OVERVIEW OF ACTIVITIES IN THE PROJECT INTEGRATED RESEARCH PLATFORM FOR AFFORDABLE SATELLITES

T. Cziep[a], F. Atzler[a], L. Cirstea[b], M. Echsel[b], M. Ehresmann[c], S. Fasoulas[c], M. Fugmann[c], D. Galla[c], N. Gottschalk[a], G. Herdrich[c], J. Hildebrandt[c], S. Hümbert[a], S. Klinkner[c], I. Sakraker[a], J. Skalden[c], T. Stindl[a], A. Vikas[c], H. Voggenreiter[a]

[a] German Aerospace Center (DLR), Institute of Structures and Design, Pfaffenwaldring 38-40, D-70569 Stuttgart
[b] Fraunhofer Institute of Manufacturing Engineering and Automation IPA, Nobelstr. 12, D-70569 Stuttgart
[c] Institute of Space Systems, University of Stuttgart, Pfaffenwaldring 29, D-70569 Stuttgart

Abstract

Highly increasing numbers and commercialisation of small satellites require the development and production process to cope with high quantities in less time at reasonable prices. Within IRAS (Integrated Research Platform for Affordable Satellites), local space and non-space businesses and research organizations work together and discuss their needs. This is done on a technical basis with the project team and industry in progress meetings. New technologies are investigated and developed to reduce cost and time in the development and production of components, satellites and satellite constellations. To achieve this, research in several different hardware and software technologies is part of the project. In the field of additive manufacturing techniques, use of polymeric and ceramic materials, combined with multifunctional and bionic structures, is investigated to achieve lightweight structures with integrated functions. Electric and water-based propulsion systems are developed as advanced green propulsion technologies that provide sufficient thrust to distribute high numbers of satellites in orbit and to safely deorbit them after their operational phase, while being cost-effective. In addition, a new approach for cooperative design of satellites without the need for physical proximity is investigated with the DCEP (Digital Concurrent Engineering Platform), which provides a web-based software platform that supports the use of automated design tools and algorithms. The design tools, also developed within IRAS, include tools for constellation design and mission analysis as well as satellite design. IRAS technologies are also a part of the technology demonstrator satellite mission SOURCE, a CubeSat, developed and operated in cooperation between the Institute of Space Systems and the student organization KSat e.V., both at the University of Stuttgart.
This paper presents an overview of the concepts, achievements and current developments in these fields of activity within the IRAS project.

Keywords: IRAS, Concurrent Engineering, Satellite Constellations, Additive Manufacturing, Automotive Electronics, Electric Propulsion, Water-based Propulsion, CubeSats.

1. INTRODUCTION

The project Integrated Research Platform for Affordable Satellites (IRAS) covers investigations of multiple technologies for sustainable, cost-efficient satellite design and production. To integrate the needs of the local space sector, the IRAS consortium includes eleven major space and non-space companies in the federal state of Baden-Württemberg, Germany which accompany the three major research facilities German Aerospace Center (DLR), Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) and the Institute of Space Systems (IRS) at the University of Stuttgart.

The technologies investigated within IRAS aim, on one hand, to enable digital support for the design process of satellites and satellite constellations. The Digital Concurrent Engineering Platform (DCEP) is developed to help connecting different entities cooperating in the design process and to enable using and sharing databases, tools and platforms, especially the tools developed within IRAS. These specialise in partially automating the software-aided design process and include TOCASTA - a tool for constellation design, and ESDC - a tool for spacecraft design.
On the other hand, the project is engaged in the development of new materials and structures for space applications. With additive manufacturing (AM), lighter and smaller structures with a high degree of freedom in design and functionality enables new options besides conventional manufacturing methods. In previous project phases, a suitable AM ceramic compound for further investigations was found. For the integration of ceramic materials into structural designs, the behaviour of joint materials is currently being analysed.
Several promising successes were achieved in AM using polymers and regarding the integration of low-cost electronic into multifunctional sandwich structures, so the next logical, required step is the transfer to larger structures.
In addition, research is done on two new propulsion concepts: an electric arcjet propulsion for which the use of tungsten AM nozzles is being investigated, and a water propulsion system, where several components such as the electrolysis unit and the tank are being developed.
To demonstrate IRAS technologies and to test payloads provided by industry partners, the CubeSat mission SOURCE (Stuttgart Operated University Research CubeSat for Evaluation and Education), developed and operated in cooperation by the Institute of Space Systems and the Small Satellite Student Society KSat, both at the University of Stuttgart, will be used.

This paper shows the latest advancements achieved in IRAS. The results of previous investigations and thus the base for the presented technical progress are described in [1] and [2].

2. DIGITALISATION

2.1. Digital Concurrent Engineering Platform (DCEP)

The Digital Concurrent Engineering Platform (DCEP) aims to support the cooperative satellite design process by providing a platform for concurrent, distributed model-based system engineering and easy integration of software tools and databases at the same time to users from different entities. The platform internal functionalities allow users to develop and access a centrally stored parametric satellite model as well as other data, such as a reference data library with user-defined units, parameter types, element categories, expert domains and more. Further, experts from different disciplines may use available software tools and data provided by the participating parties, all without the need for physical proximity. Access to the DCEP is handled by a two-tier authorization and authentication system, with assigned user roles determining general access to specific functionalities while individual permissions restrict access to specific resources based on a user's domain membership. The current DCEP development is focused on the early stages of satellite design. Potential long-term goals include an extension to all design phases including manufacturing and operations, eventually serving as a digital twin for the entire life cycle of a satellite.

The DCEP consists of a network of connected servers, databases and tools, as shown in Figure 1. Users access the DCEP via a graphical interface (GUI) that communicates with the main part, the DCEP backend through a REST API. The same API is also accessible by any other authorized tool or platform to exchange data or use any DCEP feature. The main functionalities of the DCEP are provided by the backend. It is responsible for accessing the DCEP database and manages communication with connected software tools, especially the tools developed within IRAS as well as with additional modules such as the DCEP blockchain for authorship and usage tracing. A more detailed description of the DCEP and its features and components can be found in [3].

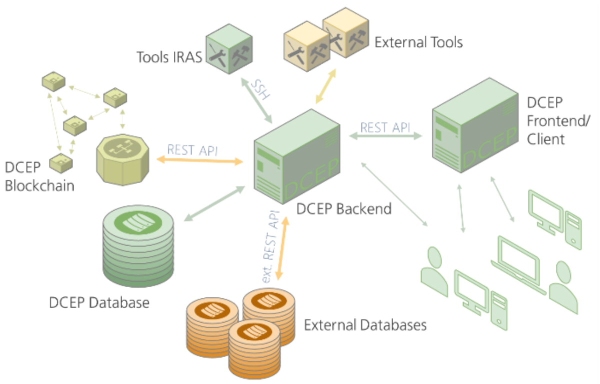

Figure 1. DCEP structure and interfaces

Newest development has been focused on tool and data usage. A method to make tools available and usable via the DCEP has been developed and implemented. While the REST API is generally open to all tools, enabling a given tool to access the interface is often not feasible or efficient, especially for research-focused and computational tools, such as those developed within IRAS. These tools often do not have a graphical user interface, but use input and output files in one of the standard data file formats instead. The implemented method allows those tools to be used through the DCEP while staying securely on their own individual tool server. The tool owner retains full control, with no need or possibility for users to access the tool directly.

To enable fast and easy coupling, the DCEP is able to parse the input and output files (currently XML only) of a tool and process them as templates for future tool uses. Users are then provided with a graphical interface to define inputs, and to map DCEP data to tool inputs and outputs. The DCEP then generates new input files from the mapping using current DCEP data, sends them to the tool server and starts the tool. Results are collected after the tool is finished and can then be downloaded or transferred directly back to the DCEP data model according to the mapping. All communication between DCEP and tool server is secured via SSH.

Tool owners can enhance the individual data entries in the provided template files with additional so-called DCEP data blocks. These can optionally contain information intended for the DCEP users (e.g. descriptions, units, default values), information on the expected data structure (e.g. number of entries, types of values) or information on the permitted values (e.g. enumeration, min/max). To enable dynamic data structures, all information in a DCEP data block can refer to or be conditionally dependent on other data entries, allowing the definition of complex input and output file templates.

Details on the new tool coupling method and the results of a first mission design using DCEP and the IRAS tools (see sections 2.2 and 2.3) are presented in [4].

2.2. Tool for Constellation and Satellite Trade-Off Analysis (TOCASTA)

2.2.1. Overview

TOCASTA is a design tool that allows to automatically generate and evaluate many solutions for a given satellite or constellation mission based on its coverage requirements. The overarching goal is to allow mission designers to select the best solution for a specific design case not only from a constellation or orbit point-of-view, but also regarding the satellite to be designed for this mission. By automating the constellation design and mission analysis, significant time savings for mission design specialists can be achieved. Additionally, other stakeholders are enabled to evaluate possible changes to mission requirements or payload performance independently. TOCASTA allows to:

- Automatically generate multiple solutions within a given design space that solve the given constellation or satellite coverage problem
- Perform an automated mission analysis to establish preliminary satellite system requirements, e.g. propulsion budgets
- Prepare and visualize the results to allow selection of the best solution from a holistic perspective

A more detailed description of TOCASTA's capabilities is given in [2], whereas the methodology of constellation design and mission analysis is described in [5]. An example use-case is depicted in [4]. This paper highlights two new features that were not published before: The implementation of multiprocessing in design and analysis, and the capability to design a constellation composed of multiple layers.

2.2.2. Implementation of Multiprocessing

Multiprocessing is a technology that allows software to make full use of modern multi-core central processing units (CPUs). By dividing a task into multiple independent processes that can be executed in parallel, significant time savings can be achieved. However, the software must explicitly support parallel processing, and the ASTOS software (used by TOCASTA for orbit and coverage simulations as well as mission analysis) as well as parts of the ESA-DRAMA toolkit (used by TOCASTA for space debris mitigation calculations) do not innately implement this.

For this reason, a new multiprocessing environment was developed that allows parallel execution of multiple ASTOS and ESA-DRAMA runs. An individual copy of a base scenario is created for each case to be solved and adapted to its specific case, e.g. with different orbital parameters. The number of parallel runs is limited to the number of CPU cores by default. Due to background processes (e.g. the operating system) and process management overhead, more parallel runs would not increase the execution speed further. While each individual case takes the same amount of time, TOCASTA's overall run time is greatly decreased.

2.2.3. Constellations Combining Multiple Layers

The implemented multiprocessing capability is especially useful when working with combinations of constellations. For example, when a constellation at very low altitude is to communicate with another constellation at higher altitude, the number of possible constellations in the solution space increases exponentially, as many high-altitude solutions exist for each low-altitude solution. Figure 2 shows an example in which two suitable solutions at low altitude lead to many more possible solutions at higher altitude to be evaluated.

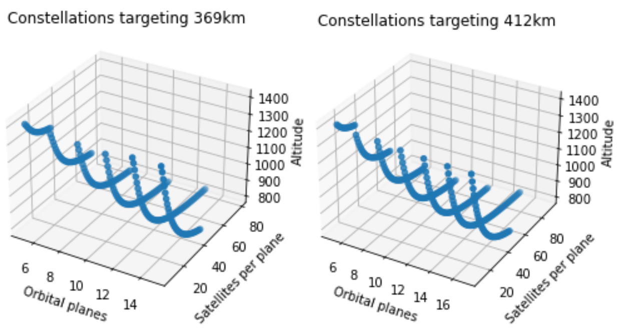

Figure 2. Example of multiple solutions for combined constellations

Combining two constellations at different altitudes can allow missions to exploit the advantages of both high and low altitudes: at low altitudes, optical sensors can achieve a higher resolution, while communication applications benefit from stronger signals and lower latency. At high altitudes, the relative speed of satellites to each other is lower, allowing for easier inter-satellite link, while ground stations can cover a larger portion of the orbit, leading to less ground stations and longer contacts with each satellite.

Figure 3 shows the result of such a mission design case, in which a low-altitude constellation employs payloads with a small footprint, leading to many satellites necessary. Meanwhile, the high-altitude constellation covers the entire lower constellation almost completely with very few satellites and serves as a data relay for near-real-time data downlink.

The methodology for finding constellations that target another, lower constellation is similar to that used for finding constellations targeting Earth directly. However, the target area now has a higher radius (Earth's radius plus the lower constellation's altitude), and is limited by the lower constellation's inclination. Additionally, Earth's rotation can be ignored when targeting another constellation. After adapting the constellation design methods already implemented to meet these conditions, TOCASTA is now capable of designing two constellations together that support and enable each other.

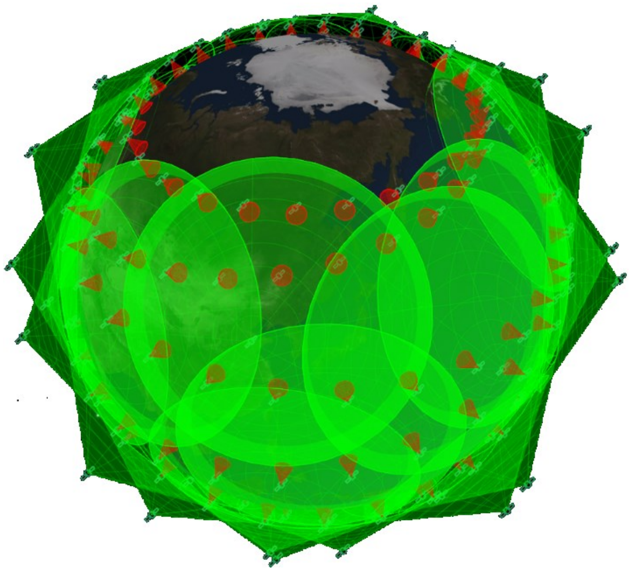

Figure 3. Example of two constellations at different altitudes, with the higher one covering the lower one.

2.3. Expert Tool Spacecraft Design: ESDC

The continuous advancement in space technology and the demand for efficient spacecraft systems as well as the need for cost reduction necessitate rapid and unbiased design iterations. The Evolutionary System Design Converger (ESDC) is a sophisticated spacecraft design software tool developed to address these challenges. This section outlines the key features of ESDC, its solver stages, and its compatibility with the DCEP for enhanced functionality and collaboration [6] [7].

2.3.1. ESDC Architecture and Solver Stages

To obtain a refined spacecraft design with just limited input system requirements, several subsequent solver stages have to be executed.

The first stage of ESDC utilizes a heuristic model to perform a preliminary estimation and scaling of spacecraft components in terms of mass and power. This stage leverages heuristic scaling laws derived from a comprehensive database of actual spacecraft with flight heritage, enabling the tool to quickly estimate an initial spacecraft composition from a low number of input requirement parameters.

The second stage employs a parametric model, which builds upon the heuristic scaling approach used in the preliminary stage. This model facilitates the parametric estimation of system and component parameters while considering available degrees of freedom. To achieve optimal solutions, ESDC utilizes evolutionary algorithms that iteratively evolve and refine the design based on predefined fitness criteria such as minimum mass or maximum design margin mass. The evolutionary algorithm can distinguish between categorical degrees of freedom (e.g. technologies, propellant type, …) and quantitative degrees of freedom (e.g. specific impulse or thrust of the propulsion system) and can automatically mutate both.

In the third stage, ESDC performs component selection and recommendation based on the data-driven space hardware component database. This step ensures that the tool proposes components that align with real-world hardware and have demonstrated performance characteristics, leading to reliable and feasible spacecraft designs.

2.3.1. Advantages and Impact

ESDC's fast and unbiased iteration capabilities significantly reduce manual efforts and design biases, resulting in a multitude of feasible and optimal spacecraft design solutions. The tool interface has been updated to work with the DCEP. It is hosted by an on-premise IRS server, which empowers the tool owner and developer with full control and update capabilities. Moreover, the seamless collaboration within DCEP facilitates efficient information exchange and enhances overall design efficiency.

2.3.2. Open-Source Implementation and Version Support

ESDC is implemented in Octave, an open-source alternative to Matlab®, ensuring accessibility and enabling further community contributions. The current version, 8.2.0, offers most features of Matlab® and contains sufficient functionalities for robust and fast spacecraft design endeavors. The ESDC tool is available on GitHub [8].

3. ADDITIVE MANUFACTURING

3.1. Silicon-carbide-based Ceramics

For specific applications in the aerospace sector, polymers and metals may not suffice and ceramics become essential. They are designed to withstand extreme conditions and possess unique properties such as a low coefficient of thermal expansion (CTE) and thermal shock resistance. Since manufacturing ceramics is expensive, DLR is working on making the production more cost-effective within the IRAS project. The extrusion-based additive manufacturing technology was implemented in the Liquid Silicon Infiltration process (LSI) as a preforming method and it is aimed to ensure broader accessibility and application in various industries.

The current research focus is on joining of individual components. An efficient and reliable method for assembling 3D printed parts is crucial for advancing technology and achieving suitable integration in various applications. Therefore, different joining methods are investigated.

3.1.1. Materials and Methods

The preform needed for the LSI process is achieved by 3D printing a near-net-shape green body with 'Pellet Additive Manufacturing' (PAM, Pollen, France). Therefore, a suitable feedstock based on thermoplastic was developed. It was processed on a co-rotating twin screw extruder (Thermofisher Scientific) in combination with different carbon and ceramic fillers, e.g. activated carbon, carbon black, short carbon fibres and SiC-powder, which act as a backbone for the following steps. The green body was chemically debinded in a solvent for 16 to 24 hours before the pyrolysis, where all of the polymer is removed. The porous carbon body is then infiltrated with molten silicon which reacts with the carbon and transforms into silicon carbide. Figure 4 gives an overview of the process. Detailed information about the LSI process is provided in [9].

With this method, dense SiSiC ceramic components with an overall shrinkage of less than 6 % can be achieved.

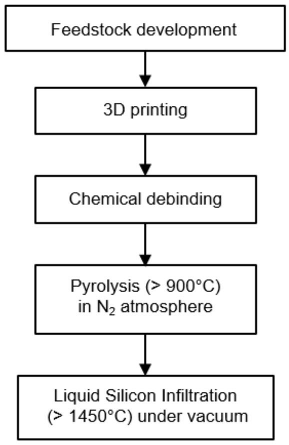

Figure 4. Overall process of the additive manufacturing of SiC-based ceramics.

3.1.2. Joining

When it comes to joining, there are mainly two different approaches: joining of components in pyrolysed state via bonding paste based on phenolic resin and carbon fillers and subsequent siliconisation of the joint components, or joining of completely processed SiSiC components via ceramic glue.

3.1.2.1. Joining of Pyrolysed Components

Several bonding pastes were investigated (see Table 1) regarding their processability and outcome after siliconisation. Since the pyrolysed samples have a CTE of close to zero, the phenolic resin is mixed with coke to adjust the thermal expansion. Different proportions (1 – 3) were produced and applied on small samples. In addition, one mixture contained the short fibres used in the feedstock (4).

No.	**1**		**2**		**3**		**4**		
Material*	R	C	R	C	R	CF	R	C	CF
Prop. [%]	60	40	55	45	71	29	60	30	10

Table 1. Different compositions of bonding paste.
* R = phenolic resin, C = coke, CF = carbon fibre

After the application of the paste, the joined samples are weighted and cured for four hours with a maximum temperature of 135 °C.

3.1.2.2. Joining of Siliconised Components

The main advantage of joining parts that have already undergone siliconisation process is an improved handling of the components. Pyrolysed samples are very fragile and can easily be damaged while joining.

Ceramabond 890 (T-E-Klebetechnik, Germany) with a maximum temperature of 1650 °C was chosen as glue. The residual silicon was removed from the surface of the samples by sanding it off. The glue was applied on two overlapping samples which will be used for a mechanical evaluation of the joint.

3.1.3. Results

The quality of the joint is evaluated via computed tomography (v|tome|x L, GE Sensing & Inspection Technologies GmbH, Wunstorf). The objective is to achieve a homogeneous result. In Figure 5 the joint sample of bonding paste No. 4 is shown. Paste 1 to 3 didn’t lead to a successful siliconisation due to CTE mismatch.

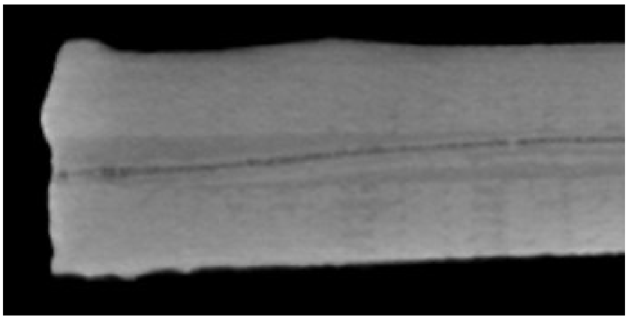

Figure 5. CT picture of a joined SiSiC sample.

Mechanical investigations for quantifying the quality of the joints still need to be conducted. What can be seen on the CT picture is the black layer in the centre of the sample. This is carbon that has not been converted.

Due to the lack of fibre reinforcement, the material is brittle and thus not damage tolerant like Ceramic Matrix Composites (CMCs). Therefore, in upcoming work, joining on a fibre reinforced plate (leading to C/C-SiC) will be investigated. Due to different CTEs, a graded structure [10] was chosen. Purpose of the gradation is a higher conversion to SiC on the surface of the plate. At the same time fibre reinforcement increases towards the inner centre. This is achieved by thermally treating single layers of carbon fibre fabrics in a graphite furnace at temperatures ranging from 600 °C to 1100 °C. For producing the CFRP green body, the fabrics are layered symmetrically from the outside (1100 °C treated fabric) to the centre (not thermally treated fabric). They are processed via resin transfer moulding and infiltrated with phenolic resin. The fibre volume content of the plate is roughly 60 %. The samples will be joined both in pyrolysed and siliconised state. This way a damage tolerant component could support the 3D-printed material and also offer a way for better connection to the satellite structure.

3.2. Multifunctional Sandwich Structures

The manufacturing of thermoplastic composite sandwich structures has been one area of interest in the IRAS project in past years. By additively manufacturing the core structure of a sandwich, multiple opportunities for load or thermal adjusted designs arise. The integration of radiation shielding in the sandwich structure has also been investigated [11]. As a polymer polyetheretherketone (PEEK) has been used due to its suitability for aerospace applications. To overcome the challenge of joining a 3D-printed core on a face sheet of a sandwich structure, the in-situ bonding of PEEK on carbon fibre reinforced PEEK laminates has been developed and investigated in the IRAS project [2]. Recent progress has been made in the upscaling of this process using industrial robots. A hybrid work flow combining AFP and Fused Granular Fabrication has been developed and is shown in Figure 6.

At first, a tooling is 3D-printed out of PA6. This allows the rapid and economical production of complex molds. The process parameters of AFP had to be adjusted for the use of PA6 substrates.

The in-situ bonding of a core structure to a thermoplastic laminate through extrusion-based AM has been adapted to large-scale AM. A single screw extruder mounted on a six degree of freedom robotic arm can be utilized to produce parts with a complex and non-planar toolpath. Thus, more optimized part geometries can be realized. The integration of components was demonstrated as well.

The bonding of the second face sheet to the core structure by in-situ AFP has already been shown in previous studies in the IRAS project. However, with the upscaling of the process new challenges have been faced. Larger core structures with larger cells of the honeycomb make it difficult to properly bond a tape on the surface. By increasing the tape force, which acts in-plane with the tape, and decreasing the consolidation pressure, which acts orthogonal to the substrate, the laminate quality can be improved.

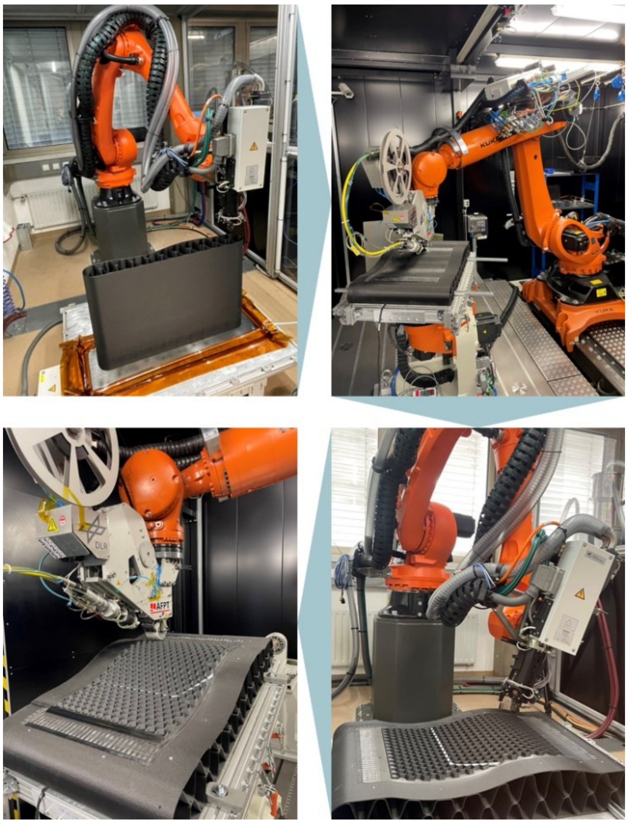

Figure 6. Workflow for the large-scale manufacturing of complex sandwich structures

4. SUSTAINABILITY IN SPACE: DESIGN FOR DEMISE (D4D)

To ensure that near-Earth space remains commercially and scientifically viable in the future, it is of great importance to reduce the amount of space debris in orbit and to minimise the generation of new debris in the future. One of the effective mitigation methods is uncontrolled re-entry into the Earth’s atmosphere, with the aim of burning up the hardware down to a point where it no longer poses a risk to the ground assets. This design philosophy, "Design for Demise (D4D)" ([12], [13]) seeks to reduce the amount of debris reaching the ground as much as possible by engineering materials and configurations to break up at higher altitudes than they would otherwise do.

At DLR Institute of Structures and Design in Stuttgart, we explore how our advanced manufacturing techniques can be used for D4D for a more efficient demise behaviour. We adopted the methodology of replacing the primary structure joints of the satellites with demisable joints, which would passively release the primary structure at a pre-defined altitude. Once the primary structure is disintegrated, the inner subsystems which are more difficult and critical to demise, can be exposed to the high temperature plasma flows for a longer time so that they demise more efficiently.

Two demisable joint concepts were originally investigated: a patch concept and an insert concept made of 3D printed CF-PEEK for an upscaled version of the Flying Laptop satellite from the University of Stuttgart ([14], [15]). After the design for 3D printing, a thorough mechanical and thermal characterization campaign on material and printed parts were conducted. Subsequently, the designs were examined using Finite Element Analysis for their stability, iteratively adjusted, optimised and finalised in order for the structure of the satellite to be able to bear the loads occurring during launch. Finally, re-entry simulations were performed with ESA DRAMA code for the finalised designs to determine the altitude at which the primary structure of the satellite is expected to fail and break apart. It was shown that a failure of the primary structure occurred above 97 km instead of 78 km.

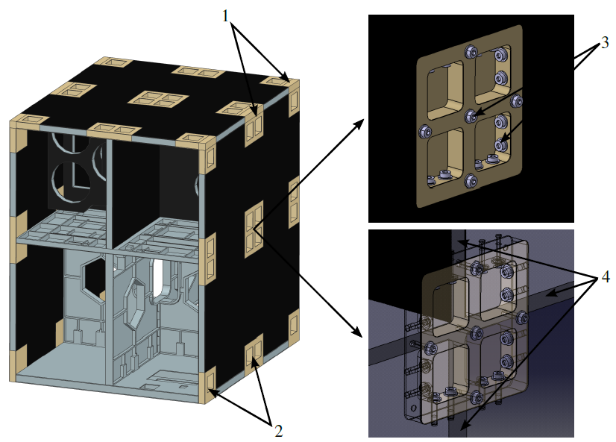

Figure 7. Initial demisable patch concept.

These initial joint concepts were later enhanced by adding passive ejection mechanisms to help with the mechanical removal of the joint to release the primary structure panels. Embedded springs and the use of shape memory alloys were examined. More details can be found in [16].

The concept for a 3D printed passive ejection demisable joint consists of a spring-loaded screw connection which separates once a certain temperature is achieved during re-entry as seen in Figure 8. The joint structures are fabricated using multi-material additive manufacturing, where a single part is 3D-printed using several different materials. The process of multi-material fused filament fabrication is used where the part is built using layers of melted filament of different materials. As such both the main structure of the joint as well as the separation interface can be printed in one piece with little increase in manufacturing complexity. This allows for interlocking designs that cannot be fabricated by conventional manufacturing processes. It also allows for integration of these joints directly into additively manufactured honeycomb structures for use in sandwich materials with added functions.

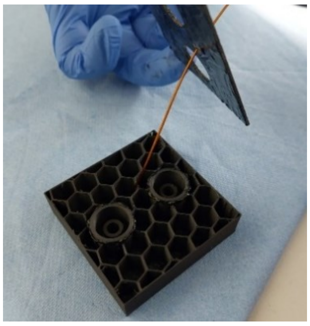

Figure 8. CF-PEEK honeycomb with integrated demisable joints

A test model was built and tested in a plasma wind tunnel at the IRS in University of Stuttgart as seen in Figure 9, where a successful separation was demonstrated in relevant atmospheric entry testing conditions.

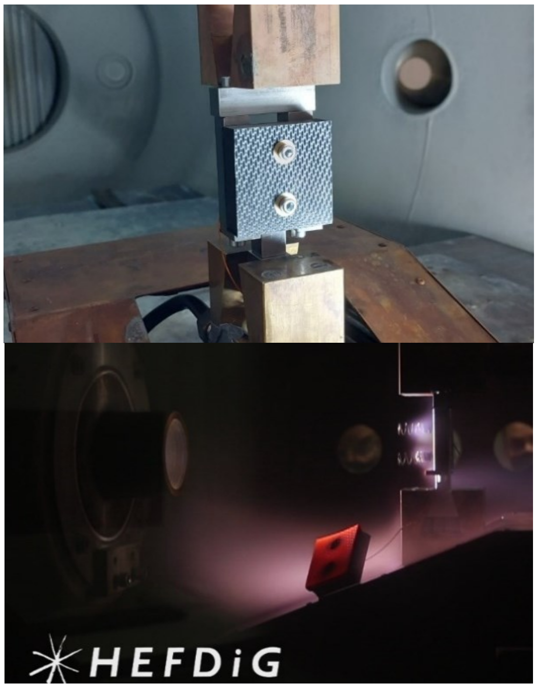

Figure 9. Test panel in jig inside of IRS PWK4

Once this process is elaborated, we focus on hybrid demisable joints made of different materials i.e. programmable shape memory materials, metals, thermoplastics, which are being investigated for the reference mission of Sentinel-6 satellite. Different configuration sets of replaced demisable joints are investigated and more accurate and resolved re-entry simulations are being conducted in the HTG SCARAB simulation tool.

5. ELECTRICALLY CONDUCTIVE INKJET PRINTING

Additive manufacturing not only makes it possible to produce complex shapes in small quantities, but also to integrate functional elements into components. One possibility for such functionalisation is the printing of electrically conductive structures, of which inkjet technology is again one of many techniques to realise this. Here, UV-curing inks are processed in high resolution and in low layer heights via an inkjet print head. IRAS is investigating in how the space industry can benefit from this technology.

Previous work within IRAS has already shown that it is possible to generate conductive structures using this technology. The new goal is to push the idea further and to be able to print passive electrical components directly into structures. In a first step, capacitors were selected as passive elements.

5.1. Ink Systems and First Parameter Studies

Non-conductive, dielectric materials, should also be considered within the current project phase. In order to print the materials (photopolymer inks) in high resolution with defined layer thicknesses and properties, the processing parameters for the materials must be defined. For this purpose, a so-called drop watching system was used. The test setup with the system allows the print heads to be controlled with different parameter sets and the respective material outputs to be observed. In this way, parameter sets can be optimized to ensure that the ejected material drops to produce results in high quality. Since the respective dielectric constant, the charge carrier areas and the layer thickness of the dielectric play a role in the definition of the capacity, each of these values has to be controllable in the printing process. The material itself determines the dielectric constant and the printing parameters influence the layer thickness and charge carrier areas. In initial tests, dielectric ink systems have already been evaluated with regard to their printing/processing parameters.

Further testing involves the combination of electrically conductive and dielectric inks. First tests showed that the chosen ink systems work well in combination and that the conductive inks can be sintered even on the challenging substrates.

6. ELECTRIC PROPULSION

Increasing numbers of satellites in low Earth orbits, due to the advent of mega satellite constellations like Starlink or OneWeb, require advanced strategies to mitigate the generation of space debris. Deorbiting decommissioned spacecrafts at end of life is considered crucial in order to operate a sustainable constellation [17]. Electric propulsion systems can provide fast deorbit with a reasonable propellant mass.

The Institute of Space Systems (IRS) is currently developing a deorbit system based on thermal arcjet technology, which features high thrust density combined with a reasonable weight-specific impulse. The design features additively manufactured nozzles made of tungsten to improve performance in terms of thrust efficiency and weight-specific impulse. This section will give an overview of the recent activities, covering performance characterization, reproducibility investigation via neutron imaging, and outlook.

6.1. Performance Characterization

After successfully demonstrating that ALM tungsten can be operated in an electrical arc environment [18], a performance characterization campaign was conducted to assess the influence of the applied helical regenerative cooling channels on thrust and weight-specific impulse, which are depicted in Figure 10.

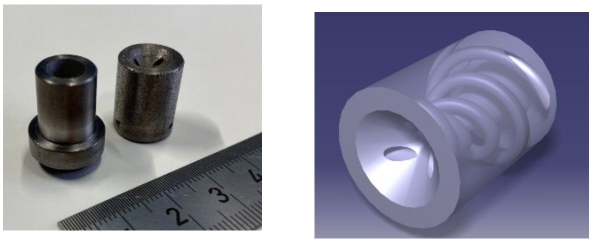

Figure 10. Nozzle with helical, regenerative cooling channels made via ALM with tungsten [19].
Left: Manufactured prototypes, right: CAD image.

The experiments were conducted in a vacuum facility with a size of Ø2 m x 6 m. It is connected to the institute's main vacuum pump system with a suction rate of 69444 l/s. The system is designed to handle large mass flow rates for reentry experiments and the resulting ambient pressure during operation with hydrogen was 2 Pa. Thrust was measured via a hanging pendulum thrust balance, by correlating displacement to a known force via calibration. Displacement is measured with a MicroEpsilon S-6 capacitive sensor and calibration is done by applying two aluminum weights of 5 g via a pulley. Hydrogen mass flow was measured and controlled with a Bronkhorst F-201AV mass flow controller. Furthermore, the temperature of the thruster housing was recorded with a LumaSense pyrometer, which is outside the image plane in Figure 11 [19].

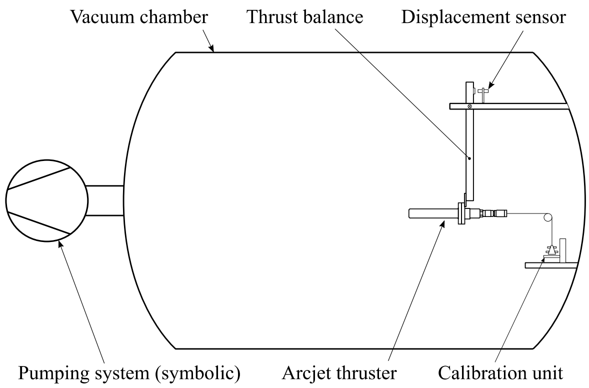

Figure 11. Schematic of vacuum test facility "Tank 4" at IRS [19].

The ALM tungsten nozzle with regenerative cooling channels was successfully operated, which demonstrates that the helical cooling channel concept is feasible. Furthermore, the performance characteristic, shown in Table 2, is in a typical range of regeneratively cooled hydrogen arcjets. However, thrust efficiencies of 40 - 50 % were mostly achieved by high-power arcjets of 5 kW and beyond [20]. The fact that this was now achieved in a power range of 500 - 800 W, which provided thrust efficiencies in the range of 30 - 40 %, further proves the effectiveness of the advanced regenerative cooling system [3].

Power P_{el}, W	Mass flow $\dot{m}$, mg/s	Thrust F_T, mN	I_{SP}, s	η_T, %
541	6.00 ±0.13	51.6 ±2.6	877 ±62	41.07 ±4.8
577	7.00 ±0.13	59.6 ±2.9	869 ±59	44.03 ±5.1
646	7.00 ±0.13	59.4 ±2.9	866 ±59	39.10 ±4.5
729	9.00 ±0.14	76.8 ±3.8	870 ±57	40.13 ±4.5
816	9.00 ±0.14	72.1 ±3.6	817 ±53	39.63 ±4.4

Table 2. Performance results of the ALM nozzle (Reworked from [3]).

6.2. Reproducibility Study

Additively manufactured parts allow for function integration, light-weight design, and potentially reduced number of fasteners. However, they are prone to slight variants when producing the same part multiple times. Since the nozzles are manufactured at the limits of what the process allows in terms of smallest internal cavities and precision, the reproducibility was investigated in a study together with the Heinz Maier-Leibnitz Zentrum (MLZ) and the Budapest Neutron Centre (BNC) of the Centre for Energy Research [21]. Figure 12 shows the three sampled investigated, with the same nozzle used in the performance characterization on the left, and two slightly adapted nozzles on the right from a different manufacturer.

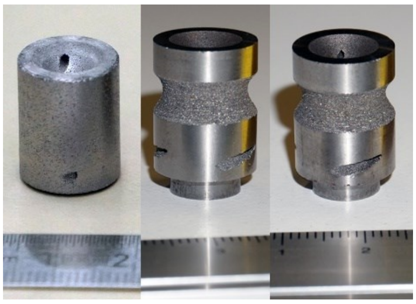

Figure 12. Samples investigated in the reproducibility study [21]. From left to right: Nozzle 1, Nozzle 2, and Nozzle 3

A common way to non-intrusively investigate a part is X-ray based computer tomography. However, this method could not be applied to investigate the additively manufactured tungsten nozzles, since attenuation was too high. With neutron imaging, a technology was identified allowing scans of tungsten samples, since neutrons only interact with the atomic nucleus. In a 3-step approach, the samples were first scanned at BNC using detectors from MLZ, then underwent standardized operational cycles at IRS, and scanned again after. Each nozzle underwent 10 ignition cycles, which lasted each 30 min under equal applied power, current, and mass flow rate conditions. The propellant used was hydrogen.

The results showed significant variations between the two manufacturers and also the two nozzles made by the same process. Results are summarized here and can be seen in detail in [21]. In general, after the first ignition cycles likely due to widening of the nozzle throat due to erosion. This effect is expected from pure tungsten. Performance then stabilized over the majority of cycles.

Nozzle 1 was produced close to the intended design and showed little changes over the test campaign. The cooling channels were almost free of residual powder and no powder movement was observed. Enclosed gas bubbles were not observed in the material. The nozzle throat was widened to about double the size [21]. Figure **13** shows exemplary the cooling channels and nozzle throat.

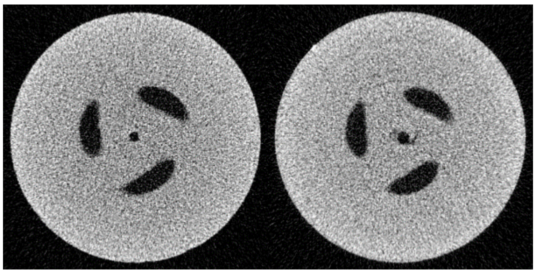

Figure 13. Neutron CT slice of the constrictor with surrounding cooling channels of Nozzle 1. Left: Prior to operation, right: after operation [21].

Nozzle 2 and 3 diverged significantly from the intended design with the cooling channel diameter being about 20 % less, which can be seen in Figure 14. Furthermore, significant residual powder and enclosed gas bubbles were found. This likely led to a collapse of the nozzle throat in Nozzle 3, shortly after the first ignition cycle. In Nozzle 2, it was found that the residual powder in the cooling channels moved during the test campaign. Aside from the variations within one process, which led to one nozzle clogged, it is also clear that the manufacturing process needs to be well understood to produce a nozzle suitable to an electric arc environment.

Pure tungsten is known to be suboptimal in terms of electrode erosion for thermal arcjet operation [22]. To exploit the benefits of ALM tungsten in terms of performance and counter the life-time issue, a design is currently being investigated featuring a doped tungsten insert in an ALM nozzle housing. Material candidates are thoriated and lanthanated tungsten, as well as, tungsten doped with a mixture of rare earth oxides. Upcoming performance characterization and life-time experiments will investigate the feasibility.

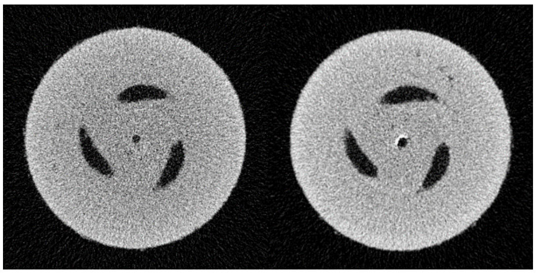

Figure 14. Neutron CT slice of the constrictor with surrounding cooling channels of Nozzle 2. Left: Prior to operation, right: after operation [21].

7. WATER PROPULSION

7.1. Motivation and Operating Principle

Hydrazine-based chemical thrusters are the standard for satellite propulsion systems [23]. Even though the number of active satellites with electrical propulsion systems is steadily increasing [24], they are not generally a suitable replacement for chemical propulsion systems for every satellite mission, as they come with a high-power demand, which usually drives the satellite's electrical power system dimensions and consequently increases their dry mass.

The strength of water electrolysis propulsion (WEP) is that it runs on inert water. Only in orbit the water is decomposed through electrolysis and gradually stored in small separate gas tanks for oxygen and hydrogen. After reaching a certain pressure level, a thrust manoeuvre can be performed by injecting both gases in the combustion chamber, where ignition is initiated by a catalyst. The fluid schematic for a WEP system is illustrated in Figure 15.

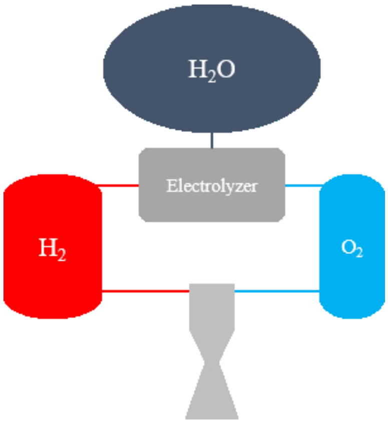

Figure 15. Fluid schematic of the water propulsion system

The propulsion system is still planned to be launched as main propulsion system for the IRS ROMEO mission [25], an 80 kg satellite, which is scheduled to be launched in 2026, to provide a Delta-v of around 515 m/s.

7.2. Electrolysis Unit

The electrolyser is based on the proton exchange membrane (PEM) principle and operated in a static water feed manner. Here the water is fed through a membrane to the cell’s cathode, allowing for the production of dry and pressurised hydrogen and oxygen in a µ-gravity environment, without the need for any pumps or gas separators. This comes at the cost of cell efficiency when compared to regular ground-based PEM electrolysers.

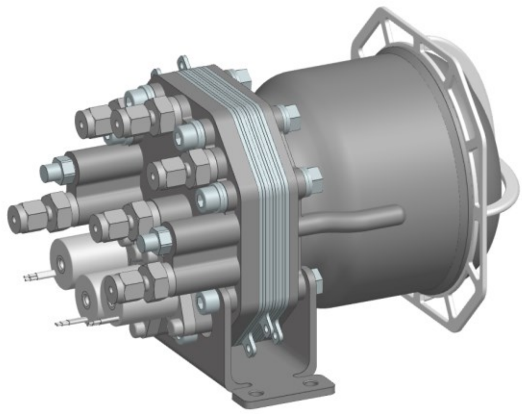

Figure 16. Assembly of the electrolyser-gas-tank-unit [26]

The new designed electrolysis unit consists of three cells, each capable to operate at 30 W in a fully redundant manner. To mitigate observed current density drops when operating at pressures above 20 bar, the cells can also be operated simultaneously, effectively increasing the cell area. The assembled unit can be seen in Figure 16 and is further described in [26]. It contains all needed valves for cell operation in its base plate and holds the 600 ml gas tanks on the top plate. The gas tanks are split to contain hydrogen and oxygen simultaneously. The overall unit comes in at 2.3 kg and has a baseplate footprint of 10 x 10 cm.

7.3. Thruster

The chemical thruster is designed for 1 N thrust and is currently planned to be operated in blow-down on the ROMEO mission. Within previous studies [27] a novel 3D printed based ceramic design was developed that allows for a huge cost reduction while increasing the potential efficiency. A first prototype, illustrated in Figure 17, was manufactured, successfully fired, and characterized in a vacuum chamber. The thruster incorporates an integral tri-coaxial injector with hydrogen wall film cooling, reaching a combustion efficiency of about 75 %. The thruster is made of SiAlON, a technical ceramic, that was precisely printed by *Alumina Systems* using the stereolithographic LCM process [28].

Between mass flows of 63 mg/s and 315 mg/s (design point) the specific impulse (I_{SP}) of this first prototype varies between 261 s and 303 s. However, combustion simulations indicated that an I_{SP} of > 350 s could be achievable with this thruster design. The post analysis showed that additional heat losses from the lab interface and slight injector adaptations that were introduced for manufacturing but are not needed anymore, can at least partly explain the difference in efficiency. All lessons learned are included in the current design iteration with multiple versions to determine the influence of the respective changes. Also, the preliminary flight design interface incorporating glass soldering will be part of the upcoming test campaign [28].

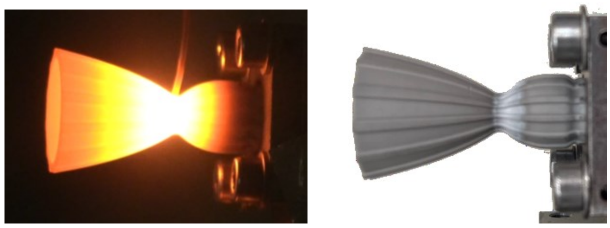

Figure 17. left: Ceramic thruster while firing in vacuum chamber; right: Thruster after approx. 500 firing cycles incl. extended operation times [28].

8. MULTILAYER SANDWICH STRUCTURE

The additive manufactured sandwich structure from the IRAS project aims to demonstrate a great possibility for weight reduction for small satellites by utilizing a 3D printed PEEK honeycomb structure, shown in Figure 19. This section gives an update to the previous paper [2] and the planned in-orbit experimental demonstration. For this demonstration, the sandwich structure will be flown as part of the SOURCE CubeSat, developed and operated in cooperation by the Institute of Space Systems and the Small Satellite Student Society KSat, both at the University of Stuttgart, seen in Figure 18.

8.1. Structure and Current Progress

Software integration into the source payload software has begun, including several electronics responsible for the measurements during the experiments which are part of this project. One of them consists of two sets of Bosch automotive sensor packages (SMI 130), of which one is radiation-shielded and for comparison the other one is unshielded.

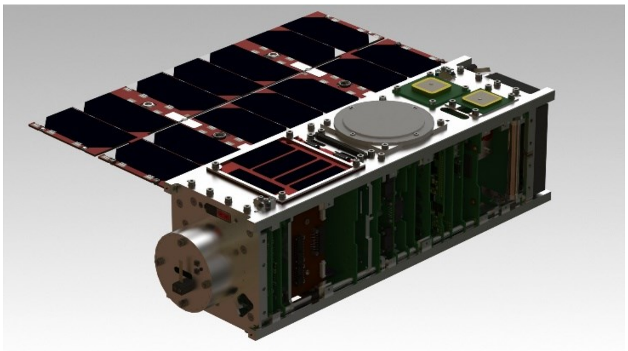

Figure 18. CubeSat SOURCE with an opened side and deployed solar arrays

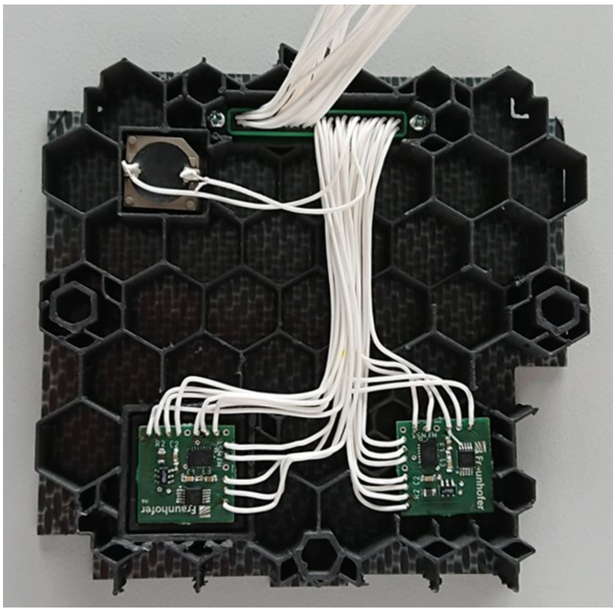

Figure 19. Inside view of the honeycomb structure and sensor components

Furthermore, two RADFETs are integrated into the sensor packages, and a 0.3 W buzzer is built into the sandwich. The buzzer is responsible for inducing a controlled vibration into the structure for the sensors to measure and compare against. The components are controlled by a microprocessor, which again controls part of the payloads during the operation, and for that reason, custom software will be implemented. The software is written in C++ and will communicate with the sensors over an SPI bus. After receiving the measurements, the data will be transferred over an RS485 bus to the main onboard computer, and from there it will be sent to a ground station. The buzzer is controlled by a PWM signal, which is also generated by the Vorago and controlled by the software. All functionalities of components are planned to be implemented into different operational modes for health monitoring, calibration, and measuring for use during the operational phase of SOURCE in LEO.

8.2. Mission Qualification

In preparation for the SOURCE project, the sandwich has to be qualified for the operational environment in LEO. The requirements are part of the Fly Your Satellite Project from ESA. Part of this qualification is a test in a thermal vacuum chamber to verify the operational and non-operational temperatures under vacuum conditions. This test was successfully carried out with the help of the facilities at TESAT in Backnang (shown in Figure 20) in December 2022. The temperature range during the test was between -40°C and 80°C for the non-operational, -30°C and 70°C for the operational phases (Figure 21). During the development of the structure, one engineering and one qualification model were built, with minor modifications between them. One problem encountered during the qualification testing was that the mounting for the Harwin Gecko connector was realised with screws through the screw holes (which can be seen in Figure 19) which are intended to secure the female connector to the male and had to be removed.

As part of the successful shaker test of the SOURCE satellite as a whole in July 2023, it could be shown that the current support for the connector with adhesive is strong enough and no further modification to the connector is necessary.

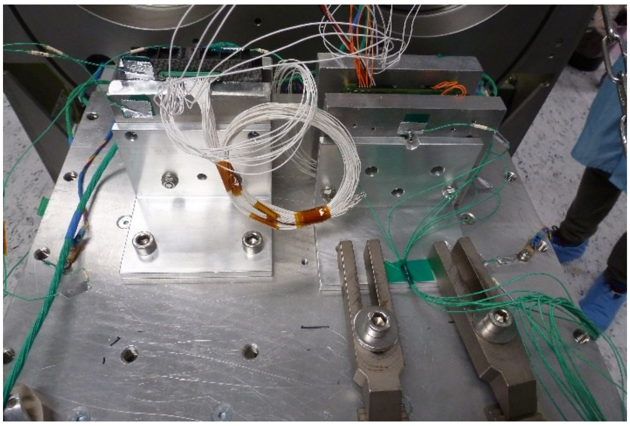

Figure 20. Test setup for the TVAC Test

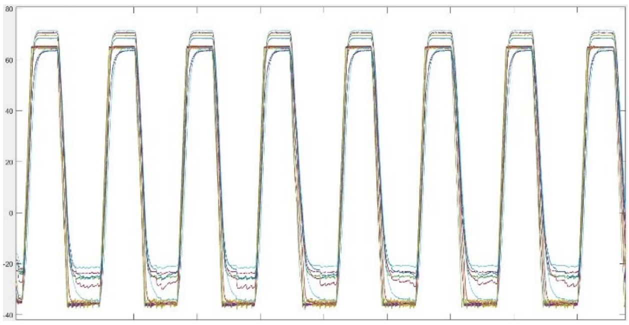

Figure 21. Temperature course of the operational test between 70 and -30 °C

8.3. Further Development

One adjustment that came up during the integration into SOURCE was the need for the insertions for atmospheric sensors integrated as a pass-through with the structure to be enlarged as a result of a change in sensor size. This modification will be implemented in the flight model, which will be the next iteration. Furthermore, the finalized software has to be implemented and functionally tested. Also, with the flight model, some scaled-back functions and vacuum testing to verify mission readiness and final qualification will be performed.

9. CONCLUSION

As the number of satellites in orbit increases drastically, new light-weight structures and novel design approaches are of critical importance. The project IRAS contributes to this by developing materials, structures, AM processes and tools that are viable for the future and help to reduce cost and production time in satellite manufacturing. The water propulsion system aims to provide an alternative to commonly-used hydrazine-based chemical thrusters, and the electric low-power thermal arcjet propulsion system utilizing AM low power thermal arcjets is investigated as an affordable and efficient de-orbit system.
Software Tools and the Digital Concurrent Engineering Platform DCEP have been connected to facilitate the design decision process.
Constant progress has been made within IRAS, increasing the maturity of some technologies or extending the knowledge and comprehension of materials and their processing behaviour.

Acknowledgements

This work is funded by the Baden-Württemberg Ministry of Economic Affairs, Labour and Tourism with the grant numbers 3-4332.62-DLR/49 (IRAS), 3-4332.62-DLR/56 (IRAS II), 3-4332.62-DLR/59 (IRAS III) and WM3-4332-157/68 (IRAS IV).

Contact:

tatjana.cziep@dlr.de

References

[1] T. Stäbler, M. Echsel, M. Ehresmann, M. Fugmann, D. Galla, N. Gottschalk, S. Hümbert, M. Lengowski, G. Marigo, I. Müller, I. Sakraker, J. Skalden, P. Springer, T. Stindl, S. Fasoulas, S. Klinkner and H. Voggenreiter, “Integrated Research Platform for Affordable Satellites,” in *70th International Astronautical Congress (IAC)*, Washington D.C., United States, 2019.

[2] T. Stäbler, K. Chen, T. Cziep, M. Echsel, M. Ehresmann, J. Fischer, L. Friedrich, M. Fugmann, D. Galla, N. Gottschalk, J. Hildebrandt, S. Hümbert, J. Skalden and T. Stindl, “IRAS - New technologies for low cost satellites,” in *72nd International Astronautical Congress*, Dubai, VAE, 2021.

[3] T. Cziep, T. Stindl and T. Stäbler, "The Digital Concurrent Engineering Platform DCEP," in *72nd International Astronautical Congress, IAC-21,D1,4A,5,x64131*, Dubai, UAE, 2021.

[4] T. Stindl, T. Cziep, M. Ehresmann, M. Fugmann, G. Herdrich and S. Klinkner, “Application of Automated Design Tools for Satellite Missions with the Design Platform DCEP,” in *Deutscher Luft- und Raumfahrtkongress (DLRK)*, Stuttgart, Deutschland, 2023.

[5] M. Fugmann and S. Klinkner, “An Automated Constellation Design & MIssion Analysis Tool for Finding the Cheapest Mission Architecture,” in *34th Annual Small Satellite Conference*, Logan, Utah, USA, 2020.

[6] M. Ehresmann and G. Herdrich, “Generic Spacecraft Design Prediction and Modelling,” in *72nd International Astronautical Congress (IAC)*, Dubai, VAE, 2021.

[7] M. Ehresmann, G. Herdrich and S. Fasoulas, “An automated system analysis and design tool for spacecrafts,” *CEAS Space Journal 14,* pp. 327-354, 2022.

[8] “GitHub Inc.,” [Online]. Available: https://github.com/aerospaceresearch/ESDC. [letzter Zugriff 08.09.2023].

[9] R. Kochendörfer, “Liquid Silicon Infiltration - A Fast and Low Cost CMC-Manufacturing Process,” in *8th Int. Conf. on Composite Materials (ICCM 8)*, Honolulu, Hawaii, 1991.

[10] M. Frieß, R. Renz and W. Krenkel, Graded Ceramic Matrix Composites by LSI-Processing, Vols. Advanced Inorganic Structural Fiber Composites IV Advances in Science and Technology, 40, R. S. Casciano, Ed., Forlì, Italien: Zini Graphis, 2003.

[11] S. Hümbert, I. Schmidt, F. Atzler and M. Lengowski, “Mechanical Characterisation of In-Situ Bonding between PEEK Filaments and Laminates in the FFF Process,” in *Proceedings of ECCM20*, Lausanne, Switzerland, 2022.

[12] D. Riley, I. Pontijas Fuentes, C. Parigini, J.-C. Meyer, P. Leyland, G. Hannema, E. Guzman, C. Kanesan and T. Lips, “'Design for Demise' Techniques to Reduce Re-entry Casualty Risk,” in *66th International Astronautical Congress (IAC)*, Jerusalem, Israel, 2015.

[13] M. Trisolini, H. Lewis and C. Colombo, “Spacecraft design optimisation for demise and survivability,” *Aerospace Science and Technology,* vol. 77, pp. 638-657, 2018.

[14] J. Patzwald, “Design-for-Demise Concepts with Additively Manufactured Satellite Parts,” in *MSc Thesis, RWTH Aachen and DLR Institute for Structures and Design*, 2021.

[15] J. Patzwald, I. Sakraker and S. Humbert, “Design-for-Demise Concepts Using Additively Manufactured CF-PEEK Patches and Inserts,” in *ESA Clean Space Industry Days*, Online, 2021.

[16] I. Sakraker Ozmen, S. Hümbert, S. Hadzic, M. Brodbeck and J. Patzwald, “Additive Manufacturing for D4D: Thermoplastic Demisable Joints for High Altitude Break-up,” in *2nd International Conference on Flight Vehicles, Aerothermodynamics and Re-entry Missions Engineering (FAR)*, Heilbronn, Germany, 2022.

[17] J. R. Wertz and W. J. Larson, Space Mission Analysis and Design, 3rd ed., Torrance, California, USA and Dordrecht, Netherlands: Microcosm Press

and Kluwer Academic Publishers, 1999.

[18] J. Skalden, G. Herdrich, M. Ehresmann and S. Fasoulas, "Development Progress of an Adaptable Deorbit System for Satellite Constellations," in *36th IEPC*, Vienna, Austria, 2019.

[19] J. Skalden, M. Ehresmann, G. Herdrich and S. Fasoulas, "Development of an AM Based Arcjet System for Deorbiting Constellation Satellites," in *37th IEPC*, Boston, Massachusetts, USA, 2021.

[20] B. Wollenhaupt, *Die Entwicklung Thermischer Lichtbogentriebwerksysteme,* Stuttgart, Germany: Ph.D. Dissertation, 2018.

[21] J. Skalden, M. Ehresmann, M. Schulz, Y. Han, A. Gustschin, Z. Kis and et al., "Neutron Imaging Investigation of AM Tungsten Nozzles for an Arcjet Deorbit System," in *ISTS 2023*, Kurume, Japan, 2023.

[22] D. Bock, *Untersuchung eines thermischen Lichtbogentriebwerksystems für die Lunar Mission BW1,* Stuttgart, Germany: Dissertation, 2009.

[23] E. Commission, "Making satellites safer: the search for new propellants," 30 03 2020. [Online]. Available: https://ec.europa.eu/research-and-innovation/en/horizon-magazine/making-satellites-safer-search-new-propellants. [Accessed 05 06 2023].

[24] D. e. a. Lev, "The Technological and Commercial Expansion of Electric Propulsion in the Past 24 Years," *35th IEPC, Atlanta, USA,* 2017.

[25] T. Löffler, J. Burgdorf, J. Hildebrandt, L. Bötsch-Zavřel, C. Holeczek, S. Pätschke, M. Kanzow, P. Largent, J. Petri, M. Lengowski and S. Klinkner, "Preliminary Design of the Radiation Protection of the ROMEO Satellite in the lower Medium Earth Orbit," in *IAC*, Paris, France, 2022.

[26] A. Vikas, J. Hildebrandt and S. Fasoulas, "Satellite Water Propulsion: Electrolyzer Development and Failure Mode Analysis," in *EUCASS*, Lausanne, Switzerland, 2023.

[27] J. Hildebrandt, J. Kaufmann, S. Fasoulas and G. Herdrich, "Development of Novel 3D Printed Ceramic Thruster and Surface Tension Tank for Water Electrolysis Propulsion System," in *Space Propulsion Conference*, Estoril, Portugal, 2022.

[28] J. Hildebrandt, A. Vikas, T. Löffler, S. Fasoulas, G. Herdrich and S. Klinkner, "Satellite Water Propulsion: Satellite Water Propulsion: 3D Printed Ceramic Thruster & Space Debris Mitigation Concept," in *EUCASS*, Lausanne, Switzerland, 2023.

[29] J. Skalden, M. Ehresmann, G. Herdrich and S. Fasoulas, "Development of an AM Based Arcjet Sytem for Deorbiting Constellation Satellites," in *IEPC*, Cambridge, Massachusetts, USA, 2022.