ADVANCEMENTS WITHIN THE SPACE TRANSPORTATION RESEARCH FIELD AT TU DRESDEN

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Abstract

This contribution presents an overview of the research and development activities within the research group for Space Transportation, which is part of the Institute of Aerospace Engineering at Technische Universität Dresden. The research focuses mainly on chemical propulsion systems, including the cutting edge academic investigations on additively manufactured aerospike engines and their thrust-vector control for various applications, such as retro-propulsion and in-space thrusters. Two of the major challenges regarding aerospike engines are the higher thermal load and the increased design complexity when compared to a bell nozzle engine, both of which might be resolved using additive manufacturing (AM). Approaches using AM with a nickel superalloy are investigated at Technische Universität Dresden. One is conducted in the framework of the ASPIRER project, in which a kerosene-hydrogen peroxide 6 kN aerospike engine is developed. Another project, called CFDμSAT, is dedicated to the development of a 500 N ethanol-liquid oxygen engine. Furthermore, aerodynamic thrust vector control on linear and annular aerospike nozzles is investigated. Within the frame of the ACTiVE research project, numerical analyses, shallow water as well as cold-gas experiments were conducted and a cold-gas test bench has been set up to study this kind of fluidic thrust vector control in detail. Within the joint research project MACARONIS, we transfer the advantageous characteristics of additively manufactured ceramic components into a cold-gas aerospike thruster to be developed, manufactured and tested with the aim of an in-orbit demonstration. In the frame of the Innovative Training Network (ITN) ASCenSIon, the utilisation of aerospikes and other advanced nozzle concepts for retro-propulsion applications is being investigated. Furthermore, the ignition of aerospikes with annular combustion chambers is being investigated. The resarch is not limited to aerospike engines. Further research is being executed on health monitioring systems for resubable rockets, the in-situ utilisiation of extraterrestrial ressources for the production of propellants and mission concepts for in-orbit servicing. Also an experimental rocket is being developed in the frame of the education project SR Dorado. This contribution strives to give a comprehensive overview of the aforementioned activities. The particular focus lies on the advancements of the state of research so far and their implications on further research activities.

Keywords

space transportation; space propulsion; chemical propulsion; aerospike; health monitoring; ISRU

NOMENCLATURE

Acronym

6-DOF	Six-Degrees Of Freedom
AFM	Abrasive Flow Machining
AG	Advisory Generator
ANC	Advanced Nozzle Concepts
BMBF	Federal Ministry of Education and Research
CFRP	Carbon Fibre Reinforced Plastic
DA	Data Acquisition
DLR	German Aerospace Center
DM	Data Manipulation
EDM	Electrical Discharge Machining
ESR	Early Stage Researcher
GNC	Guidance, Navigation and Control
HA	Health Assessment
HM	Health Monitoring
IKTS	Fraunhofer Institute of Ceramic Technology and Systems
ISRU	In-Situ Resource Utilisation
ITN	Innovative Training Network
IWS	Fraunhofer Institute for Material and Beam Technology
LPBF	Laser Powder-Bed Fusion
PID	Piping and Instrumentation Diagram
PA	Prognostic Assessment
RLV	Reusable Launch Vehicle
RUL	Remaining Useful Life
SD	State Detection
SITVC	Secondary Injection Thrust Vector Control
STERN	STudentische ExperimentalRaketeN
TBC	Thermal Barrier Coating
TRL	Technology Readiness Level
VPP	Vat Photo Polymerisation

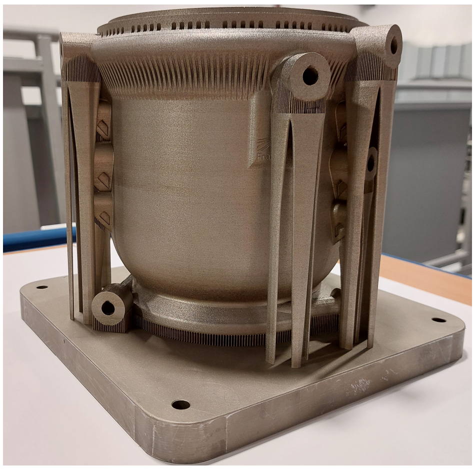

FIG 1. Shroud in the as-built state [1]

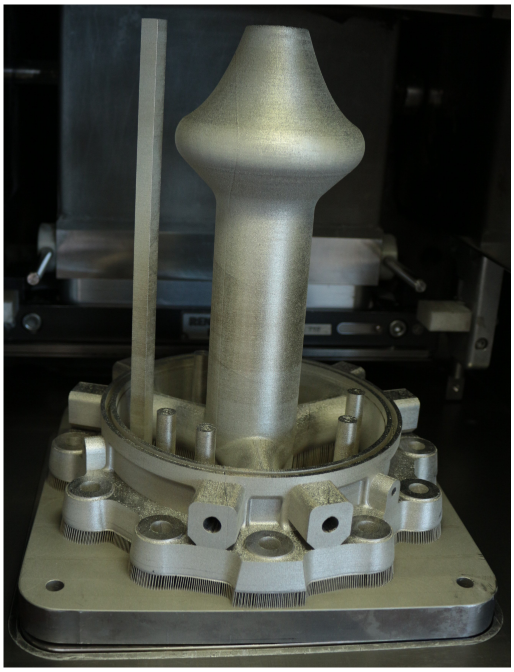

FIG 2. Spike in the as-built state [1]

1. INTRODUCTION

The research group for Space Transportation at the Institute of Aerospace Engineering of Technische Universität Dresden (TU Dresden) was founded in 2019 with the aim to conduct challenging, practical and integrative research to develop technologies that ultimately enable new missions. This contribution gives an overview of the activities that have led to the foundation of the research group as well as an status update on the current research and education projects. Further research is being executed on health monitioring systems for reusable rockets and the in-situ utilisiation of extra-terrestrial ressources for the production of propellants.

2. ASPIRER

Within the frame of the ESA-funded ASPIRER project (short for AeroSPIke Rocket Engine Realisation), an additively manufactured aerospike breadboard engine, using kerosene and hydrogen peroxide as propellants, is developed and tested. The engine is designed for 6 kN thrust at 2 MPa chamber pressure and is manufactured from nickel-based superalloy INCONEL® 718 powder using the laser powder bed fusion process (LPBF). A staged-bipropellant concept is applied, where hydrogen peroxide is decomposed by a catalyst and combustion is initiated by kerosene autoignition. The configuration of the decomposition chamber is designed as a replaceable subassembly and consists of a showerhead injector, main housing and distributor plate, to be able to test multiple catalyst compositions during the hot-fire tests. The kerosene injector uses the transverse jet penetration concept by injecting propellant orthogonal to the hydrogen peroxide oxidizer flow. The two major engine components spike and shroud are additively manufactured and include the cooling channels used for a water dump cooling system.
In the following, the manufacturing results of the two main parts of the engine assembly, shroud and spike, shall be presented in the as-built state. The manufacturing aspects of the project, such as the material study and the breadboard manufacturing, are realized at the Fraunhofer Institute for Material and Beam Technology (IWS). Powder was already removed from the shroud, which is shown in Figure 1, and the spike, shown in Figure 2. Both spike and shroud are visualized on the build plate in the as-built direction. Successful powder removal was confirmed by X-ray analysis.

Due to issues with local overheating during manufacturing, the water in- and outlets as well as the kerosene inlets of the shroud have support structures to enhance heat transfer to the build platform. The shroud in its as-built state was post-processed to remove the support structures and achieve the final geometry. Injector orifices for kerosene were introduced by electrical discharge machining (EDM). Threads of fluid connections were manufactured by milling. The spike was equally post-processed using milling, following the additive manufacturing process. Afterwards, the spike was coated with a thermal barrier coating (TBC) to cope with the demanding thermal conditions typical for aerospike nozzles. A test assembly of spike and shroud in their post-processed state is shown in Figure 3. In its final state, both components are joined by laser beam welding.
After successfully manufacturing the engine, a test campaign is going to be conducted at Łukasiewicz Research Network – Institute of Aviation, where pre-existing infrastructure and expertise with regard to the investigated thrust class and propellant combination can be utilised. The test readiness review was completed successfully and the test campaign is planned for fall 2022.

3. CFDμSAT

Within the AGENT-3D initiative of the German Federal Ministry of Education and Research (BMBF), CFDμSAT investigates the applicability of additive manufacturing processes for engine components. Such processes offer the possibility of manufacturing complex components with internal structures, such as cooling channels or propellant lines, and may also reduce the number of necessary parts in rocket engines.
These advantages, however, are accompanied by increased surface roughness, which must be compensated through suitable post-processing methods and appropriate component design. For this purpose, various channel test specimens were investigated within CFDmikroSAT, the dimensions of which are based on a water-cooled aerospike engine that has already been investigated in hot-fire tests by

FIG 3. Shroud and Spike assembly test in post-processed condition

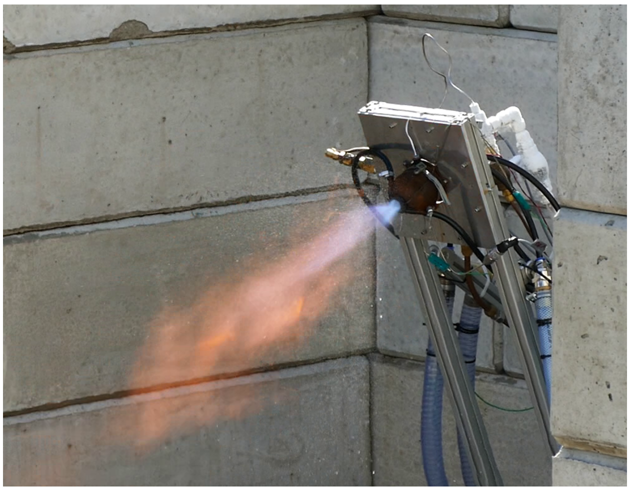

FIG 4. First hot-firing of an aerospike engine in Europe

the Institute for Aerospace Engineering in 2019 (see figure 4). A total of 23 test specimens with different cross sections and channel shapes were fabricated in cooperation with the IWS using LPBF. Flow studies were performed with these specimens, both in their as-built condition and after post-processing by the means of abrasive flow machining (AFM). This post-processing method was chosen since many conventional methods, such as grinding or milling, are not suitable for small, internal contours.
The results showed that, in general, the surface roughness within the channels can be significantly lowered with the help of AFM, but there is also distortion of the cross-sectional geometries due to inhomogeneous widening of the channels. In addition, it was observed that cross-sections with small diameters of about 2 mm can cause problems due to the occurrence of cavitation during AFM. For these reasons, at the present point of investigation, the method is considered to have only a low suitability particularly for small channel structures and further investigations are needed regarding suitable compositions of the abrasive fluids used.

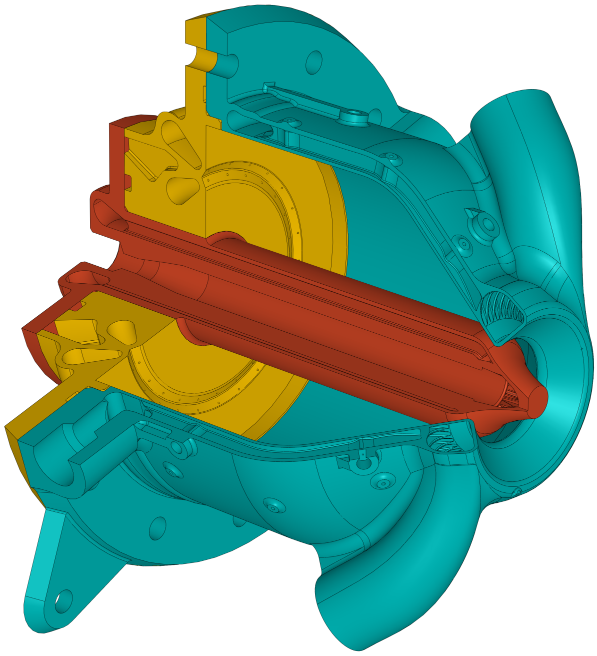

FIG 5. Partial cut through the final engine CAD design with visible cooling channels and propellant feeding lines; shroud $\triangleq$ cyan, injector $\triangleq$ yellow, spike $\triangleq$ red

In addition to the test specimen studies, a new iteration of a 500 N aerospike engine was also manufactured within CFDμSAT, representing a revised version of the aforementioned engine from 2019. The engine (see figure 5) consists of only three individual parts, namely the injector, the shroud and the spike, which are assembled using a flange connection. Compared to the predecessor engine, the measuring concept as well as the injector and cooling channel design have been revised. All components have been successfully manufactured by the IWS using LPBF and are currently being mechanically post-processed. A hot fire test campaign is scheduled for early 2023.

4. INVESTIGATIONS ON SITVC AND AEROSPIKE NOZZLES

At TU Dresden, we investigate secondary injection thrust vector control (SITVC) on linear and annular aerospike nozzles using numerical simulations and experiments initiated with the ACTiVE research project. Numerical simulations [2, 3], shallow water as well as cold-gas experiments [4–6] were conducted. A cold-gas test bench has been set up at TU Dresden [7] to investigate SITVC with focus on thrust and side-force generation.
In coperation with the German Aerospace Center (DLR), we conducted a test campaign on the test bench P6.2 in Lampoldshausen [6]. The campaign objective was to measure the surface pressure distribution on linear aerospike nozzles with SITVC. For that purpose, a dedicated test engine (see figure 6) with four different, exchangeable spikes (central supersonic part of the nozzle) were designed, manufactured and tested. These spikes were designed such that the influence of two different injection positions and two different truncations could be measured and analyzed. It could be shown, that the surface pressure measurements are in good agreement with the predictions by numerical analyses.
The basic principle of thrust vector control on aerospike nozzles by aerodynamically influencing the main nozzle flow

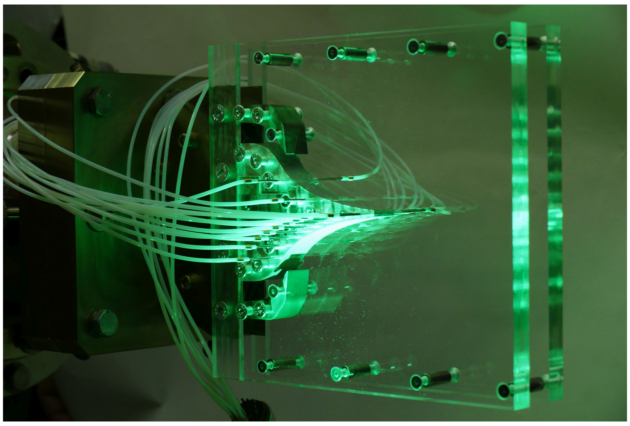

FIG 6. Linear Aerospike Nozzle for Surface Pressure Measurements at DLR P6.2 in Lampoldshausen [7]

lies in the targeted placement of an obstacle in the flow. Apart from conceivable conventional methods such as the insertion of flaps into the flow, this can also be achieved by injecting a secondary fluid jet. The resulting flow characteristics are illustrated schematically in figure 7.

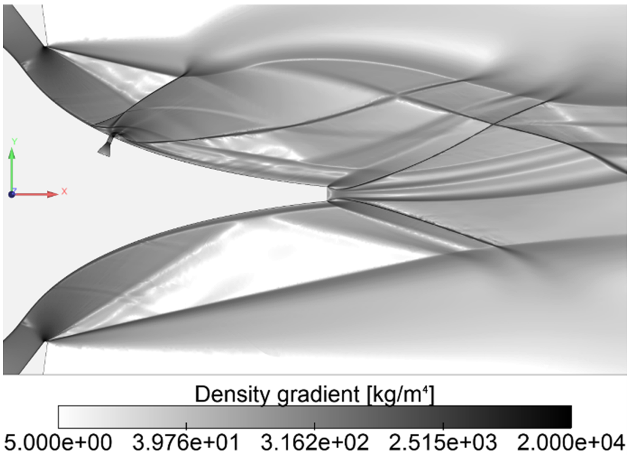

FIG 7. Distribution of density gradient exemplarily for a linear plug nozzle utilising SITVC [8]

It can be seen that the flow expanding into the crossflow forms a Mach disk with corresponding height h to the plate. A bow shock forms immediately up-stream of the injection site. The bow shock interacts with the boundary layer of the crossflow and leads to the formation of a separation shock originating from the turbulent boundary layer of the overflowed plate upstream of the bow shock. Further downstream, the separation shock eventually meets the bow shock almost tangentially. The distance between the origin of the separation shock and the injection is called the separation length l_{sep}. Together with the height of the Mach disk, this provides a metric for characterising flows of this type. [8] The generated side force F_y results from two separate effects. Firstly, the secondary injection leads to an altered pressure distribution on the corresponding side of the aerospike. The pressure distribution on the side without secondary injection remains unchanged, thus creating a pressure difference between the two different sides of the spike. The second effect is due to the momentum generated from the ejected mass of the secondary injection.

A cold-gas test bench has been realised to pursue a different approach of experimentally analysing the behaviour of aerospike nozzles with SITVC. A six-degree of freedom (6-DOF) force balance has been set up for the direct measurement of the generated thrust and side-forces (see figure 8). With this balance, all kartesian forces and torques can be obtained. In order to achieve high expansion ratios at reasonable gas flows, this balance is mounted into a vacuum chamber, which allows ambient pressures down to $5\,\mathrm{kPa}$. The gas supply for this test bench provides two separate fluid lines for primary and injection flows with pressures up to $1.1\,\mathrm{MPa}$. Figure 9 shows the correponding piping and instrumentation diagram (PID). [7, 9]

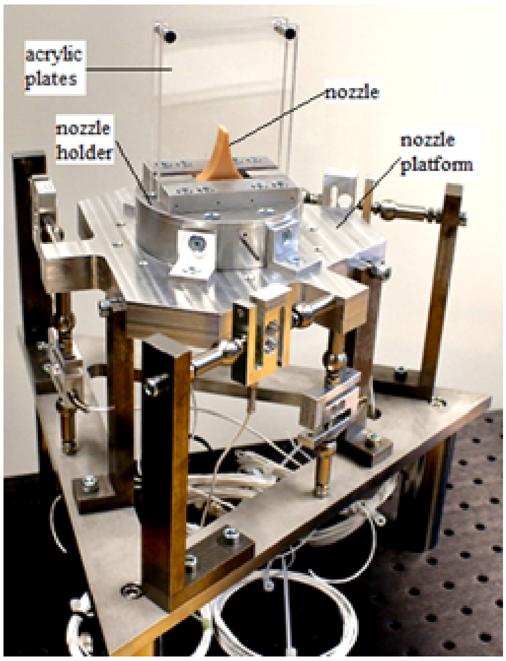

FIG 8. Six-Degree of Freedom Force Balance [9]

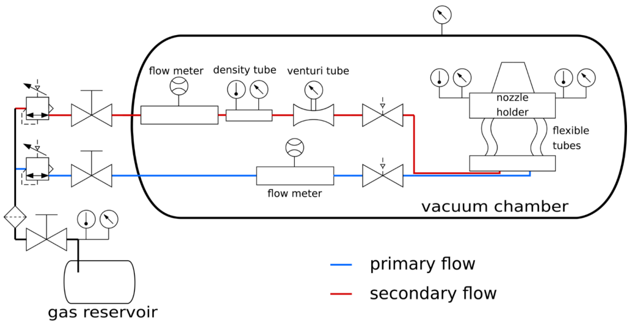

FIG 9. PID of the Cold-Gas Testbench at TUD

Linear and annular aerospike nozzles with SITVC have been experimentally measured in order to quantify the influence of various geometric and gas property parameters on the side-force generation. Examined parameters were, for example, the axial position and the angle of the injecting flow w.r.t. the main flow, the critical injection area or the total pressure ratio between the main flow and the injectant. The results showed the different effectiveness and mode of action of each parameter, which allow to derive design guidelines for SITVC on aerospike nozzles in the future.

For future experimental analyses, the 6-DOF force measurement test bench will be used to investigate other thrust vectoring methods on aerospike nozzles besides SITVC, like differential throttling. Furthermore, the secondary fluid line enables experimental base bleed surveys. Recently, the test bench is being enhanced for sub-sonic retroflow investigation on advanced nozzle concepts. These investigations conducted within the Innovative Training Network (ITN) ASCenSIon are described in section 7.

5. MACARONIS

One of the latest aerospike engine developments is recently concluded with the MACARONIS project (MAnufactured Ceramic AeROspike Nozzle In Space). In cooperation with the Fraunhofer Institute of Ceramic Technology and Systems (IKTS), we designed, built and ground tested a cold-gas thruster demonstrator to prepare future space applications. The distinguishing feature of this project is a ceramic aerospike nozzle that is produced by our project partner with the VPP (Vat Photo Polymerisation) process. The realized cold-gas thruster demonstrator (see Fig. 10) was presented to the public at the SpaceTech Expo 2021 in Bremen. [10]

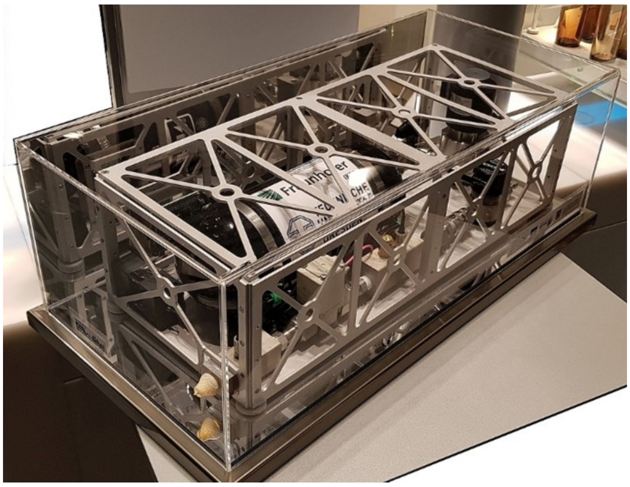

FIG 10. Demonstrator for a Cold-Gas Aerospike Thruster System

In addition to the structural design and the process design suitable for manufacturing, extensive numerical investigations were carried out as part of the project with regard to the final component properties caused by additive manufacturing. In particular, the focus was on the achievable surface roughness and the centric alignment of the two nozzle components, nozzle and shroud [11].
Thus it could be shown, that a non-concentric alignment of the nozzle components shows distinct effects on the flow pattern as illustrated in figure 11. The image represents a sectional view with respect to the xy-plane and shows that already a misalignment of $50\mu m$ (cf. Fig. 11 b) in the y-direction leads to asymmetric flow pattern. Thus, a non-concentric alignment of the nozzle components to each other does have an influence on the performance and general characteristic of the propulsion system. The associated thrust losses are of secondary importance here. Displacement of the spike relative to the shroud geometry induces lateral forces that can reach several percent of the nominal nozzle thrust. The generated lateral forces are potentially powerful enough to allow control of the thrust vector with steered spike deflection. Nevertheless, CerAM using VPP could be demonstrated to be a suitable manufacturing method to fabricate ceramic miniaturized coldgas thrusters also with respect to the maximum expected alignment deviations

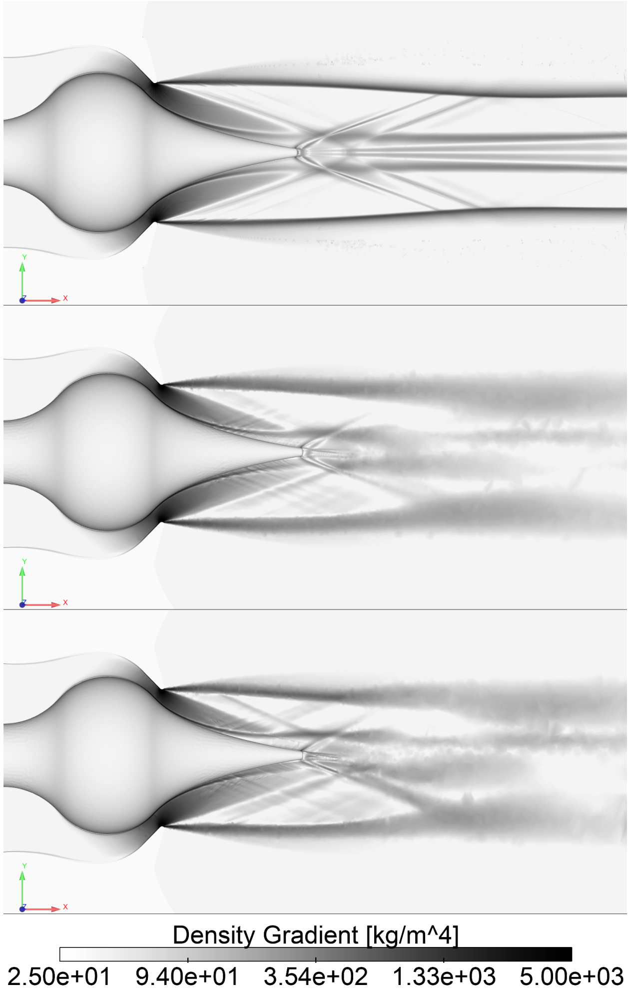

FIG 11. Distribution of density gradient for displacement of spike in positive y-direction of a) $\Delta y = 0\,\mu m$, b) $\Delta y = 50\,\mu m$ and c) $\Delta y = 100\,\mu m$ [11]

Moreover, it could be shown that, under the given boundary conditions, surface roughness up to a value of $Ra = 100\mu m$ causes only minor changes in the flow pattern and also in the performance of the nozzle. Furthermore, the components fabricated by means of CerAM VPP achieve maximum roughness values of approx. $2\mu m$. Accordingly, the given surface roughness has no significant influence on the performance of the cold-gas thruster [11].

6. INNOVATIVE TRAINING NETWORK ASCENSION

ASCenSIon acronym stands for "Advancing Space Access Capabilities - Reusability and Multiple Payload Injection", and it describes the project objective to contribute to the establishment of an economically and ecologically sustainable access to space for Europe. ASCenSIon aims to fulfil it by forming a new generation of researchers with both scientific and soft skills through a dedicated network-wide research and training programme which empowers and prepares them to become leaders in the space transportation sector in Europe. The Early Stage Researchers (ESRs) employed within the project are 15 in total and are enrolled in a PhD programme in different European partners. Within their research they focus on launcher systems that are (partially) reusable and able to inject multiple payloads into multiple orbits. The scope of the project is not to focus on one unique RLV design, but to identify and enhance technolo-

gies and solutions which are critical for the space access domain and prove their feasibility.
The ASCenSIon consortium is a synergetic group of 25 European partners. These entities include universities, small to mid-size enterprises, big companies and governmental research institutes. The Coordinator of ASCenSIon is Technische Universität Dresden, which is one of the German universities of excellence.
The ASCenSIon research programme focuses on the main research areas of launch vehicle design:

- Propulsion technologies and their reusability
- Guidance, Navigation and Control (GNC)
- Aerothermodynamics of re-entry and safe disposal.

Sustainability is an underpinning factor, and it is considered, for example, in the study of green, environment-friendly propellants or in the safe disposal of space objects, as well as taking into consideration the space situational awareness.
The training of ASCenSIon goes beyond the more traditional PhD programmes that normally focus on one discipline, one domain and one country. It develops on two levels: a local programme, carried on by the institutions that host the PhD students and include the usual offers, and a network-wide training programme which aims at expanding the training of the ESRs with a structured, multicultural and multisectoral approach and introduces them to the whole launcher development field. These network-wide trainings are offered quarterly in the form of experimentation weeks, summer schools, workshops and conferences.
Moreover, the young researchers are expected to gain not only technical, but also transferable skills (for example on scientific communication and entrepreneurship). To complement the training, they experience at least two periods of secondments during their employment, one at an academic and one at an industrial partner. They are trained by experts from industry and academia and gain not only theorical, but also practical knowledge. A structured approach is maintained to ensure that all the ESRs get equal benefits during their training, as well as multi-partner supervision and access to unique research environments.

7. ADVANCED NOZZLE CONCEPTS IN RETRO-PROPULSION

The investigation of advanced nozzle concepts (ANCs), such as aerospike or dual-bell [12], is pivotal in order to advance the technology readiness level (TRL) of critical technologies for future class of reusable launch vehicles (RLVs). A critical aspect is to tailor these novel technologies to current state of the art of recovery strategies [13], more specifically to vertical landing sustained by propulsion, i.e. retro-propulsion.
Within the aforementioned ASCenSIon project, the activities related to retro-propulsion investigations at TU Dresden include in-depth reviews of the available studies on both retro-propulsion applications and ANCs. Common points of interest between the two topics have been identified and the current findings determine inputs for numerical simulations and experimental campaigns [14], which aim to investigate if ANCs could constitute a desirable solution for the main propulsion system of the upcoming class of RLVs. In this regard, TU Dresden is currently developing a numerical and experimental database for ANCs with reverse-flow interactions for different configurations and counter-flow regimes. In order to populate such a database, a dedicated test-bench has been designed for cold-gas experiments on annular aerospike, dual-bell,

setup.png

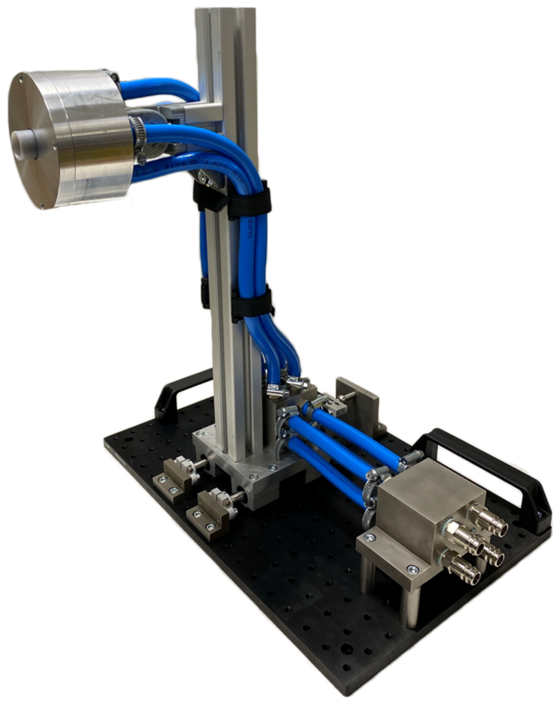

FIG 12. Picture of the setup for Subsonic Retro-propulsion experiments in the Vacuum Wind Tunnel facility.

expansion-deflection and conventional nozzles in various ambient conditions (sea-level-standard, near-vacuum and various subsonic retro-flow scenarios) [15]. The setup (see FIG.**??**,13) has been already commissioned at the vacuum wind tunnel facility in TU Dresden and multiple tests for performance evaluation with static nozzle-flows have been succesfully conducted, together with preliminary tests in retro-flow configurations. To allow qualitative evaluation of the flow-field phenomena that arise due to the flow interactions, a Background-Oriented Schlieren (BOS) has been integrated in the Vacuum Wind Tunnel facility.
In support to the experimental activities, extensive numerical simulations predict aerodynamic performance and nozzle performance for both on-design and off-design conditions. They also include evaluations on the fluid dynamics of the free-stream in absence of nozzle-flow (atmospheric re-entry simulated by interaction with counter-flow) and the aerodynamic interference between nozzle-flow and external counter-flows (retro-flow configuration). Besides, the CFD models will be extended to additional cases of interest beyond the low-subsonic counter-flow regimes tailored by the experimental campaign, thus enriching the aerodynamic database on ANCs in different retro-flow scenarios.
As part of ASCenSIon, the activities include external collaborations on numerical investigations with Università degli Studi di Roma “Sapienza" and with the industrial partner Deimos Space in Madrid. The latter involves a case study that aims to evaluate the aerodynamic performance of an RLV of interest, integrating an annular aerospike nozzle designed for high altitudes. The final goal of such a study foresees to verify the adoptability of such a system through the integration to missionisation with an in-house dedicated tool, developed by Deimos Space.

chamber model.png

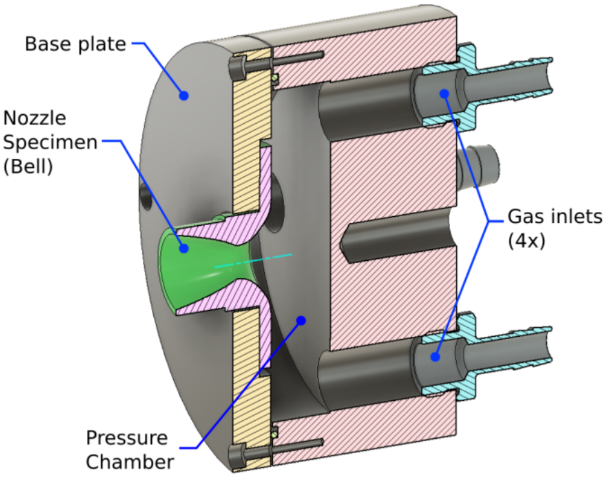

FIG 13. CAD models of the pressure chamber.

8. HEALTH MONITORING FOR SPACE VEHICLES

Health Monitoring (HM) is based on the idea that all systems are subject to flaws, occurring at a specific point in time. The system or a sub-part of it can be subject to performance degradation and faults identified by 'off-nominal states', leading even to the loss of system functionalities, partially or as a whole [16]. Thus, the main goal of the HM is to prevent failures verification and in particular the ones concerning safety-critical and mission-critical aspects. Through HM, the establishment of a system with low failure rates and easy maintenance is possible.
The following advantages can be derived from the application of HM components [17–20]:

- Increased safety and operational margins: enhanced comprehension of the working conditions can be used for forecasting the system safety parameters;
- Increased emergency states response time, success probability rate, maintenance scheduling optimization, system lifetime and lifetime predictivity: it is possible to predict when the maintenance is required and to define actions useful for mitigating the fault conditions;
- Optimization of resource management and costs reduction, reduction of human operators workload: the distribution of resources can be optimized, defining the operating status and the health conditions actively;
- Promotion of a more effective training of personnel and operators: system extracted data can be also used for improving training activities and qualification processes;
- Increased TRL: the extracted data can improve the knowledge on the system, permitting design and operative improvements.

Conversely, the main drawbacks related to the HM subsystem are:

- Increased design complexity: additional elements w.r.t data sensing, orchestration and processing have to be introduced;
- Increased system weight: an overhead in terms of mass and power consumption is introduced. Defining the operational trade-off between additional consumption and benefits is crucial;
- Increased design time and cost effort related to the single unit: more complex elements than usual are adopted for allowing data analysis and prediction;
- Increased data and resources management: a multitude of different physical domains has to be analyzed given the intrinsic multi-disciplinarity of real-world applications.

The logical pivots of the HM system are [21, 22]:

- Condition monitoring: collects, filters and stores data and information about the system;
- Failure diagnosis: uses the collected data for extracting information highlighting the system's characterizing conditions (distinguished in nominal and non-nominal states);
- Fault prediction: forecasts the more probable future states of the system and the remaining useful life (RUL);
- Failure mitigation/response: mitigates the effects of the failures for operating within the defined safe margins for a minimum defined amount of time or operation steps.

The selected architecture must be composed of units able to cover one or more of the defined points.
Considering the high complexity of RLVs, which requires many development tasks distributed among several contributors, system criteria associated to the HM implementation consist of [21, 23, 24]:

- Adaptable and modular architecture: the HM module should be compliant to different similar conditions and vehicle structures;
- Retro-adaptive approach to existing architecture: HM functionalities should be integrable also in already existing RLV structures;
- Platform independence: the hardware and software interfacing structure should allow the application of the software solutions independently to the particular underlining hardware. For this approach, a normalized and standardized signal conditioning and conversion methodology is recommended;
- Open knowledge philosophy: for establishing a sustainable progress in terms of HM development, the international space community should structure common guidelines to be followed and open data collections to be shared worldwide to the researchers;
- Scalability: the HM implementation should reconfigure and scale with the system requirements. The system requirements can change during the mission lifecycle;
- Multi-hypothesis handling approach: to effectively identify the working conditions, the system should cover the case of multiple failures originated at the same time.

The HM functionalities can be defined according to the ISO13374 [22, 24, 25] protocol, which is composed of:

- Data Acquisition (DA): senses the system behaviour and converts the associated signals into digital format. Data conditioning, cleaning and sensors maintenance processes (such as calibration, reconfiguration) are promoted;
- Data Manipulation (DM): data management is promoted in this section. Data normalization, scaling, reduction, features identification and sensing virtualization are done;
- State Detection (SD): the reasoner useful for detecting "off-nominal" conditions and evaluating the system profiles is present here. Failure detection is usually the first step of the failure diagnosis procedure. At this level, the system can be interfaced with the external world in case the it has to notify as soon as possible the user about possible detected failures;
- Health Assessment (HA): the second step of failure diagnosis is represented by the identification of the mechanisms causing the failures. At this level, the system health status and associated variations are also studied;
- Prognostic Assessment (PA): the other cardinal concept of HM is the failure prognosis. In this step, possible fu-

tures states of the system are statistically defined. In addition, the Remaining Useful Life (RUL) value can be evaluated in the system;
- Advisory Generator (AG): the last step of the HM is the failure response. At this level, both the actual system profiles and the prognosted ones are considered for defining the optimal response.

The first two functionalities are usually technology-specific, because they directly relate to the underlying hardware. The other blocks instead can be hardware independent thanks to a standardisation procedure operated through the first two steps [26]. With respect to the defined structure, the HM functionalities aim to create the shortest possible logical closed-loop able to mitigate the possible failure effects.

9. STUDENT EXPERIMENTAL ROCKETRY

The origins of the research group for Space Transportion, which was established in 2019, go back to 2012. This is where the beginnings of the "SMART Rockets" and thus the development of student sounding rockets at TU Dresden lie. This project was conducted within the framework of the programme STudentische ExperimentalRaketeN (STERN) of the DLR. A considerable amount of expertise was built up, not least through 160 firing tests (see figure 14), carried out as part of the project with the test infrastructure set up from scratch. While this was fundamental for numerous follow-up projects, it must be acknowledged that the actual technical project goal, the launch of a student sounding rocket, could not be achieved at that time.

Now, TU Dresden estabalished a new development project with the name "SR Dorado". As a follow-up project to SMART Rockets, the Institute of Aerospace Engineering in cooperation with the Student Spaceflight Working Group "STAR Dresden" are developing a new, larger and more powerful sounding rocket, starting from July 2022. Like its predecessor, the focus of this development project is placed on the practical training of students in the field of space launch systems. The aim is to promote both subject-specific training as a supplement to study content, as well as working in project structures and deepening transferable skills.

The rocket will have a dimension of about 4.5 m in length with a diameter of 20 cm and should reach a flight altitude of about 7.5 km. For this purpose, a propulsion system with a thrust of 3 kN is being developed, which will be operated with liquid oxygen and ethanol. Both propellants are supplied via a pressurized gaseous nitrogen. To withstand the mechanical stresses during the various phases of flight and to ensure an overall low mass, the rocket's structural components are made of carbon fibre reinforced plastic (CFRP). The rockets nose cone houses a recovery system as well as a measurement and telemetry system. While parachutes ensure safe landing and recovery of the rocket, the measurement system records flight data such as altitude, attitude and acceleration via various sensors to analyze the rocket's flight behavior. The telemetry system ensures the communication with the ground station and manages the transmission of mission-relevant information. In addition, the upper rocket section offers the possibility to accommodate an additional scientific payload, which will be defined in the course of the project through proposals from the students.

The rocket is planned to be launched in spring 2025 from the European Spaceresearch Range (ESRANGE) in Kiruna, Sweden. With its flight, we not only want to do

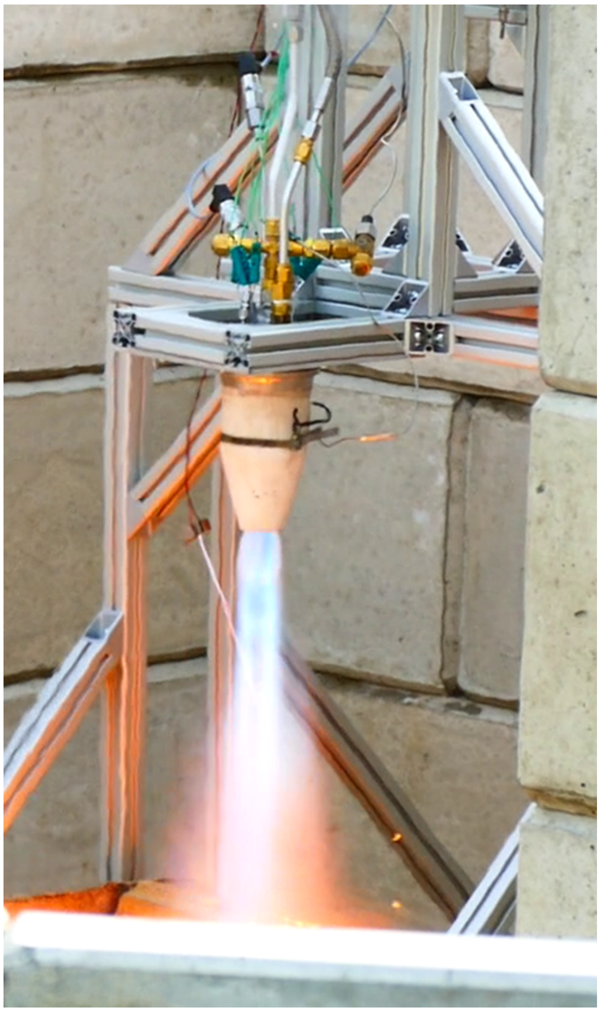

FIG 14. Final test of a 500 N ethanol/liquid oxygen engine conducted within the SMART Rockets project

justice to the outstanding commitment of all the students involved so far and in the future, or achieve a technical milestone. Much more important is building up the associated expertise in the operation of the systems involved - from planning to execution to evaluation of the launch campaign. This expertise will have a longer lasting effect than any technical milestone and far more students will benefit from it in the future than those who will have been there live.

10. IN-SITU RESSOURCE UTILISATION AND MISSION ANALYSIS

In-Situ Resource Utilization (ISRU) will be one of the key technologies for sustainable space exploration and habitation missions to Moon, Mars and beyond. Defined production systems based on hydrogen value chains are utilized as essential building blocks to transform the available resources into valuable elements for energy, propulsion, life support or production systems. The current research at TU Dresden addresses the engineering of ISRU systems using a modular plant concept of standardized, interchangeable and reusable modules. The development, production and automation processes are defined based on the existing standards on modular process plants (VDI 2776) and modular automation (VDI/VDE/NAMUR 2658) for terrestrial application. These standardized architectures and concepts are adapted to the requirements of space utilization.

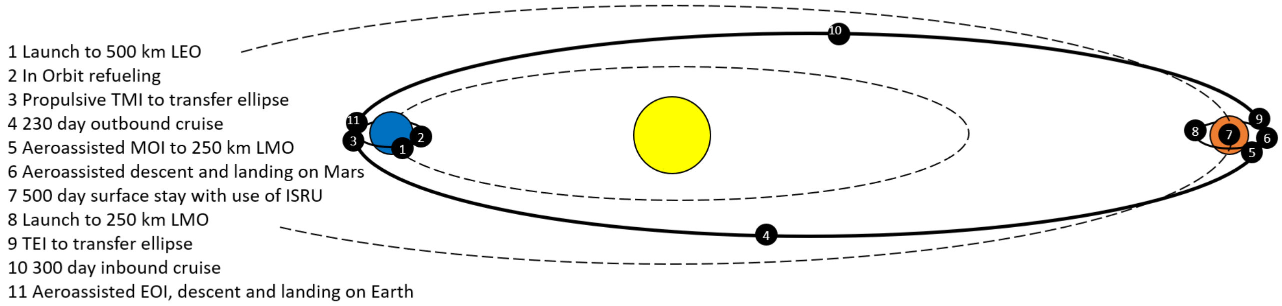

FIG 15. Mission layout Space X long-stay conjunction type trajectory

For the development of modular ISRU process plants, realistic requirements for production goods, capacity and time and cycle of the production process need to be defined. They can be derived by comparing the mission duration, velocities, Δv, propellant mass and payload mass of existing mission concepts. Different representative return missions to Moon and Mars shall be analyzed and compared via a TU Dresden in-house calculation toolbox. The SpaceX manned Mars return mission is selected as reference mission (cf. 15). Seven calculation variants based on Hohmann Transfer, Patched Conic Approximation, Aerocapture and Aerobraking are created and used to develop a feasible analytic calculation logic as foundation for the toolbox. In parallel, the feasibility of the proposed SpaceX mission is examined.
The research demonstrated that the development and execution of interplanetary missions to Mars, such as the Space X Starship mission, require a high level of detail and take strongly optimized mission profiles and technologies as foundation. It is concluded that the establishment of a calculation logic for manned Mars return missions requires to consider additional optimization strategies such as Patched Conic Approximation, Aerocapture and Aerobraking beyond a simple Hohmann Transfer. A feasible analytic calculation logic was successfully developed and will be further validated and optimised within future research work. The calculated results prove that ISRU systems present a competitive technology for the production of propellant and consumable goods for manned Mars return missions. A first set of requirements was derived and is transferred to the development process of the modular ISRU plant.

11. CONCLUSION

Over the past couple of years since its creation, the research group for Space Transportation established a variety of capabilities and experiences. This includes the testing of cold-gas systems (particularly nozzle and retro-flows) and bi-liquid engines with cryogenic propellants, the specialised design of additively manufactured components as well as numerical simulations of supercritical nozzle flows and secondary injections for thrust vectors control. Besides the core competencies in propulsion systems, further expertise in health monitoring, mission analysis and in-situ resource utilisation is being build up, making the research group for space transportation a valuable collaboration parter also for non-propulsive endeavours.

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References

[1] T. Dorau, M. Propst, A. Selbmann, S. Gruber, L.F. Toma, A.G. Joseph, J. Sieder-Katzmann, M. Buchholz, M. Leupolt, K. Sobczak, S. Soller, M. Tajmar, and C. Bach. Numerical analysis of an additively manufactured 6 kn hydrogen peroxide / kerosene aerospike breadboard engine. In *SpacePropulsion Conference 2022*, Estoril, May 9th-13th, 2022.

[2] M. Propst, J. Sieder, C. Bach, and M. Tajmar. Aerodynamische schubvektorsteuerung einer aerospikedüse. In *in J. Fröhlich, S. Odenbach, K. Vogeler (Hrsg.), Strömungstechnische Tagung 2014, Schriftenreihe aus dem Institut für Strömungsmechanik, Band 10, TUDpress*, Dresden, 2014.

[3] M. Propst, V. Liebmann, J. Sieder-Katzmann, C. Bach, and M. Tajmar. Maximizing side force generation in aerospike nozzles for attitude and trajectory control. In *69th International Astronautical Congress*, number IAC-18.C4.10.4.x47139, Bremen, 1-5 Oct., 2018.

[4] M. Propst, L. Ruemmler, S. General, V. Liebmann, J. Sieder-Katzmann, C. Bach, and M. Tajmar. Flow visualisation and surface measurements of shallow water experiments exemplary for aerospike nozzles with secondary injection. In *Proceedings of the Space*

Propulsion Conference, number Paper SP2018_466, Sevilla, May 14-18, 2018.

[5] J. Sieder, M. Propst, C. Bach, and M. Tajmar. Shallow water experiments to verify a numerical analysis on an aerodynamically thrust-vectored aerospike nozzle. In *Progress in Propulsion Physics, EUCASS Book Series 11*, pages 249–262. 2018.

[6] J. Sieder-Katzmann, M. Propst, R. Stark, D. Schneider, S. General, M. Tajmar, and C. Bach. Active - experimental setup and first results of cold gas measurments for linear aerospike nozzles with secondary fluid injection for thrust vectoring. In *8th European Conference on Aeronautics and Aerospace Sciences (EUCASS)*, number 8, Madrid, July 1-4, 2019.

[7] J. Sieder-Katzmann, M. Propst, M. Tajmar, and C. Bach. Cold gas experiments on linear thrust-vectored aerospike nozzles through secondary injection. In *70th International Astronautical Congress (IAC)*, number IAC-19-C4.10.8.x53736, Washington DC, October 21-25, 2019.

[8] M. Propst, J. Sieder-Katzmann, R. Stark, D. Schneider, S. General, M. Tajmar, and C. Bach. Active – optimisation of a fluidic thrust vector control on aerospike nozzles. In *Space Propulsion 2020+1*, number SP2020_480, March 17-19, 2021.

[9] J. Sieder-Katzmann, M. Propst, M. Tajmar, and C. Bach. Investigation of aerodynamic thrust-vector control for aerospike nozzles in cold-gas experiments. In *Space Propulsion 2020+1*, number SP2020_406, March 17-19, 2021.

[10] J. Sieder-Katzmann, J. Abel, M. Propst, E. Schwarzer-Fischer, U. Scheithauer, M. Tajmar, and C. Bach. Development of a ceramic aerospike cold-gas demonstrator for space application. In *SpacePropulsion Conference 2022*, Estoril, May 9th-13th, 2022.

[11] M. Propst, J. Sieder-Katzmann, J. Abel, E. Schwarzer-Fischer, U. Scheithauer, M. Tajmar, and C. Bach. Influence of manufacturing accuracy on the performance characteristics of miniaturized ceramic cold-gas thrusters. In *SpacePropulsion Conference 2022*, number SP2022_406, Estoril, May 9th-13th, 2022.

[12] G. Hagemann, H. Immich, T. V. Nguyen, and G. E. Dumnov. Advanced rocket nozzles. *Journal of Propulsion and Power*, 14(5), September-Oktober 1998. DOI: https://doi.org/10.2514/2.5354.

[13] Sven Stappert, Jascha Wilken, Leonid Bussler, and Martin Sippel. A systematic assessment and comparison of reusable first stage return options. In *70th International Astronautical Congress (IAC)*, Washington, D.C., USA, 2019.

[14] G. Scarlatella, M. Tajmar, and C. Bach. Advanced nozzle concepts in retro-propulsion applications for reusable launch vehicle recovery: a case study. In *IAC, 72nd International Astronautical Congress*, Dubai, United Arab Emirates, Oct. 2021.

[15] Giuseppe Scarlatella, Jan Sieder-Katzmann, Florian Roßberg, Felix Weber, Carlos T. Mancera, Daniele Bianchi, Martin Tajmar, and Christian Bach. Design and development of a cold-flow test-bench for study of advanced nozzles in subsonic counter-flows. *Aerotecnica Missili & Spazio*, may 2022. DOI: 10.1007/s42496-022-00117-6.

[16] Stephen B. Johnson, Thomas J. Gormley, Seth S. Kessler, Charles D. Mott, Ann Patterson-Hine, Karl M. Reichard, and Philip A. Scandura. *System health management with aerospace applications*. Wiley, Hoboken, New Jersey, 2011. DOI: 10.1002/9781119994053.

[17] Karl Reichard, Ed Crow, and Tim Bair. Integrated management of system health in space applications. In *2007 Annual Reliability and Maintainability Symposium*, pages 107–112, 2007. DOI: 10.1109/RAMS.2007.328098.

[18] Massimo Tipaldi and Bernhard Bruenjes. Spacecraft health monitoring and management systems. *2014 IEEE International Workshop on Metrology for Aerospace, MetroAeroSpace 2014 - Proceedings*, pages 68–72, 05 2014. DOI: 10.1109/MetroAeroSpace.2014.6865896.

[19] Ashok N. Srivastava, Robert W. Mah, and Claudia Meyer. *Integrated Vehicle Health Management*. National Aeronautics and Space Administration Aeronautics Research Mission Directorate Aviation Safety Program, 2009.

[20] S. Ofsthun. Integrated vehicle health management for aerospace platforms. *IEEE Instrumentation & Measurement Magazine*, 5(3):21–24, 09 2002. DOI: 10.1109/MIM.2002.1028368.

[21] Chang Shuo and Wang Yi. *Integrated Vehicle Health Management Technology and Its Applications in Commerical Aviation*. IEEE, 08 2017. DOI: 10.1109/SDPC.2017.145.

[22] K. Keller, D. Wiegand, K. Swearingen, C. Reisig, S. Black, A. Gillis, and M. Vandernoot. An architecture to implement integrated vehicle health management systems. In *IEEE Systems Readiness Technology Conference. (Cat. No.01CH37237)*. IEEE, 2001. DOI: 10.1109/AUTEST.2001.948902.

[23] Ian K Jennions, Octavian Niculita, and Manuel Esperon-Miguez. Integrating ivhm and asset design. *International Journal of Prognostics and Health Management*, 7(28):1–16, 2016. DOI: https://doi.org/10.36001/ijphm.2016.v7i2.2404.

[24] N. Lybeck, J. Coble, M. Tawfik, and L. J. Bond. An assessment of integrated health management (ihm) frameworks. In *3rd International Conference on NPP Life Management (PLiM) for Long Term Operations (LTO)*, 05 2012.

[25] Xinlin Qing, Wenzhuo Li, Yishou Wang, and Hu Sun. Piezoelectric transducer-based structural health monitoring for aircraft applications. *Sensors*, 19(3):545, 01 2019. DOI: 10.3390/s19030545.

[26] Tim Felke, George Hadden, David Miller, and Dinkar Mylaraswamy. Architectures for integrated vehicle health management. In *AIAA Infotech@Aerospace 2010*, 04 2010. DOI: 10.2514/6.2010-3433.