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Upcoming DLR Reusability Flight Experiment

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Abstract

After the successful hypersonic flight experiments SHEFEX I and II, the German Aerospace Center (DLR) is now investigating the realization of the Reusability Flight Experiment (ReFEx). This successor mission shall be launched on a Brazilian VSB-30 sounding rocket in 2021 and shall achieve a reentry velocity of more than Mach 5. The main goal is the demonstration of a controlled autonomous re-entry flight from hypersonic velocity down to subsonic range and to test *key technologies* required for *future reusable booster systems*. So far, two Concurrent Engineering (CE) studies were conducted to investigate the feasibility of this sophisticated project. The required subsystems, including sensors and actuators as well as their interfaces have been defined and different options were assessed regarding matters like the scientific output, complexity, risk, and cost. The current configuration of ReFEx has a re-entry mass of about 450 kg, a length of 2.7 m, and a wingspan of 1.1 m. This paper provides a system overview, addresses systems engineering aspects and main challenges regarding the mission realization. For example, to meet the VSB-30 launcher flight stability requirement, the wings of the ReFEx experiment were designed foldable. Therefore, special attention was paid to a passive and reliable lock mechanism for the wings.

Keywords: *(ReFEx, reusable booster systems, launch vehicle)*

1. Introduction

Launch vehicles are complex and expensive systems; their costs cannot be spread over many missions if the vehicles are expendable. Therefore, worldwide research activities at universities, research institutions and especially industrial companies are ongoing to find solutions to reduce the cost of launch systems for future missions via partial or full reuse of the launch vehicle. The German Aerospace Center (DLR) has been investigating a *reusable fly-back booster* LFBB concept for several years in the ASTRA study [1]. Together with German industry and universities, a large number of numerical investigations as well as dedicated wind tunnel tests were performed. Furthermore, DLR earned practical experience on national projects, e.g. SHEFEX I and II [2, 3], as well as in international cooperation projects, e.g. FOTON [4], EXPRESS [5], and HIFiRE [6–8]. Within those projects, different key technologies required for reusable booster systems were already developed and tested (e.g. thermal protection system, hybrid canards and special navigation systems). Furthermore, measurement data was collected und utilized for model validation.

Now, DLR is investigating the realization of a sub-scaled *fly-back booster* experiment. The ReFEx (Reusability Flight Experiment) shall be launched on a Brazilian VSB-30 sounding rocket in 2021 and shall achieve a re-entry velocity of more than Mach 5. The main goal is the demonstration of a controlled autonomous re-entry flight from hypersonic down to subsonic velocity and to test key technologies required for future *reusable booster systems*.

2. System Overview

Fig. 1 shows the current launch (left) and re-entry (right) configuration of ReFEx. The VSB-30 sounding rocket has a passive stabilization system (no active vector control). The payload, to be placed on top of the rocket, requires an almost rotationally symmetrical shape to enable a safe start. However, the ReFEx vehicle needs to have an aerodynamic shape for the re-entry phase, which is a contradicting requirement to the launch requirement. Therefore, the wings of the experimental vehicle were designed foldable and are covered by a fairing for the atmosphere passage phase. After separation from the rocket, the wings shall be rearranged in flight configuration. In this sense, the structure subsystem poses some challenges, since a passive and reliable folding and locking mechanism for the wings is required. In the frame of the project, a possible technical solution was already developed (patent application under review) for the mechanism which is currently being analyzed in detailed.

The main goal of the project is the demonstration of an *autonomous* re-entry flight of a *winged* vehicle from hypersonic velocity down to subsonic range which requires a number of different technologies. One of the main challenges is the vehicle design that enables a static as well as a dynamic stability of the vehicle in all flight regimes. To be able to follow the RLV trajectory (see Fig. 5 and Fig. 6), the angles of attack (AoA) need to be changed rapidly (see Fig. 7). These pose demanding requirements to the vehicles aerodynamic design as well as guidance, navigation and control subsystems. Especially the transonic region is challenging, since the position of the aerodynamic center of pressure will rapidly change. Therefore, besides the sophisticated aerodynamics activities the guidance, the navigation and the control technologies including the corresponding autonomous on-board algorithms need to be developed and tested within the ReFEx project. However, the development is not from scratch but based on experience from the already performed projects such as SHEFEX II. After the separation from the rocket, the experiment will perform a number of maneuvers by means of a reaction control system (RCS), to dump the rest spin rate and to achieve the required re-entry orientation of the vehicle. The RCS will also be utilized to control the vehicle down to an altitude were the aerodynamic control surfaces become effective (approx. 65 km - 50 km).

Furthermore, the experimental vehicle will be equipped with a number of specific sensors to perform continuously in-situ data acquisition, of the environment and vehicle state itself. The data shall be utilized for software models validation as well as technology improvements for the follow-on projects (see also [9]).

The current design of the re-entry vehicle has a length of 2.7 m, a wingspan of 1.1 m, and a total mass of about 450 kg.

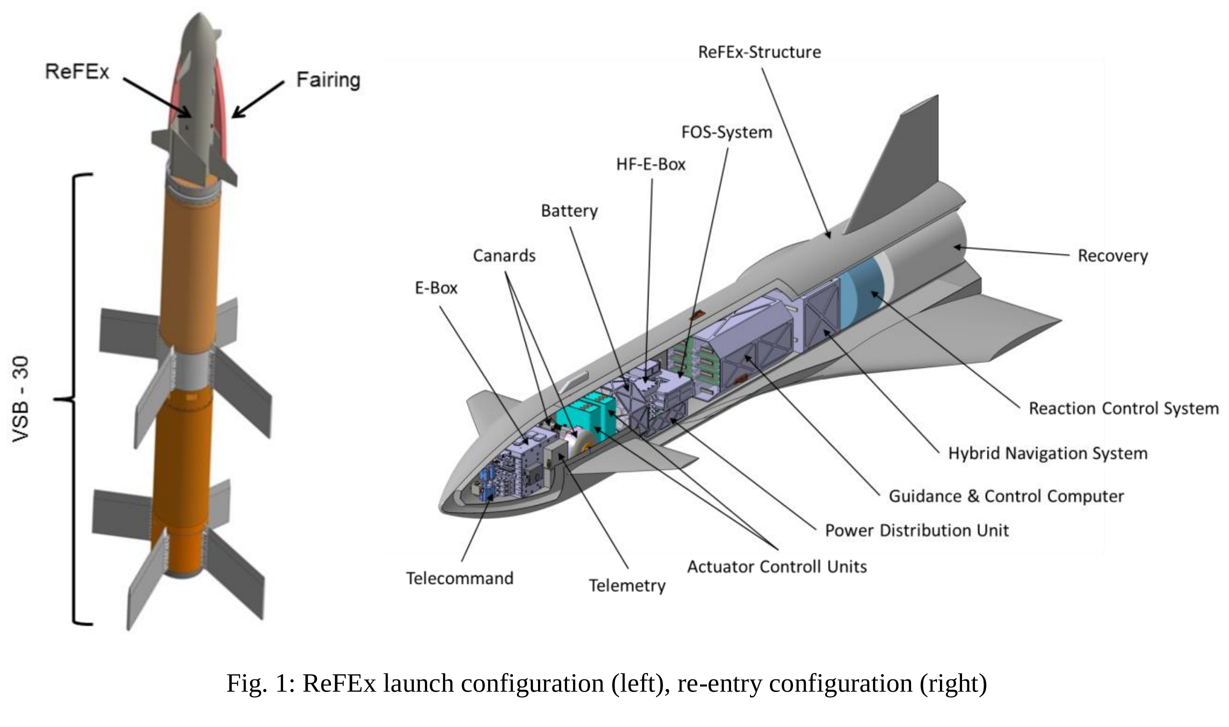

Fig. 1: ReFEx launch configuration (left), re-entry configuration (right)

3. Mission Design

3.1 Launch phase

ReFEx shall be launched by a Brazilian solid propellant two-stage VSB-30 rocket from Woomera Test Range, Australia. Following a guided rail travel, the launch vehicle builds up a roll rate aiming to reduce dispersion at payload separation and stage impact. The vehicle is unguided and passively stabilized by sets of four fins on each stage. To fulfil the flight stability requirement without major modifications on the launch vehicle, the effective aerodynamic surfaces of the payload had to be reduced, which is realized by a foldable wing design and a 0.64 m diameter hammerhead fairing covering the tail section of ReFEx during atmospheric ascent. In the exo-atmospheric flight phase after burn-out of the second stage, a YoYo-system is activated for despin and subsequently the stage is separated from the ReFEx payload. The mission events are shown in Fig. **2**. Corresponding values are summarised in Table 1.

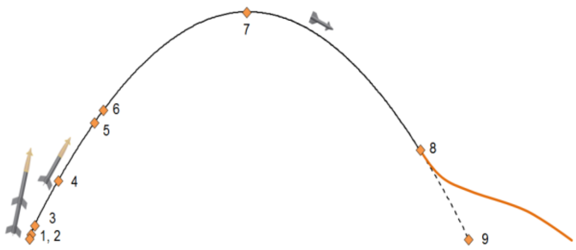

Fig. 2: Mission Events

Table 1: Mission events

Nr.	Event	Time (s)	Alt (km)	GR (km)
1	Ignition S31	0	0	0
2	Burn-out S31 & Stage Separation	12	3	1
3	Ignition S30	20	6	2
4	Burn-out S30	49	34	21
5	Yo-Yo Despin	79	70	50
6a	Fairing Separation	83	75	54
6b	Motor Separation	85	77	56
7	Apogee	194	132	163
8	Experiment Phase Entry	326	50	292
9	Ballistic Stage Impact	384	0	325

The analyses on flight performance and static stability are based on a modified VSB-30 configuration with identical fins on both stages for improved flight stability in the phase after rail exit. Total payload mass at the present stage of the project is 535 kg and the re-entry vehicle mass is 450 kg. The total payload CoG is assumed at 41% aft of the payload length including payload adapter. Table 2 summarizes the gravimetrics of the launch vehicle in lift-off configuration, whereas "Payload" includes the payload adapter, "2nd stage S30" includes the motor adapter and fairing with despin system and "1st stage S31" includes the interstage adapter.

Table 2: Gravimetrics of launch vehicle in lift-off configuration

	Length (m)	Mass (kg)	CoG aft (m)
Payload	2.995	535	1.226
2nd stage S30	3.584	1236	1.861
1st stage S31	3.308	1037	1.729
Total	**9.887**	**2808**	**4.460**

Aiming for high horizontal speed and a shallow flight path angle at re-entry, the mission profile features a low launch elevation of 76° and a delayed 2nd stage ignition time at T+20s, as successfully utilized in the HIFiRE 4 mission. The section plane comprising the ReFEx canards is the one with least static stability margin and therefore determining the flight stability assessment. Fig. 3 shows the evolution of Mach number and static stability margin as multiples of the motor diameter (calibre) based on CFD-calculated aerodynamics in the supersonic region. With a minimum static margin of 1.4 cal during 2nd stage burn phase, the configuration is sufficiently stable and provides margins allowing for potential design changes in the payload of about –25% in mass or –15% in CoG aft. With a maximum Mach number of 5.7 achieved during ascent, the performance requirement of the payload (Mach > 5.0) is fulfilled. The vehicle reaches an apogee of 132 km at 986 m/s (Mach 2.0) horizontal speed and a ballistic range of 325 km, as depicted by Fig. 4.

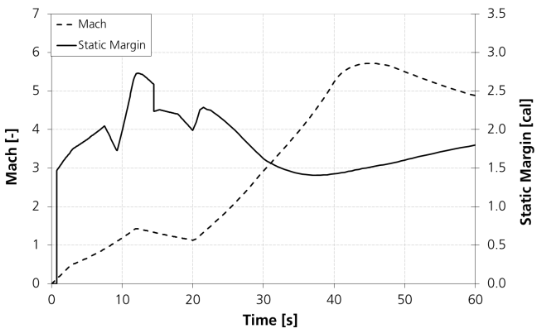

Fig. 3: Evolution of Mach number and static margin

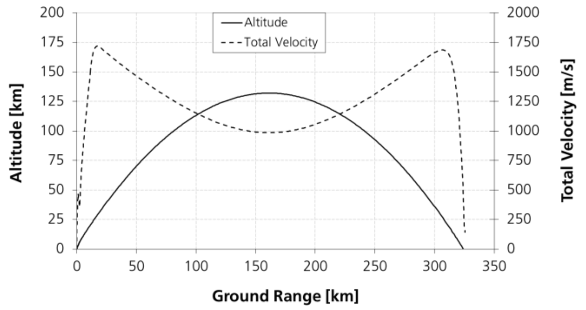

Fig. 4: ReFEx launch vehicle ballistic trajectory

3.2 Re-Entry Trajectory

ReFEx shall perform a re-entry similar to that of full-scale winged reusable stages. Since little actual flight data of such stages is available, assumptions regarding a representative trajectory of such stages have to be made. Therefore, based on former research on the LFBB [1] and sub-scaled LFBB launchers (C60), the Spaceliner [10], and the winged RLV concept EVEREST (Evolved European Reusable Space Transport) from Airbus [11], a RLV re-entry corridor (as shown in Fig. **5**) was defined which serves as reference for winged RLV trajectories. The mission goal of ReFEx is to achieve a re-entry trajectory in or close to this RLV corridor.

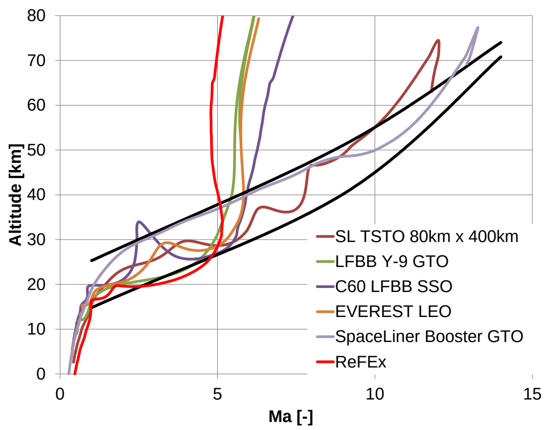

Fig. 5: Re-entry trajectories and related RLV (Reusable Launch Vehicle) corridor for different winged RLV stages including the SpaceLiner (SL), the Liquid Fly Back Booster (full-scaled final version LFBB Y-9, sub-scaled micro methane LFBB C60) and the Airbus EVEREST concept (Evolved European Reusable Space Transport)

As the flight experiment shall perform a controlled re-entry, the vehicle has to be longitudinally trimmable at every flight point of the trajectory by using the canards and RCS system as trimming CFD calculations for the preliminary vehicle's geometry with the DLR in-house tool TAU were conducted for different Mach numbers and deflection angles of the canards to determine the range of trimmable angles of attack (AoA) of the vehicle. Since the flight dynamics and trimmability are highly dependent on the position of the center of gravity (CoG), calculations for three different CoG positions (61%, 62%, and 63% with respect to the nose) were performed in this study to determine the optimal position of the CoG. The corresponding re-entry trajectories were calculated using the DLR tool tosca (Trajectory Optimization and Simulation of Conventional and Advanced Space Transportation Systems).

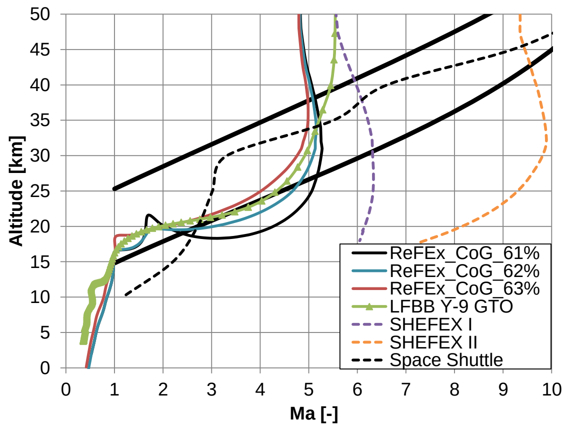

Fig. 6: RLV corridor and re-entry trajectories for ReFEx (61%, 62%, and 63% CoG position), LFBB, SHEFEX I and II (Sharp Edge Flight Experiment) and the Space Shuttle

The re-entry trajectories for the ReFEx flight demonstrator for different positions of its CoG are shown in Fig. 6. Furthermore, the trajectories of SHEFEX I and II (being ballistic re-entry experiments), the LFBB and the Space Shuttle were added to illustrate the difference between the trajectories of winged and ballistic re-entry bodies. Fig. 6 clearly shows the influence of the position of the CoG on the re-entry path of the flight experiment. A CoG positioned closer to the rear of the body allows a higher trimmable AoA during re-entry, which leads to significant aerodynamic forces in higher altitudes and therefore would be favorable to achieve a flight in the RLV corridor. However, a rear CoG reduces the range of trimmable low AoAs as shown in Fig. **7**. Therefore, the main challenge is to find a vehicle configuration that fulfils the requirement of flying a winged RLV trajectory while being aerodynamically stable and trimmable in every point of the flight. In the current configuration, only a CoG position of 63% allows for flight in the RLV corridor throughout the whole mission, while the other trajectories violate the lower boundary of the corridor. Nevertheless, the RLV corridor was defined using full-scale winged stages as reference, whereas ReFEx is a subscale flight demonstrator with a higher ballistic coefficient than its full-scaled counterparts. Taking this into account, a violation of the corridor's boundaries might be tolerable if the flight experiment still performs a controlled aerodynamic re-entry manoeuver.

The AoA and banking angle profiles corresponding to the respective re-entry trajectories are provided in Fig. **7**. The dotted lines represent the lower and upper trimmable AoAs from Mach 2 to Mach 6. It is important to note that the angle of attack is reduced to the minimum possible throughout the deceleration process in which it just takes 30 seconds to slow down the body from Mach 5 to below Mach 2. Without this reduction of AoA, the flight experiment would experience "skipping" behavior, meaning that it would gain altitude and violate the upper boundaries of the RLV corridor after the initial phase of the re-entry (compare C60 trajectory in Fig. 5). As a further measure, a banking manoeuver is performed that turns the lift vector sideways and thus additionally prevents skipping. This banking manoeuver is also necessary to fulfil one of the mission goals of ReFEx which is to perform a significant lateral change of the flight path.

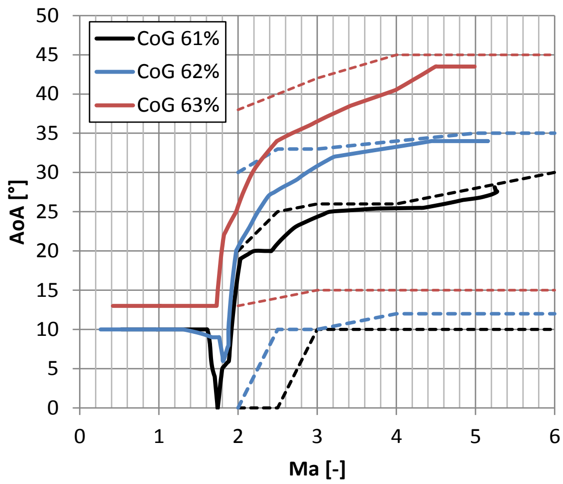

Fig. 7: Angle of Attack for different CoG positions

The AoA at re-entry greatly influences the loads experienced by the vehicle (see Fig. 8). Higher AoA at re-entry leads to less lateral forces experienced by the flight experiment, meaning that rear CoG positions are favorable for reducing loads. Hence, a rear-lying CoG seems preferable for achieving the mission goals. However, there are limitations to the range in which the CoG may be realized, since the subsystems within the vehicle have limitations regarding possible accommodation. It is important to notice that the presented results were made for a preliminary geometry and the optimal position of the CoG might change throughout the design process. Nevertheless, the CoG's position is of high importance for the feasibility of the concept and greatly influences the flown trajectory, stability, and controllability of the flight experiment.

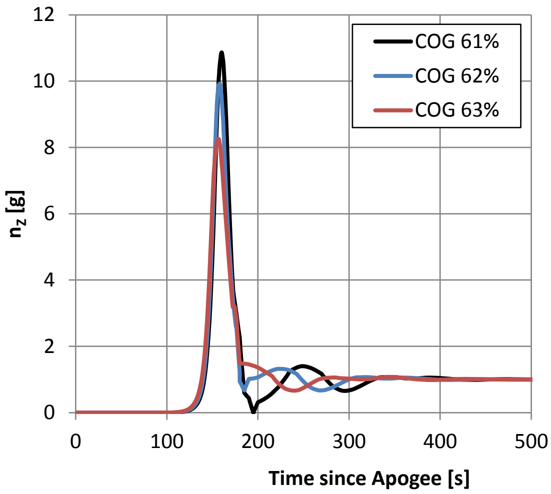

Fig. 8: Lateral load factor nZ for different CoG positions

4. RLV Technologies

4.1 Guidance

The guidance system for ReFEx will determine the trajectory and control that will satisfy the mission objectives. This operation will be performed by the on-board computer by using a database of optimal trajectories computed offline. These trajectories will be properly fused online by means of the Adaptive Multivariate Pseudospectral Interpolation (AMPI) technique [12].

The objective will be the minimization of the final dispersion, while satisfying all the other constraints acting on the system. Fig. 9 (left) shows schematically the AMPI technique concept. It is possible to divide the scheme in an offline part, represented by the discretization of the parameter space and the trajectory database computation, and an online part, where the on-board trajectory is computed. The inflight conditions will be used to detect the corresponding subspace of trajectories (see Fig. 9 right). Then, a multivariate interpolation process is performed over a relatively small number of nodes (referred as "low-density" solution).

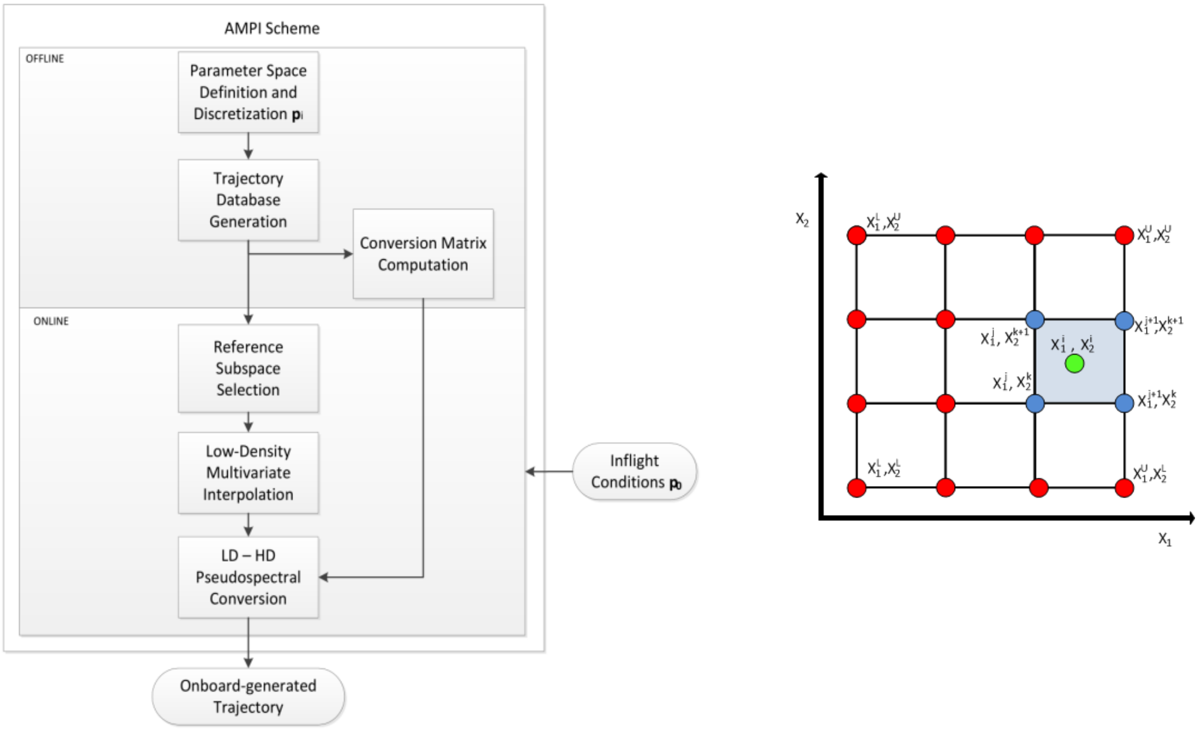

Fig. 9: Guidance for ReFEx based on AMPI scheme (left) AMPI reference subspace selection (right)

The trajectory is transformed into a "high-density" solution, i.e., with an appropriate number of nodes, by means of a pseudospectral conversion matrix, previously computed offline, and stored on-board. The result is a sub-optimal guidance solution, which can be computed on-board, and is able to deal with off-nominal conditions. Moreover, the LD-HD conversion (LD: low-density; HD: high-density) allows to have a lossless reduction of the database size up to 96%. More details about specific aspects of the AMPI technique can be found in [12–14].

4.2. Navigation

In order to control the re-entry flight, the continuous provision of a navigation solution, i.e., the estimation of position, velocity, attitude, and angular velocity of the ReFEx vehicle, to the guidance and control system is essential. For this purpose, the Department of Guidance, Navigation and Control Systems of the DLR Institute of Space Systems is developing a novel, autonomous hybrid navigation system (HNS), which is based on the results and experiences [15–20] with the navigation system experiment aboard the SHEFEX II vehicle and the preliminary design [21, 22] of the navigation system for the SHEFEX III study. It is considered as a verification of the capabilities of a highly reliable, compact, tightly coupled, integrated hybrid navigation system. The term *hybrid*, in this context, refers to the combination of high-frequency measurements from inertial sensors with measurements of a set of non-inertial sensors by methods of data fusion. This method allows for a long-term precise navigation solution.

The entire HNS architecture is designed as a highly reliable and fault-tolerant system, which comprises no single point of failure within its system boundaries. In terms of sensors, it is planned to be equipped with an in-house built inertial measurement unit (IMU), four Sun sensors, and two GPS receivers. The IMU consists of four accelerometers and four gyroscopes (both commercial off-the-shelf components) in a tetraaxial configuration. The HNS also comprises a highly reliable, fault-tolerant on-board computing and data handling architecture with the necessary infrastructure components (e.g., a fully redundant power distribution unit) incorporating a preliminary concept for failure detection, isolation, and recovery [22]. Its key characteristic is an augmented, double modular hot-redundancy scheme of two on-board computer nodes. Fig. 10 provides an overview about the functional groups and components of the HNS and their location within and on the ReFEx vehicle. The main component is the HNS box, which is a compact, self-contained compartment accommodating the inertial sensors, on-board computing and data handling system, power distribution unit, and auxiliary electronics.

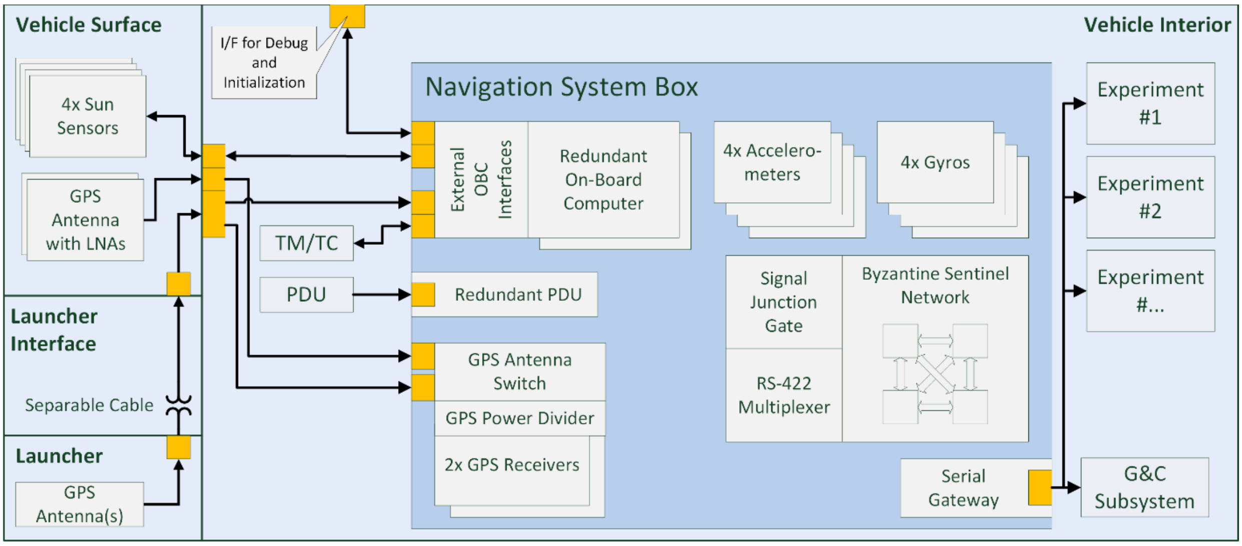

Fig. 10: Overview of functional groups and components of the Hybrid Navigation System (HNS) and their locations within and on the ReFEx vehicle.

The Sun sensors and GPS antennas are located on the vehicle surface and are connected to the HNS box, while the GPS front-end electronics is also located inside the HNS box. The HNS has data interfaces to the guidance and control subsystem, to the telemetry/telecommand subsystem, and to some instruments. In addition to the navigation solution, it also provides the time reference for synchronization of all subsystems of the ReFEx vehicle.

5.3 Control

As main function, the flight control system ensures, by utilizing the available control inputs, that the actual track of the vehicle matches as close as possible the commanded flight path. A schematic overview about the flight control loop is shown in Fig. 11. The flight path is calculated by the guidance algorithms. This serves as input for the two canard actuators and a Reaction Control System (RCS). Both, the guidance algorithms and the flight control algorithms are run on the so called Guidance & Control (G&C) computer. The G&C computer sends position commands to the Actuator Control Electronics (ACE) of the canard actuators. Each ACE runs all necessary control and monitoring algorithms for closed-loop control of the canard's position. The interface to the RCS is still under negotiation, but it is assumed that low-level Pulse Width Modulated (PWM) signals will be sent to the power stages of the RCS. Hence, in contrast to the actuator control electronics, the RCS does not contain any further data processing devices.

During the re-entry flight, handover is necessary between the RCS and the canards. At high altitudes above 70 km, where the density of the atmosphere is low, normally no relevant effectiveness of the aerodynamic control surfaces is available. During this phase of the flight, only the RCS can be used to control the attitude of the vehicle. At lower altitudes of less than 50 km, the effectiveness of the aerodynamic control surfaces increases drastically. Due to high aerodynamic forces, the effectiveness of the RCS will be negligible low. Hence, only the canards will be utilized as control input. For re-entry vehicles it is quite common to use RCS and aerodynamic control surfaces at the same time for certain altitudes [23]. For ReFEx it is still under investigation, whether such a blending between canard control and RCS is necessary at a certain range of altitudes or not. On the one hand, this would increase the complexity of the flight control system as well as the test and integration effort. On the other hand, utilizing aerodynamic and RCS as control inputs during the same time could relax the requirements for the design of the canard actuators. To provide high effectiveness at high altitudes, relatively large canards must be chosen. At low altitudes, where dynamic pressure is high, such canards would have enormous effectiveness and hence the positioning accuracy of the actuators must be extremely high and common nonlinearities, such as backlash and hysteresis, must be extremely low.

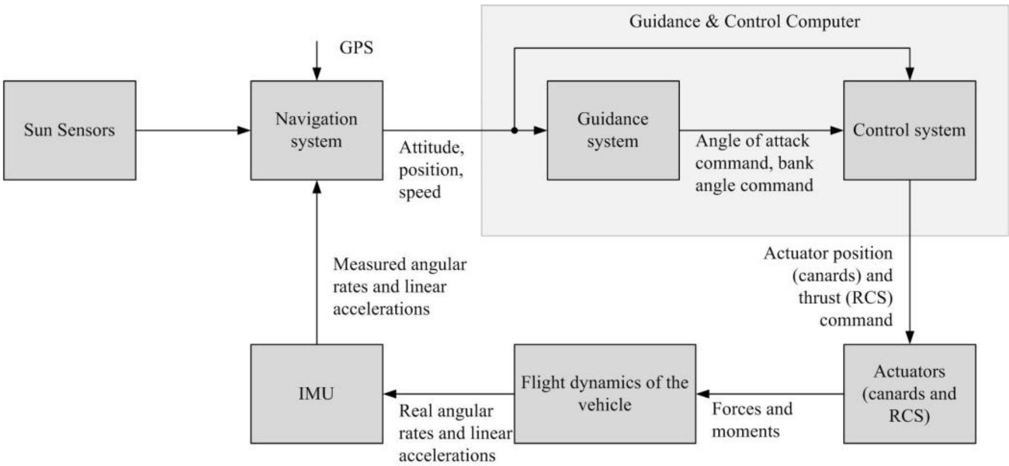

Fig. 11: Simplified signal flow diagram of the GNC system

The goal is to design a statically and dynamically stable ReFEx vehicle. Since the vehicle will fly at Mach numbers of 5 down to subsonic speed and it has no means for adapting its center of gravity, this is a challenging task due to the changing neutral point from hypersonic to subsonic flight. Since the aerodynamic properties have not been entirely characterized at the moment, it is not clear if natural stability can be ensured during the whole flight. Especially during high angle of attack flight, extraordinary conditions for dynamic stability apply. Depending on the tensor of inertia of the vehicle, there might appear an unstable Dutch roll mode or a non-phase-minimal roll transfer function [24]. During pre-design, the Weismann criteria and the Lateral Control Departure Criterion might be utilized to predict flight dynamical problems at high angle of attack [24]. If it is not possible to design an entirely stable vehicle, stability can also be realized by the flight controller. Since the development and test effort for a controller for an unstable vehicle and the therefore necessary quality and quantity of the aerodynamic database are significantly higher, this solution is not desired. Regardless if the vehicle is stable or not, it must be investigated if two canards only are sufficient for the control task. If there is significant cross coupling between the yaw and the roll axis, an additional rudder might be necessary as well. However, integration of a rudder, which provides reasonable effectiveness also during high angle of attack flight, is a complicated challenge itself.

The actuators for the canards will be realized as electromechanical actuators. The advantage of such actuators is the simplicity of installation. No fluids have to be handled, as it would be the case for hydraulic actuators. At the moment, rotary actuators are considered, as already been used for the hypersonic flight vehicle SHEFEX II [25]. Compared to SHEFEX II, the requirements of ReFEx are different. Since ReFEx will decelerate from hypersonic to subsonic speed, also the canards will be exposed to a travelling neutral point. Hence, it is not possible to match the hinge line of the canard and the aerodynamic neutral point. For this reason, significant higher hinge moments are expected compared to those within the SHEFEX II project. For high hinge moments, linear electromechanical actuators are superior compared to rotary actuators. Further analysis is required to choose a suitable actuator type for this application. However, if a linear actuator will be selected, extended development and test effort might be necessary, since there is no linear flight control actuator with flight heritage existing within the DLR.

4.4 Instrumentation and data acquisition

The ReFEx vehicle will be instrumented with a large number of sensors to measure aerodynamic and aerothermal parameters during re-entry flight. The instrumentation will include thermocouples and coaxial-thermocouples for temperature measurements, absolute and differential pressure transducers for static pressure measurements, heat flux sensors to determine the heat load on the vehicle and accelerometers. The coaxial-thermocouples will be used for fast surface temperature measurements and also for total heat flux evaluation assuming one-dimensional heat conduction and a semi-infinite wall. In addition to the temperature measurement via thermocouples, a fiber optic sensing (FOS) system will be used to determine the temperatures on vehicle surface and fin leading edges. The FOS system can also be used for strain measurements. Combining temperature and strain measurements it is also possible to perform a structural condition assessment (structural health monitoring).

Furthermore a cooling experiment is planned in the forward section of the vehicle using an internal cavity for passive cooling of a small surface area. Several thermocouples will be installed in and around the cooling area for evaluation of the cooling efficiency. To monitor the canard heating a small infrared camera will be installed above one of the canards to get a two-dimensional temperature distribution of the canard surface.

In the nose region of the vehicle, several pressure sensors will be integrated to form a Flush Air Data Sensing (FADS) system which can be used to determine the freestream parameters like angle of attack, angle of sideslip, Mach number and static pressure. The necessary calibration parameters for the FADS system are determined before the actual flight using wind tunnel tests and CFD.

The base region of the vehicle will also be equipped with several pressure sensors using a higher sampling frequency to measure transient pressure fluctuations. To get video data of ascent and re-entry, two small video cameras will be mounted to the vehicle with a field of view that includes interesting areas of the vehicle like canards or fins.

The following table shows an overview of the planned instrumentation. Because up to this point the interior vehicle structure, including possible sensor locations, is not completely defined, the listed sensor numbers are preliminary.

Table 3: Preliminary instrumentation for ReFEx

Sensor	Quantity	Remark
Thermocouple	80	Surface and internal structure
Coaxial-thermocouples	14	
Pressure sensors	30	Absolute and differential
Total heat flux sensor	12	
Accelerometers	6	
Fiber optic sensing (FOS)	4 fiber lines	Several temperature measurements locations on each fiber
IR-camera	1	Looking at one canard
Video cameras	2	

For sensor signal conditioning, amplification, and analogue to digital conversion, different data acquisition systems will be used. The first one was used for several sounding rocket experiments in the past like SHEFEX II [26] and provides a variable sampling frequency between 20-50 Hz. The second one has a higher sampling frequency between 1-10 kHz and was developed at the Supersonic and Hypersonic Technology department of DLR in the frame of the successful ROTEX-T flight experiment [27]. A picture of the box including one of its circuit boards is shown in Fig. 12.

Fig. 12: High frequency data acquisition electronics box and PCB

In addition to the data acquisition systems described above, the fiber optic sensing system also includes a separate electronic box.

Most of the digitized data will be sent to the ground station during flight via telemetry. Due to the limited telemetry bandwidth, some data is stored onboard in separate memory units which are retrieved after landing. These memory units are designed to survive a crash-landing in case of parachute malfunction.

5. Conclusion

This paper provides a short system overview and addresses challenges regarding the realization of the DLR Reusability Flight Experiment (ReFEx).

ReFEx is a sub-scaled flight experiment to demonstrate *key technologies* needed for winged *RLV first stages*. These include, among others, autonomous GNC algorithms, sophisticated aerodynamic layout, specialized control surfaces and sensors for health monitoring. As such this flight experiment shall provide real flight data. The data shall help to validate the design methodologies and algorithms used for winged reusable first stages. The ReFEx flight experiment shall be launched on VSB-30 sounding rocket in the second half of 2021.

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