Space Traffic Management Conference | 2016 Emerging Dynamics

Nov 18th, 2:00 PM

Vs controller design for simulation of the SpaceLiner suborbital two-staged reusable launch vehicle using SIFCDL (Simulation Integrated Flight Controller Development Lab)

Frank Morlang
DLR - German Aerospace Center

Sven Kaltenhaeuser
German Aerospace Center, sven.kaltenhaeuser@dlr.de

VS controller design for simulation of the SpaceLiner suborbital two-staged reusable launch vehicle using SIFCDL (Simulation Integrated Flight Controller Development Lab)

Frank Morlang,
Sven Kaltenhaeuser
Deutsches Zentrum für
Luft- und Raumfahrt (DLR)
Lilienthalplatz 7
38108 Braunschweig, Germany
frank.morlang@dlr.de

ABSTRACT
To allow the testing and evaluation of procedures and functionalities for an improved handling of space vehicle operation on ATM stakeholder level, a Space & Air Traffic Management (SATM) testbed has been established at DLR. It has to cover Aeronautical Information Management integration concepts, Air Traffic Control procedure adaptations and Air Traffic Controller Support as well as required System Wide Information Management (SWIM) based data exchange aspects. One key element of the SATM testbed is a Space Flight Simulator, which has been provided with a realistic flight dynamics model (FDM) for the SpaceLiner orbiter, a two-staged suborbital Reusable Launch Vehicle (RLV) which aims at future high-speed intercontinental passenger transport. To provide realistic flight behavior, the simulation model, based on X-Plane, shall be equipped with vertical speed autopilot controller. Core of each flight controller development is the precise derivation of the functional flight controller requirements from the aircraft dynamics. Using tabled flight dynamics data of unknown granularity contains the risk of fine grained controller tuning based on a too coarse grained fundament. The presented solution is based on the geometry modeled SpaceLiner flight dynamics in X-Plane, using SIFCDL for first findings of a vertical speed autopilot controller.

1. INTRODUCTION
The efforts of commercial space and the development of new concepts for cost efficient access to space have increased the number of launch events and further growth is expected. As a result, space vehicles passing through civil airspace will become much more common events than in previous decades. A safe and efficient integration of space vehicle operations into the air traffic system will be a necessary. Air Traffic Management (ATM) is playing a key role in this effort, providing an integration concept that is flexible and resilient enough to handle the uncertainties of launch and re-entry events and provide measure to cope with a still significantly lower target level of safety associated with space flights compared to commercial airplanes. It has to be the goal to integrate all kind of space vehicle operations into one system to ensure a seamless and efficient approach. This includes concepts of very high-speed intercontinental passenger transport via suborbital point-2-point flights, like the DLR SpaceLiner concept..

2. VALIDATION INFRASTRUCTURE
To answer the questions that arise from introducing space vehicle operations in the current ATM, DLR is developing a framework for traffic impact analysis and for testing and evaluation of procedures and functionalities for an improved handling of space flights on ATM stakeholder level..

2.1 SATM testbed
The Space and Air Traffic Management (SATM) testbed has to cover AIM integration concepts, ATC procedure adaptations and Air Traffic Controller Support as well as System Wide Information Management (SWIM) based data exchange aspects. The SATM testbed is embedded into the DLR Air Traffic Validation Center, which comprises simulators, sensor systems and flight testing equipment for testing and evaluating new ideas, concepts and technologies for all areas of air traffic management. As an integrated validation infrastructure, the Air Traffic Validation Center includes:

- Model based simulation tools for early stage and Model driven analysis of concepts and fast prototyping structured and quality assured data preparation and analysis process
- Real-time simulation tools for evaluation of technologies, concepts and procedures with human-in-the-loop; and
- Airport research Facility & External Testbeds, allowing live trial capabilities for technology and concept elements testing and evaluation

The SATM testbed will make specifically use of the model based fast-time simulation tool AirTOp, the Air Traffic Management and Operations Simulator ATMOS, which is a human-in-the-loop air traffic control simulation environment, and an interconnected Space Flight Simulator.

European air traffic as well as the airspace restrictions and space vehicle trajectories and its related hazard areas are simulated with AirTOp fast time simulator. AirTOp is an open modular and extensible tool, which allows writing of specific airspace restriction applications. This simulation environment is getting used for traffic impact analysis studies, as described in more detail in [1].

ATMOS provides up to 5 Controller Working Positions (CWP) and can be coupled with other real-time simulators of the Validation Center or external facilities in a distributed simulation setup. The CWP layout, its ATC tools, displays and interfaces can be modified according to the purpose and needs of the validation campaign, allowing full flexibility for implementation of the required support functions for space traffic integration (Figure 1).

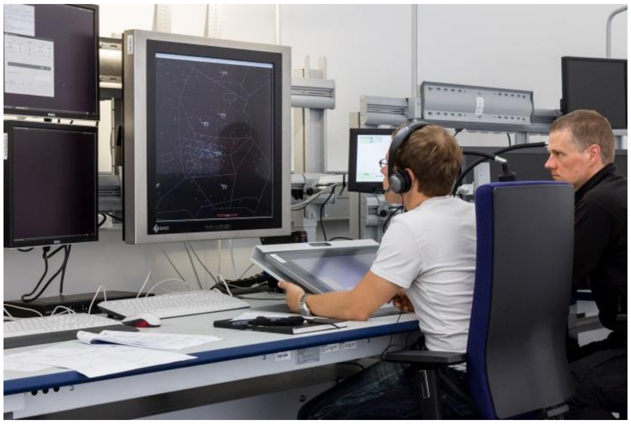

Figure 1. CWP of the Air Traffic Management and Operations Simulator ATMOS at the DLR Air Traffic Validation Center, Braunschweig, Germany

A Space Flight Simulator will represent the space vehicle within the SATM testbed, currently using the flight simulation software X-Plane, which is inexpensive, FAA certified, "simple" to use and provides open interface protocols. As a human-in-the-loop simulator, it allows full pilot interaction as well as flying the space vehicle on a predefined trajectory. Both, ATMOS and Space Flight Simulator are coupled during runtime and can use all kinds of specifically designed air traffic scenarios (based on historic air traffic data or customized to represent certain traffic requirements), e.g. by using advanced scenario editing tools developed specifically for this purpose.

The SATM testbed is open and flexible to add or replace certain elements and simulators by additional external facilities, allowing e.g. joint cross border distributed real-time simulations.

In addition to the real-time simulation capabilities a SWIM test environment has to be implemented into the SATM testbed. Allowing for integrated evaluation of SWIM applications for data distribution between the multiple involved stakeholders, the applied architecture has to cope with certain requirements, allowing feed data streams from multiple sources and replacing missing services by simulated entities, depending on the specific validation setup. The core element of the SWIM test environment will be an Enterprise-Service Bus (ESB) (e.g. by using the WSO2 ESB as an open source solution) and the capability to expand further on the prototype solution developed within [2].

The described elements are building the core of the SATM testbed. As it is a part of the Air Traffic Validation Center, it can be further expanded, e.g. by connecting it with the Apron and Tower Simulator ATS or Airport and Control Center Simulator ACCES to cover additional aspects of stakeholder involvement and ATM integration.

2.2 SpaceLiner use case

The DLR SpaceLiner concept has been chosen as a first use case to study the possible impact of space vehicle operations from, to or within Europe on the air traffic system. The SpaceLiner has been developed by the Space Launcher Systems Analysis (SART) group of DLR. Its basic idea is to enable sustainable low-cost space transportation to orbit while at the same time revolutionizing ultra-long distance travel between different points on Earth [3]. It consists of a fully reusable booster and passenger stage arranged in parallel. During the launch phase, both, orbiter and booster stage, are firing until separation, which will take place at approx. Mach 12.5. The reusable booster stage will fly back to the launch site, while the orbiter stage will proceed with its power flight until Main Engine Cut Off (MECO) with a maximum speed of around 7.1 km/s at an altitude of 69 km. The propulsive phase is directly followed by hypersonic gliding.

Figure 2. The SpaceLiner reusable booster and passenger stage during lift off [4]

To adapt the Space Flight Simulator to this use case, a SpaceLiner simulation model has been developed for X-Plane. The simulation model can be used for the aforementioned research on improved handling of space flights on ATM stakeholder level but also provides a testbed to analyze the flight dynamic of future space vehicles.

3. CONTROLLER DESIGN

3.1 Motivation

The motivation targets to the future realization of a pure simulation-based, flexible control parameter identification and tuning possibility of the SpaceLiner's autopilot functionality, ready to be used in a possible prototype in future reality. The general principle of this approach is shown in Figure 3. Simulated aircraft dynamics, acting as the control loop's disturbance injector in this solution, must be characterized by a high degree of realism.

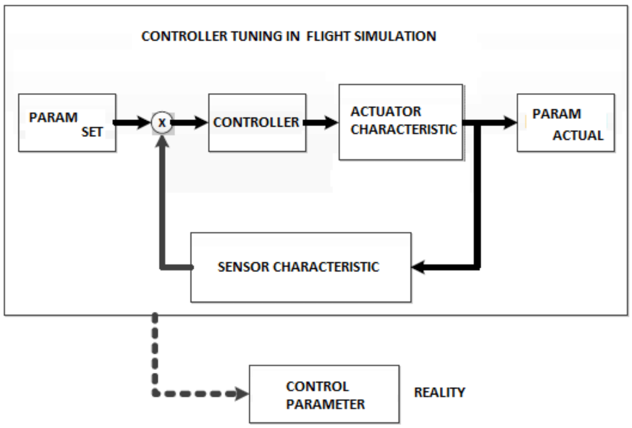

Figure 3. Principle of simulation based real-control parameter identification

For the SpaceLiner's flight dynamics, the commercial flight simulation software "X-Plane" (Figure 4) is used, because of its very high sophisticated and realistic flight dynamics model as well as its broad range of interfacing and aircraft modelling capabilities (Figure 5).

X-Plane reads the geometric shape of a modelled aircraft and figures out how that aircraft will fly by a process called "blade element theory", where the aircraft is broken down into small elements and the total behavior is determined by calculating the forces on each element and summing up these forces.

Figure 4. SpaceLiner model in the X-Plane flight simulator

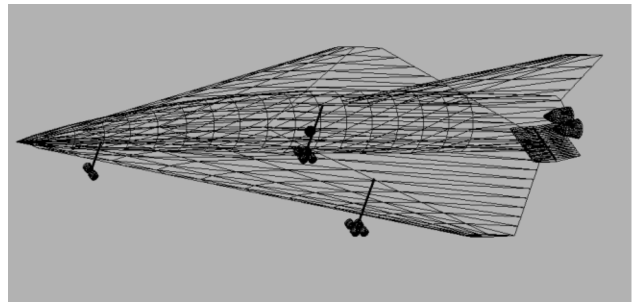

Figure 5. SpaceLiner model in X-Plane's PlaneMaker tool

A look at the used X-Planes's transport delay (Figure 6) has shown peaks not higher than 50 ms, thus fulfilling the flight simulation training device standards, requesting that the transport delay must not exceed 150 ms[5].

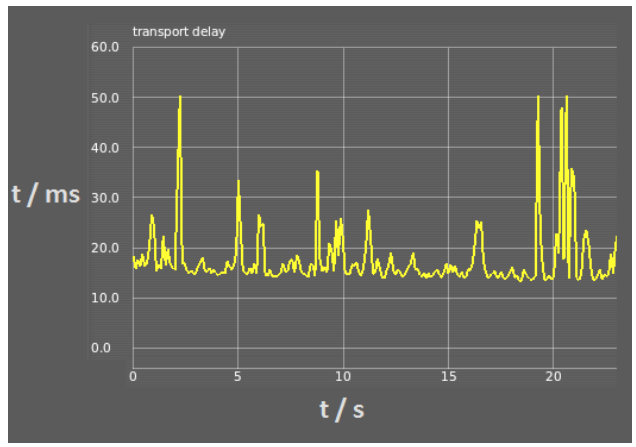

Figure 6. Transport delay vs. time

3.2 Challenge

The challenge of a pure simulation-based solution without any hardware stimulation can be summarized by the following questions:

- Does the flight dynamics model represent a realistic disturbance injector ?
- Are the sensor and actuator characterizations real enough ?

The first question is addressed by how the SpaceLiner flight dynamics model was created in X-Plane's Plane Maker tool. X-Plane uses the geometric shape of an aircraft to figure out how it will fly. This is done by finding the forces of many small breakdown elements of the aircraft's geometry, calculating the associated accelerations and integrating to velocities and positions. Wing elements can be coupled with airfoil data, where lift and drag specifics can be read in as well as modelled with an additional tool called Airfoil Maker.

In a first approach, the SpaceLiner body flap at the back was modelled acting as a continuous elevator (based on a wrong assumption) and the wing elements were associated with the NACA 65-006 profile, resulting in the black measurement C_l and C_d values (Figure 7 and Figure 8), where the values in brown represent the reference [6] from Computational Fluid Dynamics (CFD), Calculation of Aerodynamic Coefficients (CAC)[1] & PAN AIR[2] model experiments.

In a second step, the body flap was created acting as a flap with discrete target positions, shown in the red measurement C_l and C_d values (Figure 7 and Figure 8).

Against the background that the SpaceLiner aerodynamic reference database refers to modified NACA 66-003.5 (root) cut at trailing edge 50 mm and modified NACA 66-005.5 (tip) cut at the same thickness airfoils [7], NACA 66-206 airfoil data were used for the wing elements. C_l slope and C_d at 10° α fine tuning in the Airfoil Maker tool resulted in in the green measurement C_l and C_d values (Figure 5 and Figure 6).

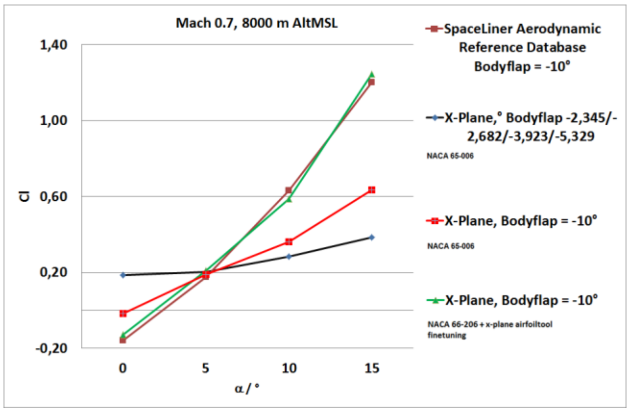

Figure 7. C_l vs. α SpaceLiner X-Plane model comparison

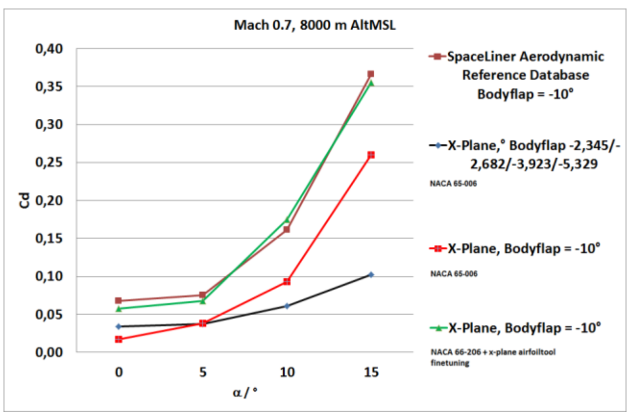

Figure 8. C_d vs. α SpaceLiner X-Plane model comparison

As far as sensors and actuators are concerned, as a first approach, simple first order dynamics with a time lag τ_a of 20 ms were modelled according to the transfer functions in Figure 9.

$$G_s(s) = \frac{1}{\tau_s s + 1}$$

$$G_a(s) = \frac{1}{\tau_a s + 1}$$

Figure 9.

3.3 Realization

A controller with feedback terms for vertical speed and rate of change of vertical speed was chosen (Figure 10).

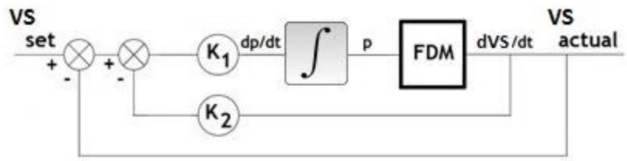

Figure 10. Controller design

The rate of change of the yoke or stick position dp/dt is zero when the vertical speed vs_{actual} reaches the reference vertical speed vs_{set} and vertical acceleration dvs/dt is zero. The derivation of the controller's tuning parameters K_1 and K_2 is shown in Figure 11. The computed yoke/stick position p is limited to a range of -0.2 to 0.2 of the normalized -1.0 (full forward) to 1.0 (full back) region.

$$p = \left(dv - \frac{dv}{dt} K_2\right) K_1$$

$$= K_1 dv - K_1 K_2 \frac{dv}{dt}$$

$$\Longrightarrow K_1 = K_p\, ,\; K_1 K_2 = K_d$$

Figure 11. K_1 and K_2 characterization

4. CONTROLLER TUNING

Parameter tuning was done using the Ziegler-Nichols method [8], where the parameters are found according to the oscillation pure proportional gain K_u and the oscillation period T_u, at which the output is characterized by time stable and consistent oscillations:

$$K_p = 0.8 K_u$$

$$T_d = T_u / 8$$

Figure 12. K_p and T_d for the PD control type according to [8]

With $K_2 = 0$, $K_1 = K_u = 0.0003$ was found (Figure 13 - Figure 15). With a T_u of 4 seconds and taking into account $K_p T_d = K_d$ gave $K_1 = 0.00024$ and $K_2 = 0.5$.

---

[1] Software developed by DLR Institute of Space Systems, Dep. Space Launcher System Analysis

[2] Software developed by BOEING

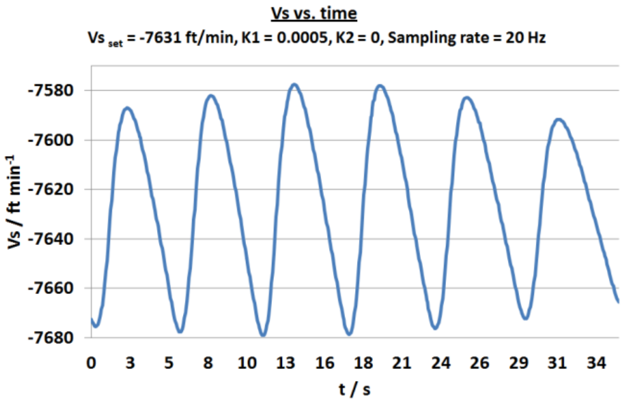

Figure 13. First experimental oscillation findings

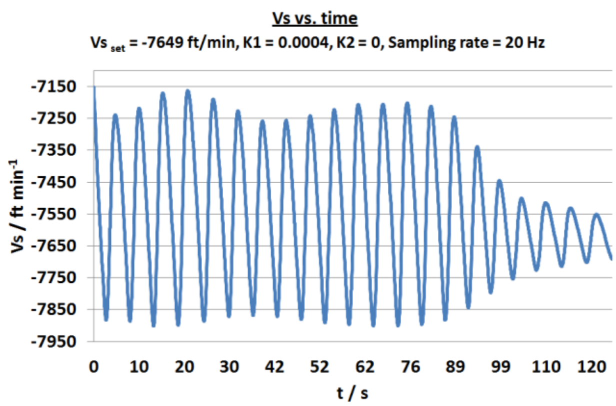

Figure 14. Oscillations at K_1 = 0.0004

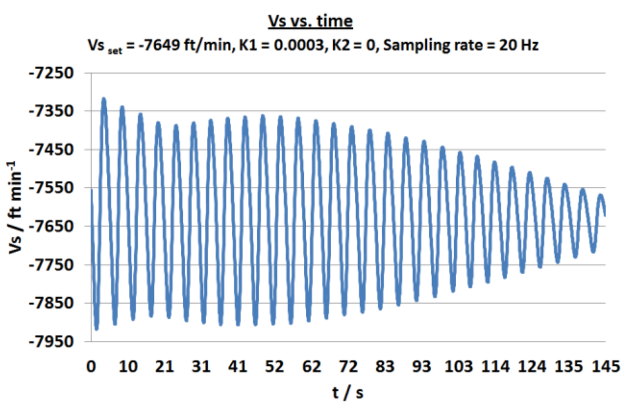

Figure 15. Oscillations at K_1 = 0.0003

The SpaceLiner's response to a change in vs from -10000 ft/min to vs_{set}-7649 ft/min is shown in Figure 16, resulting in a vs of -7611 ft/min.

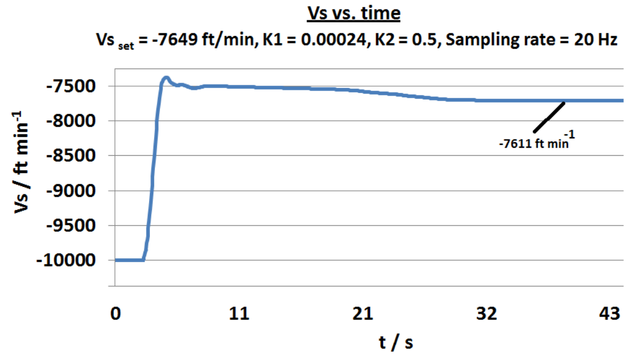

Figure 16. Vertical speed vs. time for K_1 = 0.00024 and K_2 = 0.5

The simple first order actuator dynamics, realized with a time lag τ_a of 20 ms (3.2) and a limited range of -0.2 to 0.2 of the normalized -1.0 (full forward) to 1.0 (full back) region (3.3), have been modelled with an associated minimum and maximum deflection of -45° to 45° (Figure 17) and a maximum actuation rate of 20 °/s.

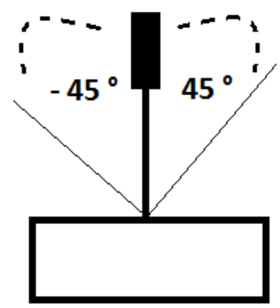

Figure 17. Modelled minimum and maximum stick/yoke deflections

The measured stick/yoke position vs. time (Figure 18) revealed a de facto actuation rate of 18.17 °/s.

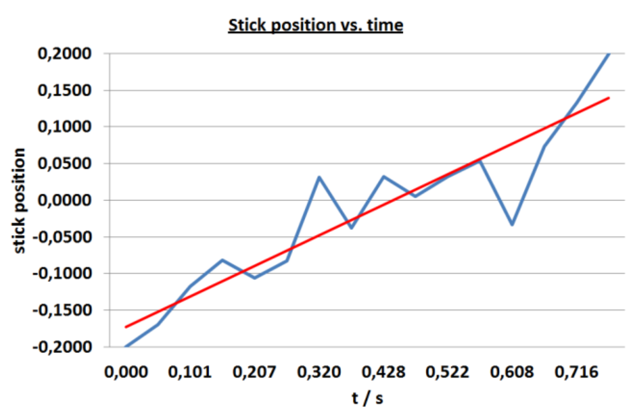

Figure 18. Stick/yoke actuator dynamics

5. OUTLOOK

Near future work will address the modelling of further controllers:

- bank angle hold,
- heading hold,
- flight path angle hold.

To further increase the realism of the control system, sensor associated imperfections that those devices can introduce will receive special attention, focusing on noise, drift and second order dynamics' realization.

Actuator responsibility for the realism of the control system will lead to a future plant modelling, consisting of models of the power amplifier, the servo motor drive and the stick/yoke lever with its refinement to a single rigid body consisting of the lever shaft and the grip.

The SpaceLiner flight dynamics model will be refined according to wind tunnel results, planned for the near future.

6. SUMMARY

With the Space and Air Traffic Management (SATM) testbed, a validation environment has been created for Space and Air Traffic Integration research. A fast-time simulation framework and a distributed real-time human-in-the-loop simulation environment can be used to study the effects and benefits of advanced concepts for the integration of space vehicle operation into ATM. As one of the core elements, the X-Plane based Space Flight Simulator represents a testbed to analyze the flight dynamics of future space vehicles.

A vertical speed controller using sensor and actuator first order dynamics with a time lag τ_a of 20 ms has been realized as a first step towards a pure simulation-based, flexible control parameter identification and tuning possibility without the need for any hardware stimulation.

7. REFERENCES

[1] T. Luchkova, S. Kaltenhaeuser, F. Morlang, "Air Traffic Impact Analysis Design for a Suborbital Point-to-Point Passenger Transport Concept", 3rd Annual Space Traffic Management Conference, Daytona, 2016

[2] Morlang, F., Ferrand, J., Seker, R.: WHY A FUTURE COMMERCIAL SPACECRAFT MUST BE ABLE TO SWIM, 8th International Association for the Advancement of Space Safety Conference, 2016

[3] Sippel, M., Klevanski, J., Steelant, J.: Comparative Study on Options for High-Speed Intercontinental Passenger Transports: Air-Breathing- vs. Rocket-Propelled, IAC-05-D2.4.09, October 2005

[4] Sippel, M., Trivailo, O., Bussler, L., Lipp, S., Valluchi, C.; Kaltenhäuser, S.; Molina, R.: Evolution of the SpaceLiner towards a Reusable TSTO-Launcher, IAC-16-D2.4.03, September 2016

[5] European Aviation Safety Agency, "Certification Specifications for Aeroplane Flight Simulation Training Devices", 2012, Annex to ED Decision 2012/010/R.

[6] T. Schwanekamp, L. Morsa, G. Zuppardi and R. Molina, "SpaceLiner 7-2 Aerodynamic Reference Database", SART TN-026/2012, Bremen, 2012.

[7] M. Sippel, T. Schwanekamp, " The SpaceLiner Hypersonic System – Aerothermodynamic Requirements and Design Process", 8th Europ. Symposium on Aerothermodynamics for Space Vehicles, Lisbon, March 2015

[8] J.G. Ziegler, N.B. Nichols (1942), "Optimum settings for automatic controllers", Transactions of the ASME. 64: 759–768