DOI: 10.13009/EUCASS2019-675

Multi-Disciplinary Modeling Environment for Reusable Launch Vehicle Dynamics and Control System Design

Lâle Evrim Briese[⋆†], *Klaus Schnepper*[⋆] *and Paul Acquatella B.*[⋆]

[⋆]*DLR, German Aerospace Center*
Institute of System Dynamics and Control
D-82234 Oberpfaffenhofen, Germany

lale.briese@dlr.de · klaus.schnepper@dlr.de · paul.acquatella@dlr.de

[†]Corresponding author

Abstract

For new reusable launch vehicles concepts, it becomes increasingly necessary to already assess relevant system dynamics and control system design aspects in early design phases. This is especially important when complex and difficult maneuvers like in-air-capturing for the return of launch vehicle stages are considered. This paper will focus on the key elements of the newly developed reusable launch vehicle multibody dynamics and control system design framework by demonstrating its capabilities for the simulation and analysis of flight dynamics aspects of the in-air-capturing maneuver as studied in the DLR project AKIRA.

1. Introduction

Future reusable launch vehicle concepts and key technologies are currently investigated within the DLR research project AKIRA focusing on vertical takeoff and horizontal landing (VTHL), and horizontal takeoff and horizontal landing (HTHL) reusable launch vehicle concepts as presented in [20] and [34]. In particular, the chosen return option for a reusable launch vehicle contributes highly to its overall design, technical feasibility and financial viability as discussed in [8] and [33]. Consequently, the systematic evaluation of return options is required already in early launch vehicle design phases like the preliminary design phase; be they realized by vertical landing (like done by SpaceX [37] and Blue Origin [4]) or by horizontal landing (like done by the Space Shuttle [16]). These early assessments are of particular importance when complex and difficult maneuvers like *in-air-capturing* are involved. The overall operational concept of the in-air-capturing maneuver is discussed in [19,28,29,31,32], while [9,10] focus on sub-scale flight tests.

In Figure 1, the full operational concept of the in-air-capturing maneuver is shown schematically. To summarize, the in-air-capturing maneuver is an innovative return option for winged first stages of reusable launch vehicles [19] such as the *SpaceLiner* booster stage (SLB) presented in [36]. In this kind of a VTHL two-stage-to-orbit (TSTO) launch vehicle configuration, the unpowered winged first stage performs a ballistic trajectory and subsequent reentry into the atmosphere. To return to the launch site, an aerodynamically controlled return maneuver has to be initiated, where at an appropriate cruise flight altitude a large capturing aircraft awaits the first stage. The first stage approaches the aircraft from above while the aircraft releases a highly agile aerodynamically controlled capturing device connected to the aircraft by a cable. The goal of the capturing device is to actively capture the first stage during final approach. For this maneuver, the aerodynamic controllability of the aircraft itself is bound to time delays and the winged stage with its relatively low lift-to-drag ratio can be considered as a passive glider with poor flight characteristics and high inertia as discussed in [10]. Furthermore, the capturing process is limited to a short flight window of approximately two minutes [29]. After successful completion of the capturing process, the unpowered first stage is towed back to the launch site by the aircraft in order to increase the downrange of the first stage and to avoid the consideration of unnecessary return propellant during the overall launch vehicle design. Near the launch site, the winged first stage is released from the capturing device and glides autonomously to the landing runway.

For such a demanding maneuver involving multiple vehicles with complex dynamics, it is imperative to consider relevant system dynamics and control aspects already during the preliminary design phase. Modeling and simulation of multiple flight vehicles within one simulation framework is a challenging task not only due to highly interconnected multiple disciplines influencing each flight vehicle on its own - but also due to the interactions between these flight

DOI: 10.13009/EUCASS2019-675

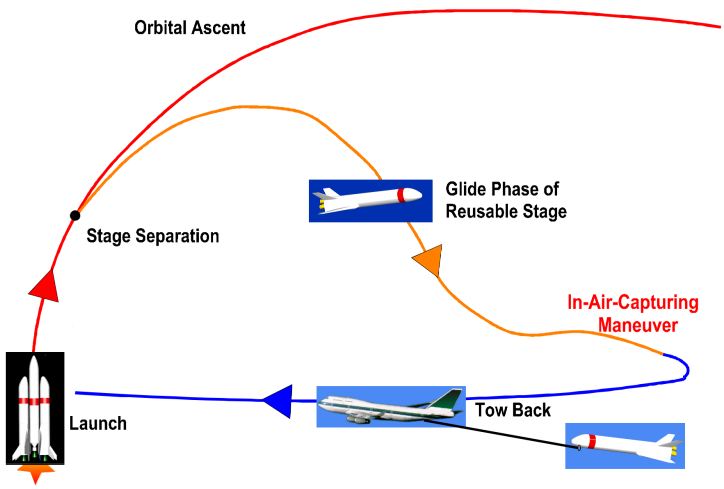

Figure 1: Schematic Overview of the In-Air-Capturing Maneuver [29].

vehicles, e.g. regarding the flexible connection between the capturing aircraft and its actively controlled capturing device. A multibody modeling and simulation framework in this context has to provide capabilities to model the highly multi-disciplinary and complex in-air-capturing maneuver including interactions of disciplines, like environmental conditions, aerodynamics, propulsion, structures, mechanisms and GNC.

Currently, most modeling and simulation approaches deal with these kinds of problems by using several independent and discipline-specific tools separately for each flight vehicle. Mostly, these kinds of methods can only account for a limited amount of interaction between vehicle-dependent disciplines and the overall system dynamics of one particular flight vehicle. To tackle this overall problem, a multi-disciplinary framework for the modeling and simulation of launch vehicle system dynamics, guidance and control design was developed at DLR's Institute of System Dynamics and Control as introduced in [2,5,7]. The key element to this framework is the consistent modeling of system dynamics from three to six degrees of freedom (DOF) models with possible structural enhancements that provides adapted fidelity models for different design phases and design purposes. In particular, it is possible to change nearly effortlessly from a 3-DOF model for guidance design [7,17,27] to a full 6-DOF simulation model for controllability assessment [2,5].

Since it is necessary to not only consider one but three flight vehicles for the in-air-capturing maneuver including a flexible cable, the modeling and simulation framework had to be enhanced to support the investigation of multiple vehicles and their interactions and studying of relevant guidance and control aspects of this particular maneuver. These changes will improve the quality of the preliminary design of the launch vehicle and remove the need of costly design loops regarding control design difficulties that may arise in later design phases. Similar challenges related to towed cable systems are for example discussed in [38].

The objective of this paper is to present the key elements of the modeling and simulation framework based on the object-oriented and equation-based modeling language MODELICA [21] considering multiple flight vehicles as required for the in-air-capturing maneuver. In particular, the preliminary modeling concept is presented using 3-DOF aircraft (AC), capturing device (CD) and launch vehicle (LV) models, covering their kinematics and flight dynamics formulations, environmental effects, aerodynamics and propulsion models. Furthermore, the connection between the aircraft and the capturing device by a cable is shown based on a simplified semi-analytically derived beam model to incorporate structural elastic effects. After introducing the modeling framework in Section 2, the implementation of each flight vehicle required for the in-air-capturing maneuver is presented in Section 3. Finally, the capabilities and benefits of our framework for the preliminary simulation of the in-air-capturing maneuver are demonstrated and discussed in Sections 4 and 5.

2. Methods

The object-oriented multidisciplinary and multibody modeling and simulation framework uses the equation-based modeling language MODELICA. In addition to the standard multibody modeling approach provided by MODELICA's *Modelica Standard Library* and its *MultiBody* package, the flexible multibody modeling approach using the *DLR FlexibleBodies Library* [14, 15] will be highlighted. Furthermore, the launch vehicle modeling and simulation framework included in the *DLR LauncherApplications Library* [5,7] will be discussed shortly.

DOI: 10.13009/EUCASS2019-675

2.1 Modelica

MODELICA is a modern object-oriented and equation-based modeling language which can be used to model complex physical systems containing, e.g., mechanical, electrical, hydraulic, thermal, control, data, or process-oriented subsystems and components [12, 13, 21], for applications such as aeronautics, automotive, or robotics. In general, models can be described using differential, algebraic, and discrete equations which are then mapped into *Differential Algebraic Equations* (DAE) or *Ordinary Differential Equations* (ODE) by reordering the derivatives and algebraic variables. These equations can then be solved and simulated by MODELICA-based simulation environments such as DYMOLA [11]. More information regarding the history and main features of MODELICA is summarized in [1, 12, 21]. Although MODELICA itself can be seen as *domain neutral*, the *Modelica Association* provides and updates the *Modelica Standard Library* (MSL) [21] containing multi-physical models from signal-based control blocks to equation-based fluid models underlining MODELICA's multi-domain modeling capabilities. If not otherwise required, individual models and modeling frameworks can be created using these standardized models obtained directly from the MSL. For instance, the MSL includes the *Modelica.Mechanics.MultiBody* package [23, 24] with which the modeling of rigid multibody applications can be accounted for.

2.2 Rigid Multibody Modeling

Typically, a multibody system is described by a collection of *bodies* and their interactions. Generic body components, as defined in the *Modelica Standard Library*, are represented by their physical properties like constant mass, moments of inertia, and dedicated geometric quantities mainly used for visualization. The translational and rotational dynamics of each body are obtained by the *Newton-Euler* equations of motion. Interface elements, defined as *frames*, are assigned to each body and contain cut-forces $\boldsymbol{f}$ and cut-torques $\boldsymbol{t}$ together with position $\boldsymbol{r}_0$ and orientation $\boldsymbol{R}$ with respect to an inertial Cartesian coordinate system (world) as shown in Figure 2. Physical couplings between multibody components are ideally constrained if *frames* are connected directly with each other, whereas *joints* can be used to apply motion constraints or to define specific degrees of freedom between two *frames*.

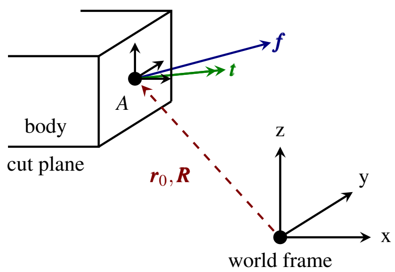

Figure 2: Schematic Representation of a Frame Connector [24].

2.3 Flexible Multibody Modeling

On top of the previously introduced generic rigid body components, the capability to model structural elastic effects is required for modeling the flexible connection between the aircraft and its capturing device. For this purpose, semi-analytical beam models implemented directly in MODELICA and provided by the *DLR FlexibleBodies Library* [14,15] are used in this paper. In general, the mechanical formulation for the flexible multibody modeling is based on the floating frame of reference approach as shown in Figure 3. The floating frame of reference approach uses the multibody *frame*, for instance attached to a bodies' center of mass, as the reference frame. The absolute position of a point along the beam's longitudinal x-axis is then described by the superposition of the position vector $\boldsymbol{r}_R$ to the body's reference frame with respect to the inertial Cartesian coordinate system (world frame), the undeformed position $\boldsymbol{c}$ of the point with respect to the body's reference frame, and the elastic displacement $\boldsymbol{u}(\boldsymbol{c},t)$:

$$\boldsymbol{r} = \boldsymbol{r}_R + \boldsymbol{c} + \boldsymbol{u}(\boldsymbol{c},t). \tag{1}$$

This approach allows for the superposition of the large non-linear multibody motion of the reference frame with small structural elastic deformations. The displacement field based on the classical beam theory of *Rayleigh* and *Bernoulli* can be calculated analytically as discussed in [15]. The deformations are then expressed by the Rayleigh-Ritz approximation which uses a linear combination of space-dependent mode shapes and time-dependent unknown modal

DOI: 10.13009/EUCASS2019-675

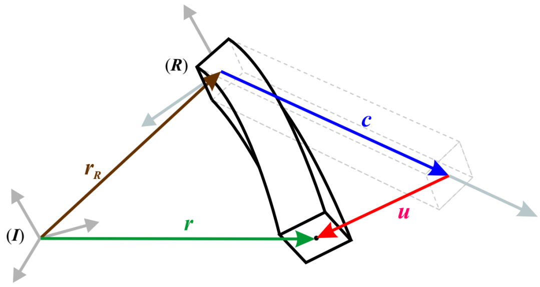

Figure 3: Schematic Overview of the Floating Frame of Reference Approach [15].

amplitudes, where the spatial shape functions for each deformation type – lengthening, bending in *xy* and *xz* planes, as well as torsional deformation – can be calculated separately with analytical solutions of the spatial problem depending on the chosen boundary conditions *clamped*, *supported*, or *free*. The *DLR FlexibleBodies Library* supports a straight, homogenous and isotropic beam formulation where structural properties are obtained from geometrical and physical properties such as the cross section shape, beam length, material density, Young's modulus and Poisson's ratio.

2.4 Launch Vehicle Modeling Framework

Reusable launch vehicle flight dynamics models have to incorporate several disciplines such as environment, flight dynamics, aerodynamics, propulsion, structures, mechanisms and GNC. Furthermore, the models have to be adaptable for different design and mission aspects taking into account vertical or horizontal takeoff and landing options. Additionally, the chosen launch vehicle design can have a significant influence in the modeling approach specifically regarding actuators and has to be accounted for in the modeling concept. In this paper, we focus on generic 3-DOF flight dynamics models for each flight vehicle which shall be used for subsequent trajectory optimization with DLR-SR's trajectory optimization package MOPS trajOpt via so-called *Functional Mock-up Units* as described in [7, 22, 27]. However, as highlighted in [5], these 3-DOF models can be extended effortlessly to 6-DOF nonlinear direct and inverse models for subsequent controllability studies if all required flight vehicle properties are available.

In Figure 4, the modularized and replaceable components of the original 3-DOF model are shown for a single flight vehicle. The *world* component provides inertial and rotating reference coordinate systems, and functions to obtain the gravity acceleration based on a bodies' position. In the *geosphere* component atmospheric parameters depending on the chosen atmospheric model can be determined as introduced in [6]. The *stage* component is used for the calculation of the main stage dynamics obtained by the most basic *Newton-Euler* equations of motion for a point mass subjected only to gravity acceleration. In this context, variable mass effects can be considered for the flight vehicle and any external forces (or moments for a 6-DOF model) can be included to the equations of motions by capitalizing on the equation-based frame connectors between the *stage* and other subsystem components. Dedicated

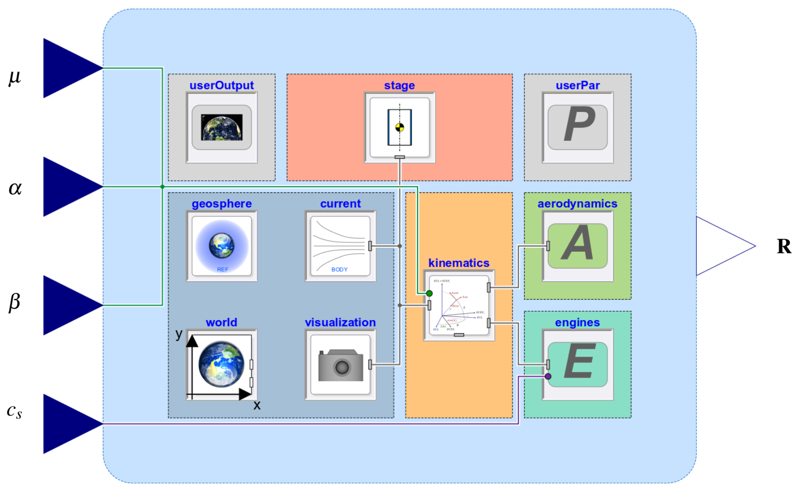

Figure 4: Overview of a Generic 3-DOF Launch Vehicle Model [5, 7].

DOI: 10.13009/EUCASS2019-675

kinematic states, functions and transformation matrices are provided in the *kinematics* component. This includes the definition of appropriate *frames* for any attached subsystems. The *aerodynamics* component provides aerodynamic forces and the *engines* component is used to calculate and apply thrust forces. All relevant parameters as well as multi-dimensional datasets for the interpolation of aerodynamic coefficients are stored in the *userPar* component, while all output parameters are collected by the *userOutput* component or inside the external output vector **R**. The *current* component, which applies wind effects or turbulences to the flight vehicle as external perturbations, is not used in the preliminary in-air-capturing model but can be integrated again into the framework for subsequent controllability studies and control system design.

If required, all subsystems except for the *world*, *kinematics* and *stage* dynamics components can be neglected. For instance, the unpowered winged first stage investigated in the in-air-capturing maneuver does not require an *engines* component during its descent, and consequently, this component can be removed from the launch vehicle model. As shown in Figure 4, the standardized external control inputs of the 3-DOF launch vehicle model are the aerodynamic angles $\{\mu, \alpha, \beta\}$ and the thrust throttle factor c_s. If necessary, the external control inputs can be extended, removed or redefined according to the needs of particular launch vehicle models. Additional information including the equations of motion and transformation matrices regarding the guidance of 3-DOF point mass models can be obtained from [7]. With these features, the launch vehicle modeling and simulation framework supports a highly modular and flexible modeling approach while still maintaining the consistent modeling in between chosen levels of detail.

The aforementioned subsystem components included in the launch vehicle modeling framework as shown in Figure 4 are used to represent the flight dynamics of one particular launch vehicle. An intuitive approach to add an additional flight vehicle to the overall launch vehicle modeling framework would be to simply duplicate all subsystems directly related to the flight vehicle itself while using the environmental components such as the *world* and the *geosphere* components for both flight vehicles. This can be ensured by capitalizing on MODELICA's *inner/outer* modeling concept where any functions, variables or submodels contained in the top-level *inner* models can be referenced from inside the subsystems by including the appropriate *outer* statement pointing to the corresponding *inner* model [6].

However, to duplicate all launch vehicle subsystems would mean, that any internal references in between specific subsystems would have to be renamed losing their highly modular, flexible, and object-oriented model design. By rearranging the launch vehicle subsystems into dedicated flight vehicle system modules with individual inputs and outputs, and by extracting the *world* and *geosphere* models from these modules to a higher level, multiple flight vehicles can be instantiated without requiring additional efforts for renaming or restructuring. Such an object-oriented approach is shown schematically in Figure 5 for the in-air-capturing model, which will be explained further in the following Section 3.

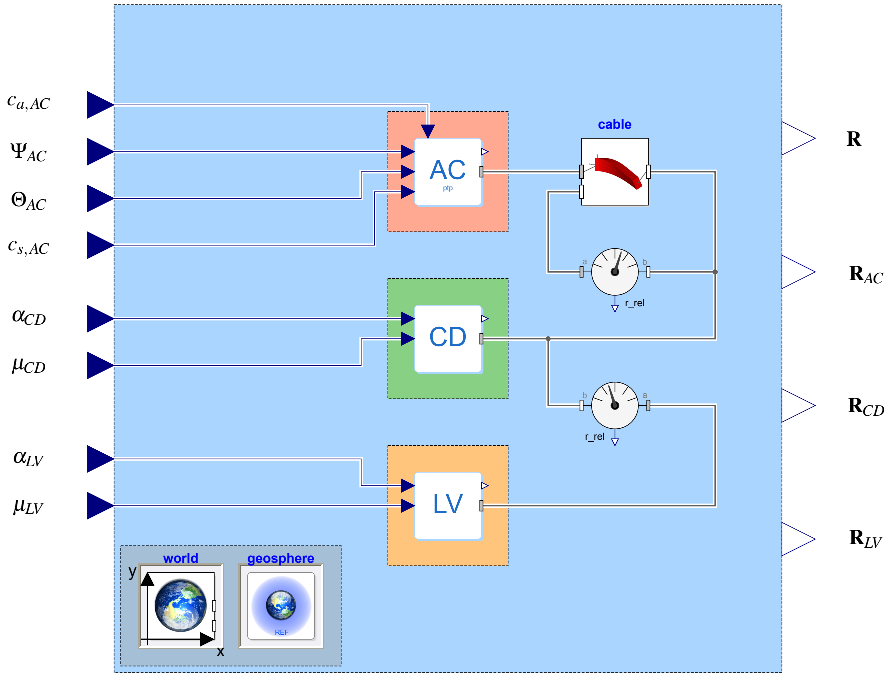

Figure 5: Overview of the In-Air-Capturing Model including Multiple Flight Vehicles.

DOI: 10.13009/EUCASS2019-675

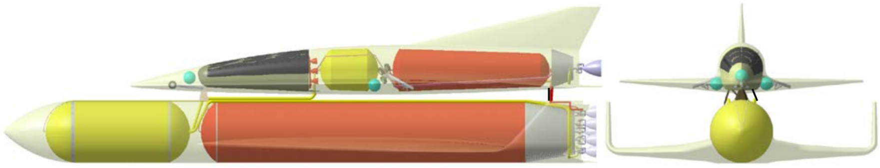

Figure 6: Sketch of the SpaceLiner Launch Vehicle Configuration [35].

3. Implementation

The in-air-capturing model as presented in Figure 5 consists of basically two model layers – the top-level environment layer and the flight vehicle dependent model layer on subsystem level. The top-level model layer contains the *world* and *geosphere* components. This top-level layer can be interpreted as the environment in which all implemented flight vehicles operate – meaning, that all flight vehicles are subjected to the same planet definition, gravitation and atmosphere models which provide individual environmental conditions depending on the flight vehicles' position. For the in-air-capturing maneuver, the *Earth Gravitational Model 1996* (EGM96) and the *U.S. Standard Atmosphere 1976* are used as described in [6]. Similar to the launch vehicle model shown in Figure 4, the external input and output parameters can be accessed in this top-level model layer. Furthermore, problem specific components like sensors measuring the relative distance between flight vehicles or additional models like the flexible multibody model can be included in this layer. The flight vehicle dependent model layers together with their respective inputs and outputs will be described in more detail in the following.

3.1 Launch Vehicle (LV)

The SpaceLiner launch vehicle design has been investigated at DLR's Institute of Space Systems (RY) for several years [35, 36]. The design concept is based on a fully reusable, vertical takeoff and horizontal landing TSTO launcher configuration including a winged reusable booster stage and a winged reusable ascent stage as shown in Figure 6, where the booster stage is located underneath the winged ascent stage. A typical target orbit would be a Geostationary Transfer Orbit (GTO) with a desired payload of more than 8.2t. However, for the trajectory in this paper a Sun-Synchronous Orbit (SSO) is targeted. For each stage, the chosen propellant combination is LOX/LH2. After separation from the ascent stage, the booster stage performs a ballistic flight and a subsequent atmospheric reentry at a low flight path angle. As soon as it enters the atmosphere, a return maneuver to orient the booster stage towards the landing site is initiated. During the following descent phase, the aerodynamic angle of attack is kept at roughly 18°, whereas the aerodynamic bank and sideslip angles remain at 0° as specified by the reference trajectory provided by DLR-RY's in-house trajectory optimization tool TOSCA [18]. During the unpowered descent and in-air-capturing maneuver, the overall mass of the launch vehicle is constant at around 205t. The aerodynamic coefficients for lift and drag are provided by DLR-RY using tools like CAC [30] and HOTSOSE [25].

The booster stage is implemented as a 3-DOF model using the components described in Section 2, neglecting the *engines* component. Therefore, the throttle factor c_s shown in Figure 4 is no longer necessary. Since the booster stage is a winged stage operating mainly by controlling its aerodynamic bank angle μ instead of its aerodynamic sideslip angle β, the only external inputs for the launch vehicle model are defined by the aerodynamic angle of attack α and the aerodynamic bank angle μ. The aerodynamic sideslip angle β is nominally kept at 0°, but can also be used as a control input if required. The translational states are defined by the position of the launch vehicle represented by the geocentric latitude, longitude, and altitude, and the velocity with respect to the *North-East-Down* (NED) coordinate system instead of using the more common flight path parameters as explained in [7]. The resulting output vector $\mathbf{R}_{LV}$ can contain user-defined information about the launch vehicle's Mach number, current aerodynamic coefficients and corresponding forces, atmospheric parameters, or load factors, which are also provided for the other flight vehicles.

3.2 Aircraft (AC)

The aircraft, denoted as (AC) in the in-air-capturing model, is used for the capturing and towing of the launch vehicle (LV) back to the launch site. Although specifications of this flight vehicle are almost as important as specifications of the launch vehicle itself, there is little information on the aircraft flight qualities required for the in-air-capturing maneuver. In general, the aircraft by its sheer mass is assumed to be quite passive during the maneuver and has to be capable to tow a launch vehicle of similar mass, inertia and geometric properties back to the launch site.

DOI: 10.13009/EUCASS2019-675

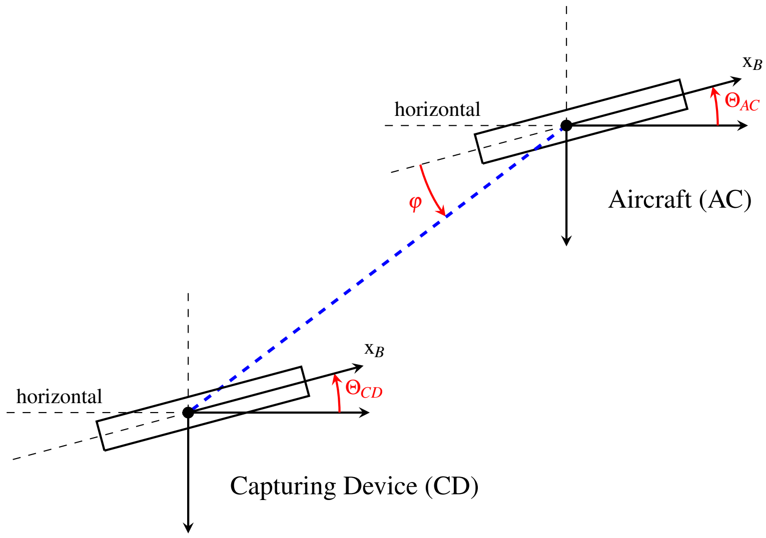

Figure 7: Schematic Overview of the Connection between Aircraft and Capturing Device.

In this paper, the aircraft is assumed to be similar to a Boeing 747 configuration with a total mass of 200t. The aerodynamic coefficients for lift and drag, and the engine specifications are provided by DLR-RY and lead to a total maximum thrust of 270kN at an altitude of 10km. The aircraft is implemented as a semi-3-DOF model to enable a coupling to the 6-DOF beam formulation. The external inputs are the throttle factor $c_{s,AC}$, the aerodynamic scaling factor $c_{a,AC}$, and the body attitude angles including the heading angle Ψ_{AC} and the pitch angle Θ_{AC}, where the bank angle Φ_{AC} is assumed to be constant at $0°$. In contrast to generic launch vehicle 3-DOF models and their respective aerodynamic control parameters, the body attitude angles are chosen as control parameters to decouple the flight path angle γ and the flight path azimuth angle χ retrieved from the kinematic velocity states from the actual orientation of the aircraft. The aerodynamic angles to be used for the calculation of the aerodynamic forces are then algorithmically computed from the flight path and applied body orientation angles. The aerodynamic scaling factor $c_{a,AC}$ is included as an external input to approximate the influence of spoilers which can be used to support the simultaneous descent of the aircraft relative to the launch vehicle's flight path.

3.3 Capturing Device (CD)

The capturing device is a highly agile, aerodynamically controlled, unpowered flight vehicle attached by cable to the towing aircraft. Within the in-air-capturing framework, the capturing device is implemented similarly to the launch vehicle model in terms of subsystem components. Since the capturing device is unpowered, the *engines* component and a throttle factor are not considered. Globally, the flight performance of the capturing device depends primarily on the flight performance of its towing aircraft. But due to its own aerodynamic control surfaces and the highly flexible cable in between the aircraft and the capturing device, the flight vehicle is able to perform maneuvers necessary to catch the launch vehicle. The chosen external control inputs are the aerodynamic angle of attack α_{CD} and the aerodynamic bank angle μ_{CD}. The overall mass of the capturing device is constant at around 135kg and the aerodynamic coefficients for lift and drag are provided by DLR-RY using Missile Datcom [26] for the subsonic flight regime.

For modelling purposes, we consider the capturing device to be attached to the cable by a ball bearing. This means, that the orientation of the capturing device is independent from the cable's attitude. The cable in turn is connected to the aircraft with an initial rotation φ of the cable attachment point around the aircraft's y-axis with respect to its body fixed coordinate system. These motion constraints are assumed to be ideal without friction. Additionally, the cable is implemented by using the flexible multibody beam formulation described in the previous Section 2. The steel cable length is initialized with 300m and the cable mass is assumed to be 500kg. At the attachment point to the aircraft, the boundary conditions of the beam are chosen to be *clamped* and at the attachment point to the capturing device they are assumed to be *free*. In this context, bending with respect to the xy and xz planes, lengthening effects, and torsional deformations are considered. It has to be noted, that the material and geometric properties of the cable as well as the usage of a flexible beam formulation based on the classical beam theory are based on preliminary assumptions and have to be investigated further.

DOI: 10.13009/EUCASS2019-675

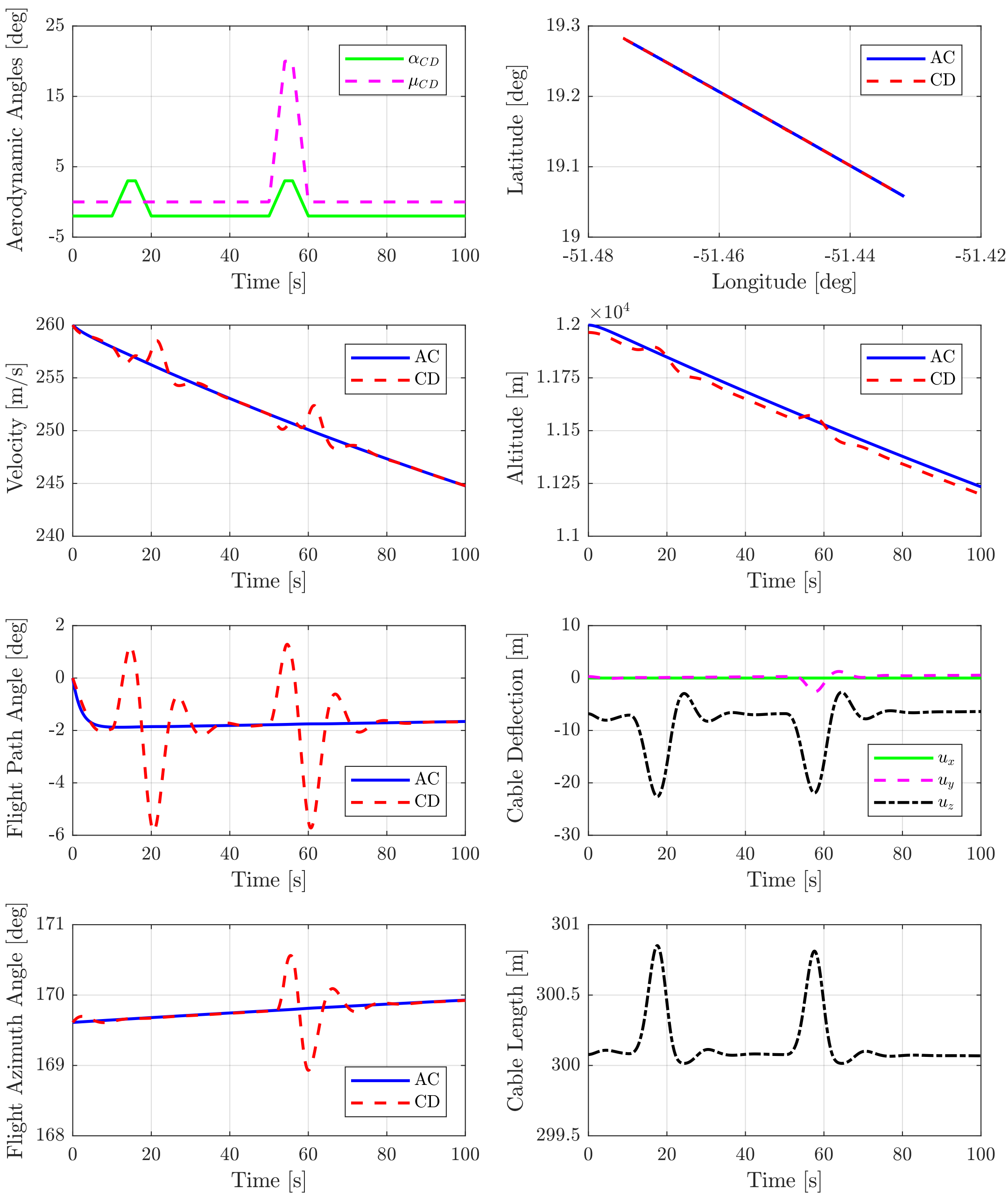

Figure 8: Combined Flight of the Aircraft (AC) and its Capturing Device (CD).

4. Results

The results presented in this paper are divided into two dedicated studies. First, only the aircraft and its capturing device are investigated in terms of flexible multibody dynamics induced by the flexible cable between the two flight vehicles. Second, the preliminary simulation results of the formation flight involving all three vehicles as introduced in Section 3 are shown. These results are not based on a trajectory optimization and shall be used only for demonstrating the general capabilities of the multiple flight vehicle modeling and simulation framework.

In Figure 8, the results for the combined flight of the aircraft and its capturing device connected by a flexible cable are shown. The states of the overall model incorporate the position and velocity of the aircraft, and the generalized elastic coordinates of the cable. If necessary, the generalized elastic coordinates can be automatically removed from the equations of motion resulting in a rigid connection between the two flight vehicles. The position and velocity of the

DOI: 10.13009/EUCASS2019-675

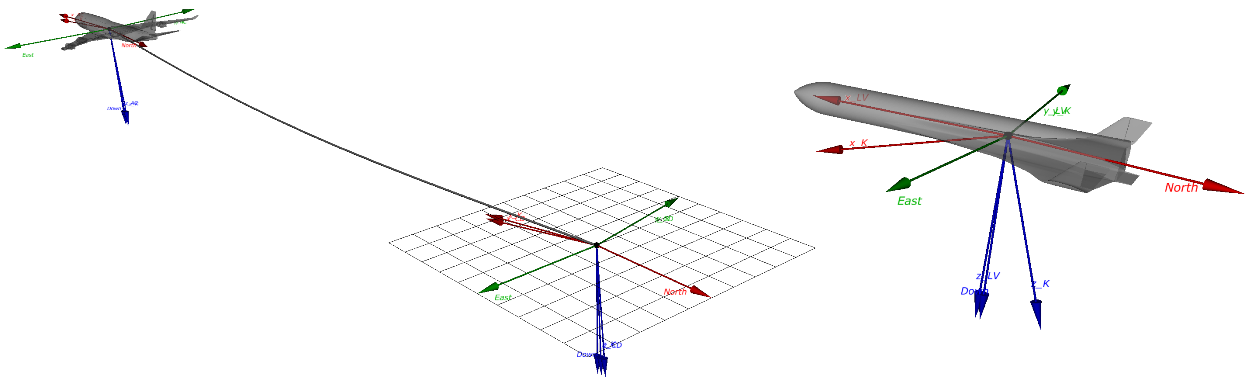

Figure 9: Visualization of the In-Air-Capturing Maneuver using the *DLR Visualization Library* [3].

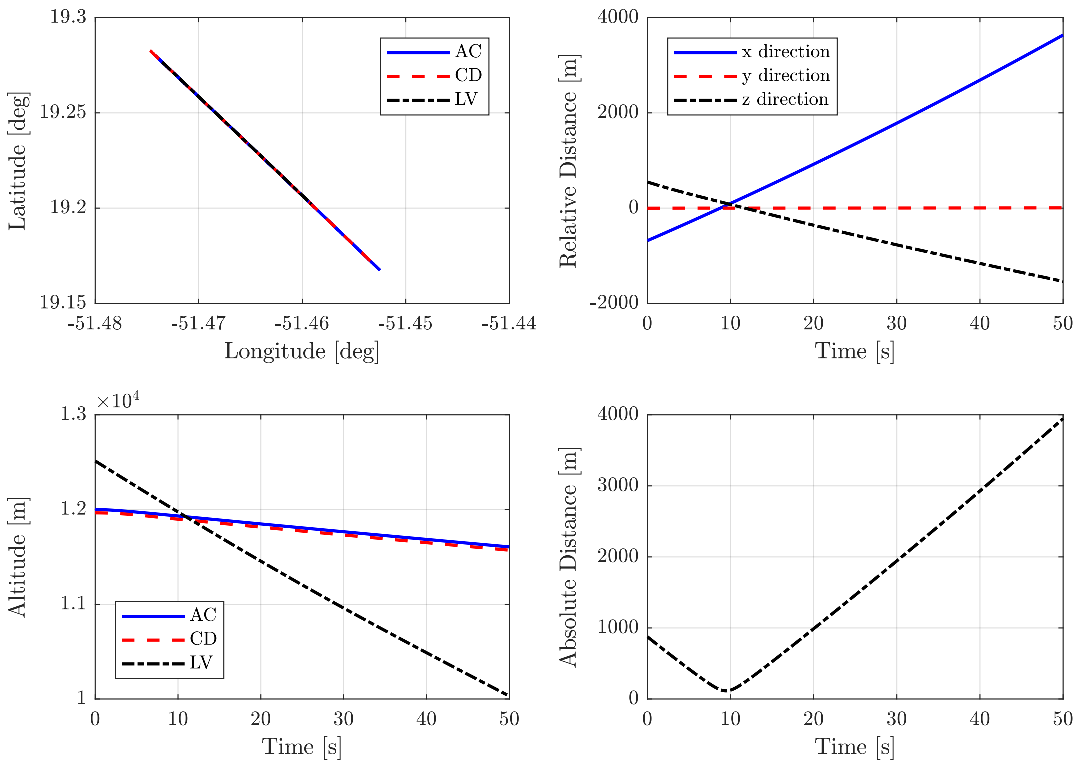

Figure 10: Combined Flight of the Aircraft (AC), its Capturing Device and the Launch Vehicle (LV).

3-DOF capturing device are completely dependent on the translational states of the aircraft and the generalized elastic coordinates of the cable. These generalized elastic coordinates consist of bending deflections with respect to the *xy* and *xz* planes, lengthening effects and torsional deformation with only one mode shape considered in each case. It has to be taken into account, that in addition to the aerodynamic and thrust forces acting on both vehicles, the cable is also subjected to aerodynamic loads which have been modeled as distributed forces along the cable approximated by the drag coefficient of a generic cylinder. For this purpose, the flight path and atmospheric parameters are measured at each interpolation point along the cable in order to obtain the dynamic pressure and the corresponding aerodynamic loads, respectively. The visualization of the in-air-capturing maneuver is shown in Figure 9.

To study the aerodynamically controlled motion of the capturing device under flight conditions, the aircraft is initialized at a cruise altitude of 12km with a velocity of 260m/s followed by a continuous descent maneuver. During the descent, the aerodynamic angle of attack and the aerodynamic bank angle of the capturing device are excited sequentially at 10s and at 50s. Figure 8 shows, that the first excitation of the aerodynamic angle of attack results in a corresponding change of the altitude, velocity, and flight path angle of the capturing device. If the aerodynamic

DOI: 10.13009/EUCASS2019-675

angle of attack and the aerodynamic bank angle are excited simultaneously at 50s, the motion of the capturing device influences also the flight path azimuth angle as expected. Since the connection between the aircraft and its capturing device is implemented as a flexible beam, the overall motion of the capturing device results in a damped oscillation. The actual deflections and lengthening of the cable at the attachment point to the capturing device with respect to its floating frame of reference are also presented in Figure 8. Using this method, the highly agile capturing device can be controlled by its aerodynamic angles to actively catch the approaching launch vehicle. Future research will focus also on nonlinear effects regarding the cable motion since the obtained results show deviations between first and second order beam formulations.

The in-air-capturing model is also used for the simulation of the aircraft, its capturing device and the launch vehicle as shown in Figure 10. The launch vehicle performs a steep descent, while the aircraft remains at an almost horizontal altitude. The coupling between the capturing device and the approaching launch vehicle is not considered in this case. As indicated by the measured distance between the launch vehicle and the capturing device, the aircraft has to be capable of adequately matching the trajectory of the launch vehicle. The presented in-air-capturing model will be used for trajectory optimization using all available control inputs to obtain an optimal reference trajectory which then can be used for control system design of the participating flight vehicles.

5. Conclusion

The objective of this paper was to present the key elements of the modeling and simulation framework for reusable launch vehicles based on the object-oriented and equation-based modeling language MODELICA. Further, the aim was to show recent improvements of the modeling framework regarding its capabilities to simulate multiple vehicles as required for the in-air-capturing maneuver. The highly modular and multi-disciplinary modeling tool is applicable to preliminary design efforts especially for future guidance and control studies regarding the challenging and complex in-air-capturing maneuver. This is demonstrated by implementing three flight vehicles – winged first stage of an RLV, towing aircraft and capturing device – considering multiple disciplines like environment, aerodynamics, propulsion, kinematics, and flight dynamics. Additionally, the flexible connection between the aircraft and its capturing device was modeled based on the classical beam theory. Finally, preliminary results for all three flight vehicles were presented based on the reference trajectory of the launch vehicle.

Future research will be dedicated to the extension of this framework adding more modeling capabilities, particularly regarding the incorporation of structural elastic effects to all flight vehicles. The flexible connection between the aircraft and its capturing device shall be investigated further regarding nonlinearities and alternative modeling possibilities like dedicated rope dynamics models as already available at DLR's Institute of System Dynamics and Control. Finally, the flight vehicles considered in the in-air-capturing model shall be upgraded from 3-DOF models to full 6-DOF models taking into account changing aerodynamic coefficients due to aerodynamic control surface deflections.

6. Acknowledgments

This study was performed within the DLR research project AKIRA which evaluates key technologies for future reusable launch vehicles. The authors would like to thank DLR colleagues from these projects, in particular colleagues from the *Space Launcher System Analysis* department (SART) of the DLR Institute of Space Systems (DLR-RY) in Bremen, for providing data for the implemented flight vehicles. Furthermore, the authors would like to thank Dr. Andreas Heckmann and Dr. Dirk Zimmer of the DLR Institute of System Dynamics and Control for their insightful comments and suggestions.

References

[1] P. Acquatella B. Launch Vehicle Multibody Dynamics Modeling Framework for Preliminary Design Studies. In *6th International Conference on Astrodynamics Tools and Techniques (ICATT)*, 2016.

[2] P. Acquatella B., L. E. Briese, and K. Schnepper. Guidance Command Generation and Nonlinear Dynamic Inversion Control for Reusable Launch Vehicles. *Proceedings of the 69th International Astronautical Congress (IAC)*, 2018.

[3] T. Bellmann. Interactive Simulations and advanced Visualization with Modelica. In *Proceedings of the 7 International Modelica Conference*, 2009.

[4] Blue Origin. New Glenn Payload User's Guide, 2018. Revision C.

DOI: 10.13009/EUCASS2019-675

[5] L. E. Briese, P. Acquatella B., and K. Schnepper. Multidisciplinary Modeling and Simulation Framework for Reusable Launch Vehicle System Dynamics and Control. In *7th International Conference on Astrodynamics Tools and Techniques (ICATT)*, 2018.

[6] L. E. Briese, A. Klöckner, and M. J. Reiner. The DLR Environment Library for Multi-Disciplinary Aerospace Applications. In *Proceedings of the 12th International Modelica Conference*, 2017.

[7] L. E. Briese, K. Schnepper, and P. Acquatella B. Advanced Modeling and Trajectory Optimization Framework for Reusable Launch Vehicles. In *IEEE Aerospace Conference*, 2018.

[8] L. Bussler and M. Sippel. Comparison of Return Options for Reusable First Stages. In *21st AIAA International Space Planes and Hypersonics Technologies Conferences*, 2017.

[9] S. Cain, S. Kraue, and J. Binger. Entwicklung einer automatischen Koppeleinheit für das Einfangen einer wiederverwendbaren Trägerstufe im In-Air-Capturing. In *Deutscher Luft- und Raumfahrtkongress*, 2017.

[10] S. Cain, S. Krause, and J. Binger. First Development Steps of an Actively Controlled Drogue. In *International Conference on Unmanned Aircraft Systems*, 2018.

[11] DYMOLA. *Version 2018*. Vélizy-Villacoublay, France, Dassault Systèmes, 2018.

[12] H. Elmqvist, S. E. Mattsson, and M. Otter. Modelica - An International Effort to Design an Object-Oriented Modeling Language. In *Summer Computer Simulation Conference*, 2003.

[13] P. Fritzson and P. Bunus. Modelica - A General Object-Oriented Language for Continuous and Discrete-Event System Modeling and Simulation. In *35th Annual Simulation Symposium*, 2002.

[14] A. Heckmann, S. Hartweg, M. Otter, J. Tobolář, and J. Brembeck. The Modeling of Flexible Bodies in the object-oriented multi-domain Framework Modelica. In *The 2nd Joint International Conference on Multibody System Dynamics*, 2012.

[15] A. Heckmann, M. Otter, S. Dietz, and J. D. López. The DLR FlexibleBodies Library to model large motions of beams and of flexible bodies exported from finite element programs. In *Proceedings of the 5th International Modelica Conference*, 2006.

[16] D. R. Jenkins. *Space Shuttle: The History of the National Space Transportation System - The First 100 Missions*. 2010. 3rd Edition.

[17] H.-D. Joos, J. Bals, G. Looye, K. Schnepper, and A. Varga. A multi-objective optimisation-based software environment for control systems design. In *IEEE International Symposium on Computer Aided Control System Design Proceedings*, 2002.

[18] H. Kayal. Aufbau eines vereinfachten Simulationsmodells für den Bahnaufstieg in der Grosskreisebene. Technical Report DLR IB 318-93/05, DLR German Aerospace Center, 1993.

[19] J. Klevanski, A. Herbertz, M. Sippel, and J. Kauffmann. Verfahren zum Bergen einer Stufe eines mehrstufigen Raumtransportsystems, 2001. Patent DE10147144C1.

[20] A. Kopp, M. Sippel, S. Stappert, N. Darkow, J. Gerstmann, S. Krause, D. Stefaniak, M. Beerhorst, T. Thiele, A. Gülhan, R. Kronen, K. Schnepper, L. E. Briese, and J. Riccius. Forschung an Systemen und Technologien für wiederverwendbare Raumtransportsysteme im DLR-Projekt AKIRA. In *Deutscher Luft- und Raumfahrtkongress*, 2017.

[21] Modelica Association. *Modelica - A Unified Object-Oriented Language for Physical Systems Modeling, Language Specification Version 3.3. Revision 1*, 2014.

[22] Modelica Association. *Functional Mock-Up Interface for Model Exchange and Co-Simulation*, 2015.

[23] M. Otter, H. Elmqvist, and F. E. Cellier. Modeling of Multibody Systems with the Object-Oriented Modeling Language Dymola. In *Nonlinear Dynamics 9*, 1996.

[24] M. Otter, H. Elmqvist, and S. E. Mattsson. The New Modelica MultiBody Library. In *Proceedings of the 3rd International Modelica Conference*, 2003.

DOI: 10.13009/EUCASS2019-675

[25] U. Reisch and Y. Anseaume. Validation of the Approximate Calculation Procedure HOTSOSE for Aerodynamic and Thermal Loads in Hypersonic Flow with Existing Experimental and Numerical Results. Technical report, DLR German Aerospace Center, 1998.

[26] C. Rosema, J. Doyle, L. Auman, M. Underwood, and W. B. Blake. *Missile DATCOM, User's Manual - 2011 Revision*. AFRL, 2011.

[27] K. Schnepper. Trajektorienoptimierung in MOPS - Das Paket trajOpt Version 1.0. Technical report, DLR German Aerospace Center, 2014.

[28] M. Sippel, L. Bussler, S. Krause, S. Cain, and S. Stappert. Bringing Highly Efficient RLV-Return Mode 'In-Air-Capturing' to reality. In *HiSST: International Conference on High-Speed Vehicle Science Technology*, 2018.

[29] M. Sippel and J. Klevanski. Progresses in Simulating the Advanced In-Air-Capturing Method. In *5th International Conference on Launcher Technology*, 2003.

[30] M. Sippel and J. Klevanski. Preliminary Definition of an Aerodynamic Configuration for a Reusable Booster Stage within Tight Geometric Constraints. In *Proceedings of the 5th European Symposium on Aerothermodynamics for Space Vehicles*, 2004.

[31] M. Sippel and J. Klevanski. Simulation of Dynamic Control Environments of the In-Air-Capturing Mechanism. In *6th International Symposium on Launcher Technology*, 2005.

[32] M. Sippel, J. Klevanski, and J. Kauffmann. Innovative Method for Return to the Launch Site of Reusable Winged Stages. In *52nd International Astronautical Congress*, 2001.

[33] M. Sippel, S. Stappert, L. Bussler, and E. Dumont. Systematic Assessment of Reusable First-Stage Return Options. In *68th International Astronautical Congress*, 2017.

[34] M. Sippel, S. Stappert, J. Wilken, N. Darkow, S. Cain, S. Krause, T. Reimer, C. Rauhe, D. Stefaniak, M. Beerhorst, T. Thiele, R. Kronen, L. E. Briese, P. Acquatella B., K. Schnepper, and J. Riccius. Focused research on RLV-technologies: the DLR project AKIRA. In *European Conference for Aeronautics and Space Sciences (EUCASS)*, 2019.

[35] M. Sippel, O. Trivailo, L. Bussler, S. Lipp, and C. Valluchi. Evolution of the SpaceLiner towards a Reusable TSTO-Launcher. In *67th International Astronautical Congress*, 2016.

[36] M. Sippel, C. Valluchi, L. Bussler, A. Kopp, N. Garbers, S. Stappert, S. Krummen, and J. Wilken. SpaceLiner Concept as Catalyst for Advanced Hypersonic Vehicles Research. In *European Conference for Aeronautics and Space Sciences (EUCASS)*, 2017.

[37] SpaceX. Falcon User's Guide, 2019.

[38] Liang Sun. *Dynamic Modeling, Trajectory Generation and Tracking for Towed Cable Systems*. PhD thesis, 2012.