structures such as upper rocket stages burn incompletely in 5-40% of cases today when performing uncontrolled re-entry with about 70% of all re-entries being uncontrolled [14, 15], which then results as a serious hazard on the ground. Even targeted design changes for higher demisability might not make large structures such es rocket stages fully demisable at any point which means they will either always have to perform controlled re-entry or, in the long term, be part of in-orbit recycling circles [16]. However, both destructive re-entry or controlled ocean disposal makes reuse or recycling impossible and there is no near future realization of in-orbit recycling. Also, the general public is more and more concerned by re-entry risks and by expendability of costly elements thrown away in the oceans [17]. Figure 5 shows examples of potentially dangerous impacts during uncontrolled re-entry such as the "planned" uncontrolled re-entries of large upper stages, such as the CZ-5B of the Chinese "Long March" rocket in November 2022, or the uncontrolled impact of unburned upper stage fuel tanks.
Another aspect are the combustion products resulting from destructive re-entry as they are suspected of promoting environmentally and climatically harmful effects, such as damage to the ozone layer [18]. The main emission during hot plasma induced burn is Al_2O_3 from aluminium for metal structures, CO_2 and soot for carbon fibre reinforced polymer (CFRP) structures. However, these emissions are difficult to avoid. The influence of aluminium and its oxides is of particular interest, since the effects are not yet clearly known: On the one hand, alumina particles scatter shortwave solar radiation back into space, but on the other hand, they absorb longwave infrared radiation from the troposphere and the Earth's surface, and thus have a greenhouse effect. Since alumina particles see both downward and upward radiation, it is not clear which process dominates. Also unknown is the exact lifetime of the particles at these altitudes (estimated up to 5 years in some cases!), which could also lead to a corresponding accumulation if space activities continue to increase. In addition, alumina is considered to be a demisable alternative for components such as reaction wheels and tanks, which require design changes in the future if design for demise is required and this in addition could increase the amount of alumina particles in the future.

2.3 Economics

According to M. Ragab et al. [19], recent developments in commercial launch vehicle providers, combined with strong competition in this market, are causing renewed interest in finding alternative ways to recover launch vehicles in order to reduce the cost of access to space. Economic efficiency of reusable spacecrafts is strongly related to refurbishment costs, also described by M. Ragab et al. In the case of reusable upper stages, there are high performance requirements on the system due to the loads on re-entry, which can be a key cost driver for refurbishment. However, an alternate approach to reusable systems for economic efficiency and ecologic sustainability could be recovery for recycling. An important aspect regarding future launching systems also is the increased focus on smaller payloads in lower orbits

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and related to this, the increased use of smaller launchers, whose recovery is potentially less complex. Reusable upper stage concepts such as the Space Shuttle, X-38 [20] or Space Rider [21], are designed and intended to be profitable for limited, specific applications and such concepts usually only provide for the recovery of this stage and still leave behind launcher remnants in orbit, such as service modules in the case of the Space Rider concept. A more holistic concept is now Space X's Starship [22] with a potentially reusable upper stage intended to replace all other SpaceX-operated launcher systems in the long term. The question of a comparison of possible recovery concepts with such an upper stage arises especially if this form of spaceflight should have the potential to replace common launcher systems and micro launchers. However, the capability of a reusable launcher systems to reduce not only costs, but also negative or even hazardous environmental impacts is not necessarily given by reusability alone and whether and to what extent reusable concepts improve costs as well as environmental footprint is the subject of recent research [23–25].

3. Launcher recovery novel concepts – State of the art

In this chapter, the specifics for orbital stage recovery are summarised and deployable systems are presented as novel technology for launcher recovery.

3.1 Aspects of orbital stage recovery and re-entry

When discussing options for extending orbital stage systems so they can be recovered, the degree of difficulty bringing back objects from orbit largely depends on their mass and inertial velocity [19]. While first stage recovery technologies are well developed today just as Space X’ Falcon 9, Blue Origin’s New Shepard or Rocket Lab’s Electron [26, 27] where velocities are low enough for the efficient utilization of retropulsion, orbital rocket stages recovery faces significantly more challenges. Typical inertial velocities of suborbital first stages are in the range from 3-6 km/s, whereas recovering from LEO with an orbital velocity of 7-8 km/s requires a de-orbit manoeuvre and at higher orbits such as GEO-Transfer, one deals with velocities of about 10 km/s at perigee [19]. When an object is to be returned from an Earth orbit, it has to perform atmospheric re-entry, passing different flight regimes, which are shown in Figure 6. When considering a recovery concept for an orbital stage, it must cover deorbit, atmospheric flight with the corresponding heat shield concept and aerodynamic deceleration and control capabilities for descent and landing. Also, orbital stages have strongly varying geometries between the different launcher systems and correspondingly varying mass distributions. Figure 7 shows examples of different active or future upper stage systems to demonstrate the system variety. However, an entry vehicle needs to have its centre of gravity near the entry shield for stability reasons, which can be hardly achieved for long upper stages [17] and heavy, exposed engine nozzles. Also, without a payload and emptied fuel tanks, dynamics of the stage can change a lot, which must be considered for the deorbit manoeuvre [28]. Examples of this are deployable entry systems, which are described in more detail within the next section.
If an object is to survive re-entry, for example for reuse, the required design is essentially defined by the maximum permissible loads, which in turn depend on the trajectory. A key indicator for categorising entry trajectories is the glide ratio L/D which determines the ability to generate shear forces. Here, L is the aerodynamic lift force and D the aerodynamic drag force. Gliding bodies such as the Space Shuttle, usually have a glide ratio of about 0.75 or higher and are classified in terms of entry trajectories as lifting bodies.

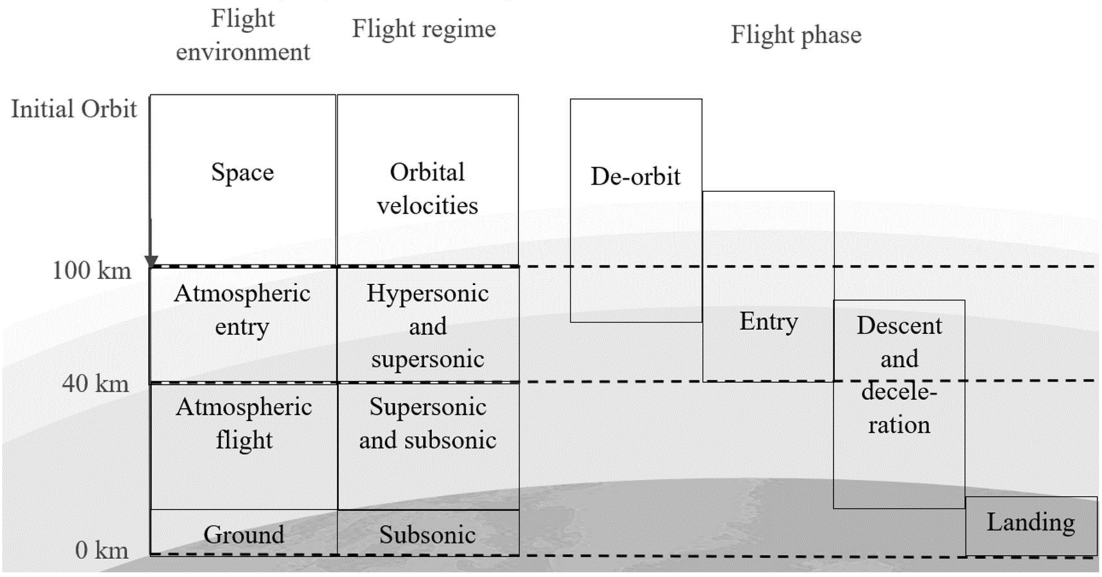

Figure 6: Mission phases and flight regimes for re-entry systems, recreated after Pepermans [29]

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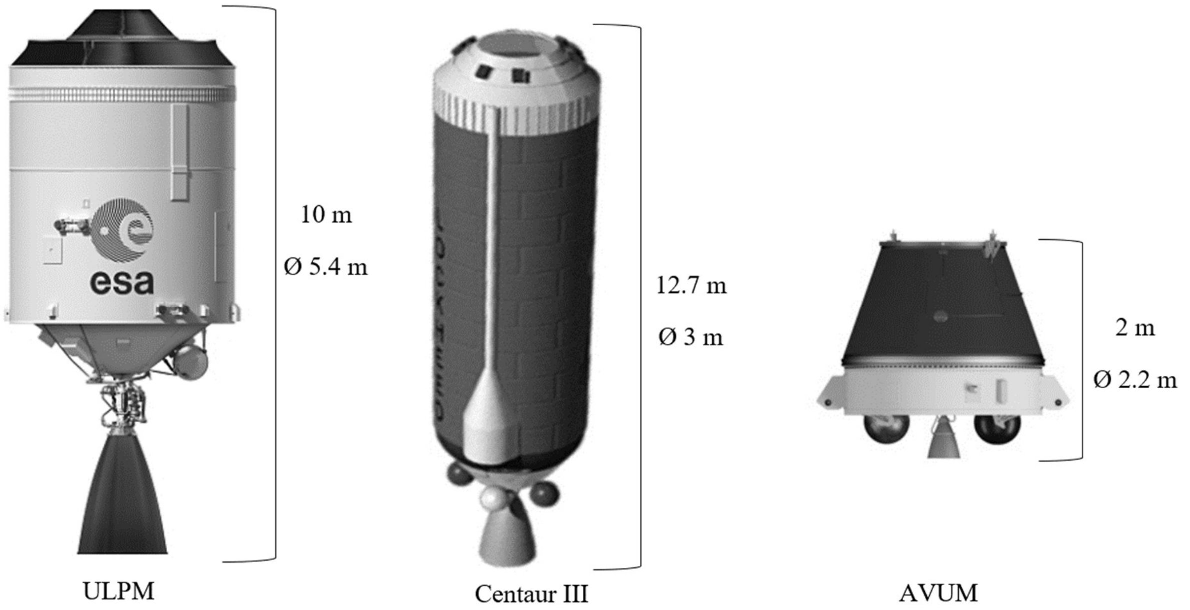

Figure 7: Dimensional comparison of three active upper stages (left ULPM [30] on Ariane 6, centre Centaur III [31] e.g. on Atlas V, right AVUM on Vega), not to scale.

Trajectories where little or no lift generation are achieved are ballistic trajectories. In the case of ballistic re-entry, the maximum occurring loads can be estimated from the ballistic coefficient

$$\beta = \frac{\mathrm{m}}{\mathrm{A}\, c_D} \quad [\mathrm{kg/m^2}] \quad \mathbf{(1)}$$

with m being the mass of the entry body, A the effective surface and c_D the aerodynamic drag coefficient of the entry vehicle. A low ballistic coefficient means lower thermal and pressure loads and thus a higher probability of survival during re-entry. Used launcher stages often contain a number of components that have an inherently low ballistic coefficient, such as empty tanks or large structural parts made of lightweight material, which significantly degrades their capability to demise or complicates the design for demise. However, this property can be advantageous for a recovery concept. If β could be reduced right before re-entry by moderately increasing the effective area, the stage would survive ballistic re-entry. This fact makes the use of deployable decelerators or deployable heat shields, that can be added to the existing stage system, interesting for cost reduced recovery of orbital stages. Concepts already investigated and possible additional approaches for deployable elements for stage recovery are summarised in the following.

3.2 Novel concepts for orbital stages to survive re-entry

Heinrich et al. [17] and Ragab et al. [19] sum up the state of the art of launcher recovery and reusable launcher systems and they also mention non-propulsive approaches such as deployable aerodynamic decelerators for launcher recovery. Existing deployable concepts for re-entry and recovery trajectories are summarised in section 3.2.1 to 3.2.3. In general, the effective area for re-entry of a vehicle is increased by using a deployable aerodynamic drag-generating surface which, as it is stowed within the stage volume, has no aerodynamic influence on the performance during launch and allow for systems with high mass efficiency. Deployable technology utilizes existing storage volume or structures efficiently and can expand a system, decreasing vehicle development costs. Furthermore, they allow for new entry trajectories with significantly reduced loads compared to previous systems and, due to larger aerodynamic surfaces, aerodynamic drag forces for velocity reduction can be utilized up to lower altitudes. Deployable re-entry systems can be divided into inflatable aerodynamic decelerators and rigid deployable aerodynamic decelerators. Both are described in more detail in the following two sections.

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3.2.1 Inflatable aerodynamic decelerator

Research is already being done in the area of inflatable aeroshells for orbital stage recovery. Inflatable aerodynamic decelerators use an inflatable structure which (via stored gas) deploys a flexible thermal protection system (TPS) [32] and achieves stability through internal pressure. This requires pneumatic accessories such as tanks. For upper stage re-entry, the Inflatable Re-entry technology (IRDT) was the first such system, tested on the Soyuz-Fregat upper stage, compactly stowed into the upper stage during launch and inflated before entry. This was the first flight demonstration from orbit [33]. With a maximum diameter of 14 m, this demonstration served as a good example of IRDT applications in the fields of reusable and expendable launchers, their safe disposal and aerobraking [34]. Today, this technology is being further developed and often referred as hypersonic inflatable aerodynamic technology (HIAD) with NASA's concept being the most developed today. It uses a multi-tori architecture. Inflated, it allows controllability entry via a centre of gravity offset or aerodynamic control surfaces. The potential application of HIAD for upper stage recovery has already been investigated in studies [35]. With the Sensible Modular Autonomous Return Technology (SMART) from the United Launcher Alliance (ULA), shown in Figure 8, a concept for the recovery of a first stage engine recovery with the NASA HIAD is currently under development [23, 36]. With the successful test flight of NASA in 2022 with Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID), the technology of HIAD can be estimated at a Technology Readiness Level (TRL) of 7. It is utilizing an inflatable aerodynamic decelerator. The system has lowest impact on performance and minimizes masses and dead system for recovery, but doesn’t recover the entire first stage or tank module which results in a 45% loss of the launcher costs. The European Flexible Heat Shields (EFESTO) project is the European approach to increase capabilities in designing inflatable heat shields for re-entry vehicles [37]. It proposes an alternative shape of the inflatable structure in the form of an annulus. The project identified and want to compensate critical issues of a multi-tori architecture such as non-scalability, structural indeterminacy and instability, high complexity of assembly and integration and high costs. Within the project, the retrieval of the VEGA upper stage AVUM, shown in Figure 8, was chosen to analyse its reusability capabilities as a study case.

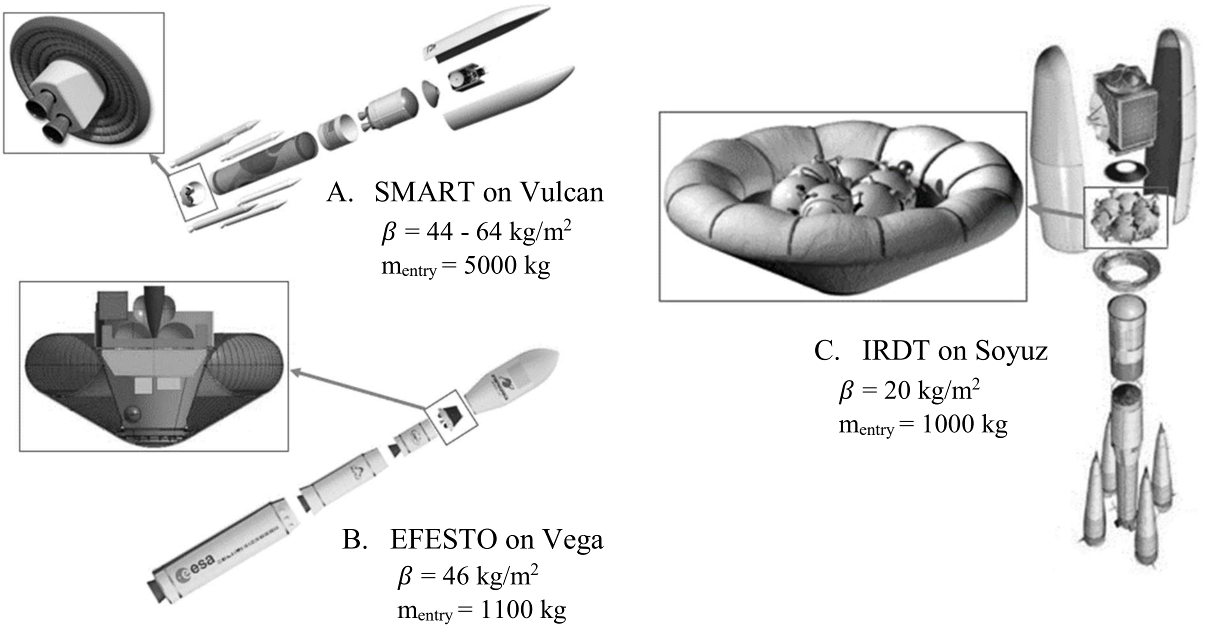

Figure 8: Deployable concepts from the category of inflatable decelerator that where or are considered for recovery of launcher stages. A: SMART (Sensible Modular Autonomous Return Technology) from ULA (United Launcher Alliance) for Vulcan booster stage engine recovery with HIAD (12 m inflated diameter) for entry, guided parafoil descent and helicopter mid-air capture (MAR), under development with HIAD being successfully tested from orbit [23]. B: EFESTO (Inflatable Heat Shield Technology for Re-Entry Systems) for return of Vega upper stage AVUM, under development [37]. C: IRDT (Inflatable Re-entry technology) for Soyuz Fregat upper stage recovery, successfully tested from orbit, development discontinued [33].

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The HIAD concepts from NASA and EFESTO envisage using inflation gas carried during the launch to fully deploy the inflatable heat shield before entering the atmosphere. This requires pneumatic accessories such as tanks. An alternative concept that is particularly interesting for small launchers is the air-breathing inflatable aerodynamic decelerator (IAD) from KLAUS Space Transportation [38], which does not require tanks. Also, while HIAD and EFESTO are currently focussing on the recovery of compact elements and stages, the inflatable geometry in the case of the IAD completely encloses the rocket stage and thus improves the aerodynamic stability of an elongated stage geometry. It would also achieve a lower terminal velocity, which is usually achieved by parachutes for HIAD or EFESTO.

3.2.2 Rigid deployable decelerator

Rigid (or mechanically) deployable decelerators do not utilize a pressure body but are consisting of a deployable structure of panels, rips, struts or other to increase the effective area. The Adaptable Deployable Entry and Placement Technology (ADEPT) [39] by NASA is the most mature concept, shown in Figure 9 A., and is part of the Game Changing Development Program (GCDP [32]). Its structure contains deployable rigid struts, such as an umbrella, that span a flexible TPS cloth. Like HIAD, it was originally developed as a deployable decelerator for interplanetary missions. Both technologies utilize flexible thermal resistant materials. The ADEPT concept was conceived in 2012 and preliminary design suggested its mass would be comparable to that of HIAD. However, for rigid deployable decelerators the focus currently mainly is on small entry probes, for example for CubeSat return [40, 41], drag modulated aerocapture [42] or micro-exploration landers [43, 44]. With Nano-ADEPT [45] the project took another path to advance the technology by going really small, achieving rapid technology development extensible to large applications but also giving rise to novel applications for small spacecraft by offering an entry system [32]. NASA proposes the technology readiness level (TRL) of ADEPT to be 3, which puts this technology behind the inflatable systems, while the 1-m-class Nano-ADEPT, reached TRL level of 5 with a successful suborbital flight test [45]. Another concept, MINI-IRENE [46], where the flexible TPS is stretched with telescopically extendable struts, was also successfully tested in suborbital flight [47]. A third, yet only theoretical concept is the DLR Mars Micro Lander (MML) [43], where the foldable structure combines the umbrella principle with telescopic struts. The entry masses of Nano-ADEPT, MINI-IRENE and DLR MML each are below 25 kg. Rigid deployable decelerators utilizing a flexible TPS cloth are hot structure technologies where the material of the deployed surface does not serve as thermal insulation. However, due to the increased effective area that reduces the ballistic coefficient, the maximum heat loads encountered decrease.

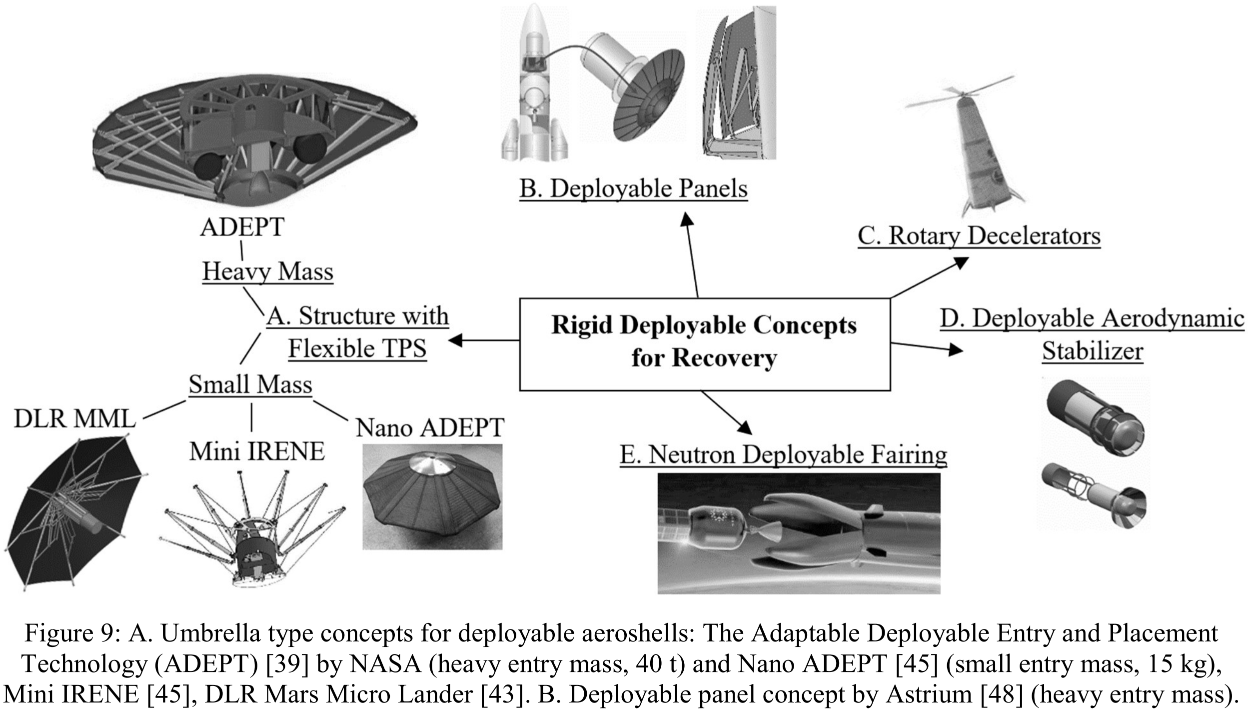

Figure 9: A. Umbrella type concepts for deployable aeroshells: The Adaptable Deployable Entry and Placement Technology (ADEPT) [39] by NASA (heavy entry mass, 40 t) and Nano ADEPT [45] (small entry mass, 15 kg), Mini IRENE [45], DLR Mars Micro Lander [43]. B. Deployable panel concept by Astrium [48] (heavy entry mass). C. Rotary decelerator concept Roton [49]. D. Deployable panel concept as Aerodynamic Stabilizer by Astrium [48] (small entry mass) E. Deployable nose cone area concept by Rocket Lab [50].

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Other approaches to deployable decelerators exist such as deployable decelerating rotors as Roton [49], shown in Figure 9 C. or deployable rigid panels as heat shield [48], shown in Figure 9 B. Also, deployable structures such as rigid panels are well suited to be utilized as control surfaces [51] or for aerodynamic stabilization during re-entry [48], as shown in Figure 9 D. While the initial ADEPT concept was developed for re-entry masses up to 40 t, used upper stages usually have a dry mass below 5 t. Since the technology is less developed than inflatable concepts, especially for application to larger masses, it is difficult to compare the two concepts in terms of upper stage return so far. However, rigid deployable decelerators could be interesting for cost-reduced stage recovery, which is being discussed in section 3.

3.2.3 Additional aspects on deployable elements

In the following, further possibilities of exploiting deployable elements in the recovery of orbital stages are summarised.

Synergies with existing structures
Existing rigid structures can be modified so that they are integrated into the recovery concept, for example by means of a deployable outer shell, which provide higher mass efficiency. An example for this is the deployable nose cone area proposed by Rocket Lab for their next generation Neutron rocket, shown in Figure 9 E.

Utilisation of flexibility effects
An important aspect of deployable systems such as ADEPT is that unlike conventional rigid heat shields, deployable decelerators usually do not exhibit absolute stiffness against mechanical influences and deform under the influence of aerodynamic loads, which in turn can have an influence on their entry trajectory. In the case of rigid deployable decelerators, this property can be used to the advantage of the mission as analysed by Peacocke et al. [52, 53] as some flexibility is beneficial if the resulting mass savings can be reallocated towards increasing the entry vehicle diameter, resulting in significantly reduced peak heat fluxes and improved flight stability.

Deorbit concepts
The deorbit of orbital stages can be performed either with deorbit burn, or by taking advantage of the atmosphere to reduce velocity of the vehicle passively enhancing the aerodynamic drag. In case of passive, drag based deorbit techniques, it is complex to predict the exact point of re-entry which is why this is usually used for uncontrolled re-entry. Long et al. [54] discuss different deorbit techniques to deorbit upper stages with concepts such as drag sails, inflatable balloons and using residual propulsion capacities with the last to be the lowest costs option since the system does not require any technical changes. However, this reduces the launchers payload capacity. In addition, Alpatov et al. [55] developed another passive, also inflatable concept for upper stage deorbiting. Deployable decelerators could also serve synergistically as a passive deorbit mechanism analogous to drag sails or balloons to simplify the system. However, passive orbit decay with a large drag area means an increased collision risk due to the time-stretched decent through several orbit altitudes with a large surface. Also, particle impacts could reduce the performance of a drag surface and or, in the case of inflatable systems, lead to failure.

Decent and landing concepts
Controlled re-entries with landings on land require high reliability due to the population factor. Landing on water allows larger margins for the landing zone, but salt water is a destructive factor for components that are to be reused or recycled. Heinrich et al. [17] discuss different options for the descent and landing phase of recovery systems such as retro propulsion, aerodynamic surfaces, parachute and legs, skids or wheels (depending on trajectory and terrain compatibility) and crushable structures. SMART, as a complete recovery concept, is utilizing an inflatable aerodynamic decelerator to recover a first-stage booster engine module, and parafoil deployment together with mid-air capturing. Inflatable decelerators also have the potential to land on water directly while still inflated keeping the payload in a stable dry position until the final recovery. Another interesting approach for trajectory optimisation, e.g. to adapt aerodynamic stability to the flight regime, is to change the entry geometry during atmospheric flight. This approach has already been tested with the inflatable concept IRDT, which unfolds in two cascades and thus achieves a lower terminal velocity [33]. Rigid deployable systems promise to provide synergy potential within the mission phases. For example, the ADEPT concept intended to utilize deployable struts for both, the deployment of the aerodynamic decelerator and, after further deployment as landing legs. Utilizing one element for multiple mission phases increases mass-efficiency and costs. This could be a significant advantage of rigid deployable systems over inflatable decelerators.

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4. Gap analysis and research approaches

The following is a gap analysis for orbital stage recovery, not necessarily aiming for full reuse but for a full recovery of material and components. In addition, possible next steps in the analysis of the application of deployable concepts for orbital stage recovery are discussed.

4.1 Gaps for orbital stage recovery

The recovery of orbital stages from the LEO regime not only serves the essential necessity of debris reduction but is required in terms of more sustainability and reuse potential, environmental protection mainly by avoiding the generation of harmful particles in the Earth's atmosphere and ocean contamination. For a limited number of mission types, reusable gliding body upper stages such as Space Rider are being considered, although no such active system exists, but these concepts usually do not provide for full recovery of orbital stage components and are designed to be feasible for payload return missions. However, the majority of launcher missions are aimed to place satellites in Earth orbit via a “one-way” upper stage. For the orbital stages of such launches, recovery is yet not part of the missions and has hardly been explored. **An established concept that fully recovers orbital stages is still lacking**. SpaceX’s Starship has an upper stage with the potential to become the first universally applicable and recoverable upper stage. Such systems are expected to significantly increase economic efficiency, but which form of reusability and recovery is most sustainable, both economically and environmentally, is still the subject of research.

An alternative to concepts such as Starship is the extension of existing standard orbital stages with an integrable EDL system so they can be recovered, such as inflatable or rigid deployable decelerators. While for the recovery of compact upper stages and components such as engines, the inflatable conical decelerator is a promising technology, there are less mature studies for their application to elongated geometries. The latter pose a challenge to flight stability during a recovery mission. The use of rigid deployable concepts could enable recovery of elongated rocket bodies. However, this technology is far less developed than the inflatable concepts and has hardly been analysed in the context of orbital stage recovery. They offer potential in atmospheric decelerator applications, but also in aerodynamic stabilisation and flight control.

Rigid deployable entry systems
Rigid deployable decelerators should be discussed as an integrable recovery system such. One promising approach is the rigid deployable decelerator for atmospheric re-entry. Concepts such as ADEPT, as the most developed example, where originally considered as an equally feasible decelerator technology [56, 32] in terms of mass efficiency compared to inflatable systems but their development for high mass applications was discontinued and they have not been discussed in the context of application to orbital stages.

The potential of rigid deployable elements
Rigid deployable systems could fill a gap in the area of recovering especially long orbital stages with heavy, exposed engine nozzles from orbit due to the variety of possible geometries or successive geometry change through controllable elements for trajectory optimisation. Rigidly deployable elements such as panels, struts etc., do not have to be deployed from one single position in the vehicle, like inflatables that deploy a pressure body, but can be distributed over the entire structure, for example in the form of flaps and panels. They also promise a possible high synergy potential within the mission phases. For example, the ADEPT concept intended to utilize deployable struts for both, the deployment of the aerodynamic decelerator and, after further deployment as landing legs. Utilizing one element for multiple mission phases increases mass-efficiency and costs. This could be a significant advantage of rigid deployable systems over inflatable decelerators. Also, utilizing rigid structural elements could allow for synergies with the structure available such as outer shells or the firing. Wall elements, providing strucural integrity during high accelerations and covering the payload during launch, could be designed to unfold before re-entry to increase the affective aerodynamic area, thus reducing the ballistic coefficient. Moreover, orbital stage structures such as tanks or outer structure elements have low mass compared to the total system mass and therefore potentially low ballistic coefficients when separated from the stage. Also, the increased use of heat-resistant carbon fibre-based materials in the launcher industry is favourable for design not to demise. If this is combined, individual components with low ballistic coefficient could be recovered separately. The only practically tested example for this is the fairing recovery SpaceX demonstrated within the launch of a Falcon 9 rocket. Recovering the stage elements separately could be supported with the assistance of deployable and actuatable elements.
In addition, the applicability of rigid deployable systems for micro launchers, which are predicted to be used more frequently in the future, is interesting because of the performance advantages in terms of emty mass and volume after deployment compared to inflatable systems due to the absence of pneumatic elements like inflation tanks

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4.2 Research approaches

The potential of applying rigid deployable systems to orbital stage recovery are to be analysed at the Institute of Space Systems. The following research question is proposed:

How can deployable structures be used to modify the entry trajectory of orbital rocket stages in such a way that these stages can be recovered and possibly reused or recycled?

Based on the literature review, the following steps to assess the potential of rigid deployable systems are proposed:
1. Categorisation of upper stages on the basis of parameters important for recovery, e.g. geometry
2. Selection of a suitable reference system for a category
3. Quantifying the basic requirements such as permissible loads for a recovery mission of the reference system. For the requirements, a differentiation between return for reuse and return for recycling could be done
4. Analysis of the application of deployable elements for de-orbit, re-entry, decent and landing
5. Iterate concrete design approaches

The following sub-research topics are proposed:

- Utilizing reduction of the ballistic coefficient with rigid deployable elements, possible component separation (engine, tank etc.)
- Deployable elements for entry flight stabilisation or aerodynamic control, possible combination with inflatable entry systems
- Structural synergies of deployable systems with structure of existing orbital stages
- System synergies for cost reduction of deorbiting, decent and landing
- Rigid deployable decelerator system comparable to inflatable decelerators such as HIAD for SMART or EFESTO for technology comparison
- General disposal analysis of the individual components of various launcher systems and definition of requirements for their recovery
- Separate analysis on application of rigid deployable elements for the recovery of micro launcher

5. Conclusion and outlook

Aspects such as environmental impact and sustainability create additional requirements in the development of future space missions and technology and in the motivation to develop reusable launcher systems. The recovery of orbital rocket stages is crucial to reuse or at least recycle them. So far, there is no established concept for recovering standard orbital stages and a particular challenge is finding solutions for elongated launcher stages. They differ in their geometry and orbital parameters and a categorisation would be a first step in analysing possible recovery approaches. One possibility for returning orbital stages are integrable and partially scalable deployable atmospheric decelerators. While inflatable decelerator concepts are already partially explored for upper stage and launcher component recovery, the technology of rigid deployable structures is not yet explored for orbital stage recovery. Applications of rigid deployable structures could relate to deployable aerodynamic deceleration devices or deployable aerodynamic control or stabilisation elements such as flaps. In addition, the conceivable synergies with existing orbital stage structures offer the potential for significant mass and thus cost savings. Particular application potential is seen in micro-launch vehicles and elongated geometries. The application of rigid deployable elements to upper level recovery is the subject of current research at the Institute of Space Systems (IRS). The potential of economic and ecologic gain of these recovery methods and the comparison with concepts like Starship is difficult to estimate and should be also addressed in the future.

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