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AMoCSiS: A Flexible Approach for Building Large and Stiff Structures in Space

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Abstract

The AMoCSiS-Approach (Automated Manufacturing of Composite Structures in Space) is a technology experiment in on-orbit manufacturing conducted by the German Aerospace Center (DLR). Distinguished from prevailing methodologies reliant solely on 3D printing technologies, AMoCSiS leverages the synergistic potential of two primary components: carbon fiber reinforced plastic (CFRP) tubes and additive manufactured thermoplastic nodes. This distinctive approach makes use of the inherent strengths of CFRP's specific stiffness and the flexibility offered by additive manufacturing processes, establishing AMoCSiS as a standout in the field of on-orbit manufacturing technologies. The core of the AMoCSiS approach lies in the integration of manufacturing processes for both tubes and nodes within its framework, utilizing densely packed, premanufactured materials. The continuous CFRP tube manufacturing process consists of a series of units designed to autonomously load a coil of material and automatically unroll, cut, and form it into tubular a shape. Subsequent to this, a joining unit applies heat and pressure to melt and distribute a thin strip of thermoplastic along the overlapping region of the formed tube, resulting in the creation of closed tubes with selectable lengths. This innovative process not only ensures the integrity of the structures but also allows for replenishment, thereby extending their lifespan and enabling the construction of larger, more intricate structures. Nodes, fabricated from established thermoplastics such as PEEK or PEI via additive manufacturing, serve as components connecting tubes to form truss structures. Robotic arms are employed in the assembly of these structures, facilitating precise bonding between tubes and additive manufactured nodes through a mechanical snap mechanism. The inherent flexibility of the AMoCSiS approach enables the development of truss structures with diverse dimensions and physical properties, even post-deployment. This adaptability, coupled with its wide-ranging applicability, particularly in the construction of large and robust structures, underlines the transformative potential of AMoCSiS in space engineering endeavours. Moreover, considerations for scalability envision its integration as a submodule for future missions, further amplifying its utility and relevance in the context of evolving space exploration initiatives. This paper provides an in-depth exploration of the AMoCSiS-Approach, clarifying its operational intricacies. It delves into the creation of a Technology Readiness Level 4 demonstrator for tube manufacturing, offering detailed explanations of each unit's function. Furthermore, it discusses the field of applications, highlighting its potential in comparison to established rigid and deployable structure technologies.
Keywords: On-Orbit Manufacturing, Composite, Additive Manufacturing, Structure, Manufacturing, Demonstrator

1. Introduction

As space exploration advances, the demand for larger and more complex structures continues to grow. However, spacecraft and space infrastructure are still constrained by the size and payload capacities of current launch vehicles. Traditional solutions, such as fully assembled or deployable structures, face significant limitations in scalability. Deployable structures, while useful for overcoming size constraints during launch, require extensive testing to ensure they can survive the harsh conditions of launch, including extreme vibrations and mechanical stresses. This testing process increases complexity, adds weight due to deployment mechanisms, and limits the overall size of these structures.

In contrast, In-Space Manufacturing (ISM) offers a transformative solution by enabling the construction of large structures directly in orbit. Structures built in space do not need to withstand the intense forces of launch, allowing for more efficient designs that are optimized for the space environment rather than launch conditions. This eliminates the need for heavy reinforcement or complex deployment mechanisms, reducing both mass and cost. ISM also offers flexibility in design, enabling the construction of much larger, lighter, and stiffer structures that can meet the growing demands of space exploration.

While ISM is still in its early stages, its potential to change space infrastructure. By removing the constraints imposed by launch vehicles, ISM can significantly expand mission capabilities and provide a stepping stone for more ambitious projects, such as large space habitats, advanced satellite systems, and space-based solar power arrays.

2. The AMoCSiS Concept

AMoCSiS (Automated Manufacturing of Composite Structures in Space) is a technology experiment conducted by the German Aerospace Center (DLR). Its primary objective is to enable the in-space manufacturing of composite truss structures. The fundamental structures that AMoCSiS builds are composed of CFRP (Carbon Fiber Reinforced Polymer) tubes and additive manufacturing (AM) joints, both made from compact, readily storable materials. The system utilizes robotic actuators outside the satellite.

AMoCSiS aims to provide a flexible, scalable, and autonomous solution for the construction of large, stiff structures in orbit, overcoming the constraints imposed by traditional launch methods.

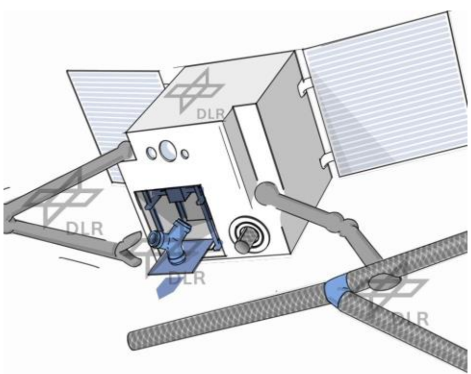

Fig. 1. Simplified Representation of AMoCSiS[1]

AMoCSiS was developed as a response to the growing need for more adaptable and sustainable space infrastructure. By leveraging the principles of ISM, AMoCSiS focuses on building composite truss structures entirely in space, using lightweight materials that can be stored efficiently and assembled autonomously. The system utilizes robotic arms to fabricate and assemble structures using carbon fiber reinforced plastic (CFRP) tubes and additive-manufactured thermoplastic nodes. This approach eliminates the need for pre-built or deployable structures, offering significant advantages in terms of cost, mass efficiency, and scalability.

2.1 Advantages of AMoCSiS

AMoCSiS presents several key advantages over traditional and deployable space structures:

Scalability: AMoCSiS can create large and complex structures in space without being limited by the size constraints of launch vehicles. This flexibility allows for the construction of vast truss systems, antennas, or support frameworks that can be expanded based on mission needs.

Material Efficiency: By using composite materials like CFRP, AMoCSiS reduces the overall mass of the structure, which is crucial for minimizing launch costs. By utilizing the properties of CFRP and 3D-printing These materials are lightweight, durable, and can be efficiently transported in dense reels, taking up minimal space during launch.

Autonomy: The system is designed for fully autonomous operation in space, utilizing robotic arms to manufacture and assemble structures. This reduces the need for human intervention and enables long-term operation in orbit.

Flexibility: AMoCSiS's ability to utilize a wide range of Halbzeuge (semi-finished products) enables the production of structures long after its launch. This capability allows for the development and customization of structures even in deep space, with new designs or modifications being sent from Earth as needed.

Stiffness: Unlike other in-space manufacturing approaches that rely solely on 3D printing, AMoCSiS benefits from a combination of 3D-printed nodes and CFRP tubes. The rigid, lightweight CFRP tubes, which make up the bulk of the structure, work in tandem with the strong, precisely manufactured nodes to create large, stiff, and lightweight structures.

Production Speed: While 3D printing large structures in space can be time-consuming, AMoCSiS enhances production efficiency by concurrently manufacturing CFRP tubes and 3D-printed nodes. This streamlined process allows for faster assembly and deployment of structures.Flexibility:

2.2 Structures built by AMoCSiS

AMoCSiS consists of two main structural components that are key to its innovative approach: the AMoCSiS-Node and the AMoCSiS-Tubes.

2.2.1 The AMoCSiS-Node

The AMoCSiS-Node (Fig. 2 as an example) is a critical component that connects the CFRP tubes to form truss structures. These nodes are manufactured using additive manufacturing (3D printing) in space. The materials typically used for the nodes are proven thermoplastics such as Polyether Ether Ketone (PEEK) or Polyetherimide (PEI), chosen for their high strength, durability, and resistance to extreme space environments, including vacuum and radiation.

Additive manufacturing allows the nodes to be customized for the specific requirements of each structure, making the design flexible and adaptable to various mission needs. Their design can also incorporate convenient mounting points for equipment, further enhancing the versatility of the structures built by AMoCSiS. To connect the nodes with the tubes, a simple snap mechanism (see. Fig. 3) is used to avoid adhesives and the associated requirements.

Fig. 2. Example Node for the construction of a tetraeder

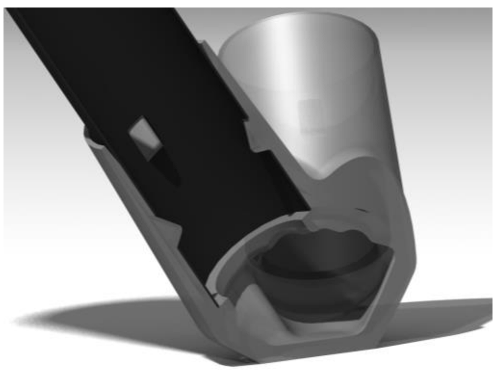

Fig. 3. The example Node with its inner geometry

2.2.2 The AMoCSiS-tube

The AMoCSiS-Tubes form the primary load-bearing elements of the structure and are made from carbon fiber reinforced plastic (CFRP). These tubes are produced using a novel process that transforms flat strips of CFRP material into cylindrical tubes directly in space. The CFRP is chosen due to its high strength-to-weight ratio, corrosion resistance, and thermal stability, making it an ideal material for space applications.

The tube-forming process (simplified in Fig. 4) involves elastically rolling the flat CFRP strips into a tubular shape and bonding the edges using thermoplastic welding. This method allows the tubes to be efficiently stored on spools and deployed as needed, making them highly space-efficient during launch. The tubes are lightweight yet exceptionally stiff, contributing to the overall structural integrity of the truss systems constructed in orbit.

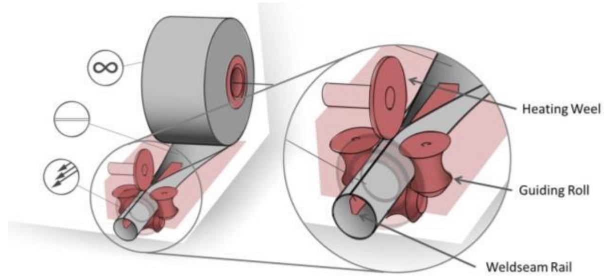

Fig. 4. Simplified Representation of the Tube production process[1]

3. Demonstrator for the Tube Production Unit

This chapter describes the demonstrator for the AMoCSiS CFRP-Tube Production Line. It highlights the implementation strategies integral to achieving the high degree of automation required. The demonstrator is designed to produce CFRP tubes through thermoplastic welding from precured CFRP strips, emphasizing the need for efficient, autonomous operation in space.

3.1 Requirements

The following requirements outline the essential functionalities and constraints for the demonstrator, distinguishing between general operational needs and those specific to space applications.

3.1.1 The basic requirements

- Produce tubes via thermoplastic welding from precured CFRP strips.
- Handle and store flat CFRP material.
- Autonomous material loading and feeding.
- Precision cutting of CFRP material into predefined lengths.

3.1.2 Space-specific requirements

- Be able to operate under zero-G conditions.
- Be compact and lightweight.
- Be designed with materials that can withstand the harsh conditions of space.
- Should be able to operate autonomously without human intervention
- Precision cutting of CFRP material into predefined lengths.
- Be as energy efficient as possible.
- Have an effective heat management

3.2 The Basic Design

Given the experimental nature of the project and the need for significant adaptability, the design is tailored to meet the specific requirements for space application. Although it may not initially satisfy all criteria fully, future iterations will aim to better align with these requirements and improve overall compatibility.

To support this adaptability, the demonstrator's components are mounted on two aluminium profile. This approach allows for flexible adjustment and reconfiguration of the units to meet specific needs while maintaining stability.

Most of the demonstrator's parts are produced using additive manufacturing techniques, primarily with PLA and PETG. These materials provide a suitable balance of strength, durability, and ease of fabrication, making them appropriate for the functional components at this stage of development.

The selected tube has a diameter of 28mm, and the material width was set to 105mm, providing an overlap of approximately 17mm to ensure sufficient bonding area. These specifications are chosen to achieve effective handling and easy observation, while keeping the required volume minimal.

The demonstrator is composed of several key units:

- Storage Unit
- Cutting Unit
- Conveyor Unit
- Joining Unit
- Electronics

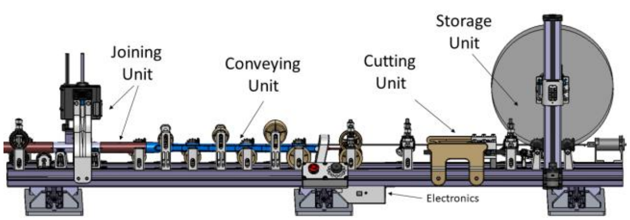

Fig. 5. Schematic of the AMoCSiS Tube Production Unit

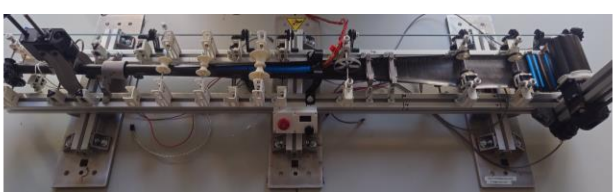

Fig. 6. The tested demonstrator of the AMoCSiS Tube Production Unit

3.2

3.3 The Storage Unit

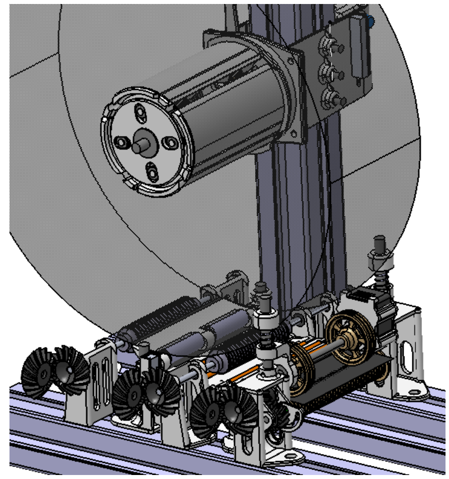

Fig. 7. A representation of the Storage Unit

The storage unit (See Fig. 7 and Fig. 8) is a crucial component responsible for efficiently storing and dispensing the composite material during the manufacturing process. Designed to support autonomous operation, it can load, unload, and continuously feed the CFRP material to the succeeding units, ensuring a smooth and uninterrupted manufacturing flow. The unrolling speed of the storage unit is synchronized with the processing speed of the downstream units, maintaining consistent material handling throughout.

To regulate material tension and prevent unwanted backrolling, the spool is equipped with a pawl and ratchet mechanism. This ensures that the CFRP material unrolls smoothly without obstruction, maintaining the correct tension for efficient feeding into the following manufacturing steps.

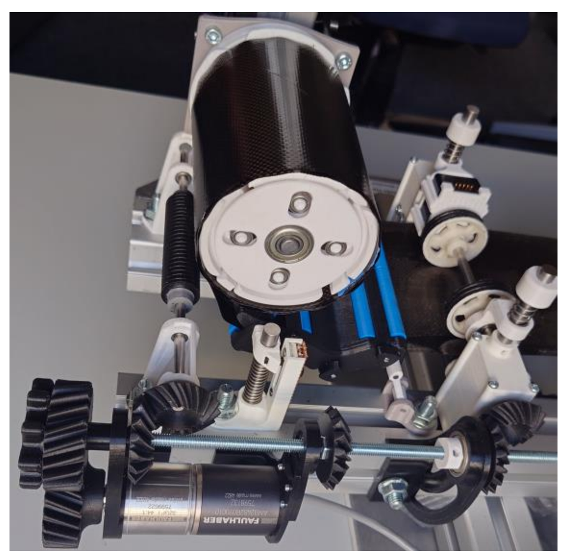

Fig. 8. The tested Storage Unit

For loading and unloading new reels, the spool's diameter can be reduced, allowing new material to be easily mounted. The design of the material spools eliminates the need for supporting cores or additional structural materials, simplifying the loading process and preventing the buildup of excess material within the AMoCSiS system. To ensure the efficient transfer of CFRP to the next units, the spool storing the material in the storage unit can be moved vertically for safe unloading. The material is unrolled by applying a defined pressure onto the conveying rolls, ensuring controlled feeding. In this position, a material guide is pressed onto the material to direct it toward the succeeding production steps (see Fig. 9). The remaining material on the spool can be monitored using a spring-loaded slider to which the material guide is attached, allowing real-time tracking of the material's status.

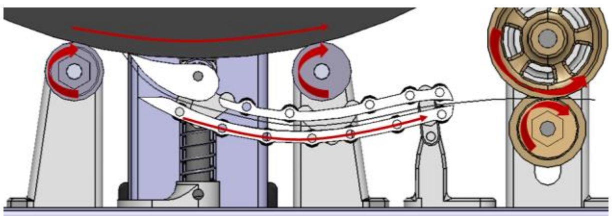

Fig. 9. Material unroll and guidance system of the Storage Unit

Once a spool is depleted, the storage unit returns to a homing position, allowing for the automated loading of new material (see Fig. 10). This ensures the continuous production of tubes without the need for manual intervention, supporting the autonomous objectives of the overall manufacturing system.

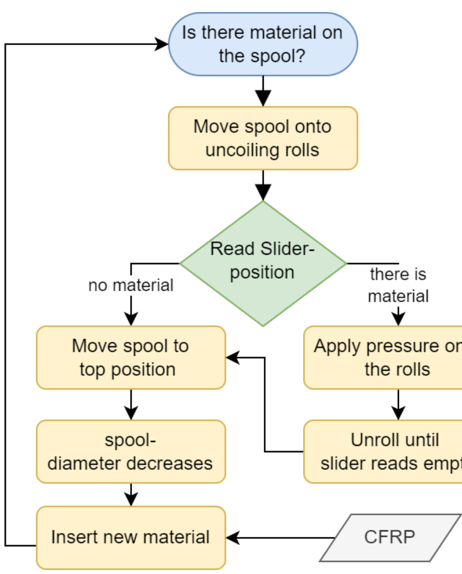

Fig. 10. Flow Diagram of the storage Unit

3.3 Cutting Unit

The cutting unit (see Fig. 11) is designed to precisely cut the CFRP material without interrupting the continuous manufacturing process.

The cutting mechanism is based on a simple and effective design. A blade is positioned on a cutting carriage that moves in synchronization with the material flow. The blade is attached to a guide system, with supports positioned on either side of the unit. When cutting is required, the blade is lifted and aligned to a specific position on the guide. As the carriage follows the movement of the material, the blade gradually lowers and makes the cut without disrupting the overall material feed.

Once the blade reaches the end of the guide and the cut is completed, the cutting carriage moves back to its starting position, resetting for the next operation. During the return movement, the blade remains in a lifted position to avoid unnecessary contact with the material.

This simple system ensures precise cuts without compromising the continuity of the manufacturing process, contributing to both the reliability and autonomy of the overall production system.

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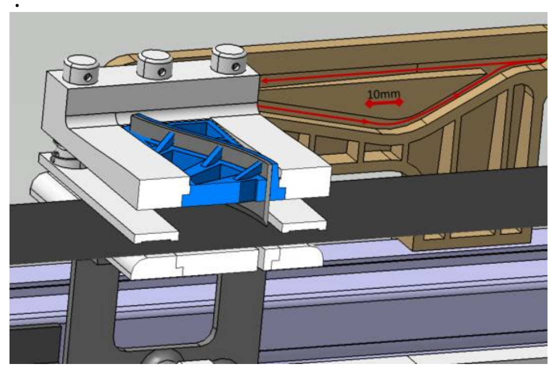

Fig. 11. A CAD Representation of the cutting unit and its guide

3.5 Conveying Unit

The conveying unit conveys the carbon CFRP material as it undergoes transformation into its tubular shape. Throughout this process, the material adopts an unique curvature (see Fig. 12), necessitating a highly flexible system to handle the complex transformation. The experimental nature of this demonstrator demands that the stages for forming and conveying be continuously adjustable, ensuring they can move along the profile to accommodate the material's evolving shape.

Fig. 12. Side profile of the calculated transformation curvature of the CFRP material

Key to this flexibility is the ability to adjust the height of the rolls at various stages. These rolls are designed to align with the unique curvature of the CFRP as it transitions into its tubular form, offering support while minimizing friction.

To further protect the material during processing, a forming tube is integrated into the conveying system. This tube ensures the CFRP maintains its structural integrity, preventing it from being crushed as it enters the joining unit.

Both the conveying unit and storage unit are driven by a single adjustable drive rod, ensuring that the entire system operates at the same speed. This eliminates the need for additional synchronization mechanisms between different units, ensuring consistent speed and tension across all stages of transformation.

In the integration of "Top Rolls" providing guidance from the upper side and "Pressing Rolls" (as shown with Fig. 13) to provide the necessary traction for conveyance has been proven to be essential. The Top Rolls ensure the formation of the tubular shape and for the overlap to form on the required side to ensure bonding.

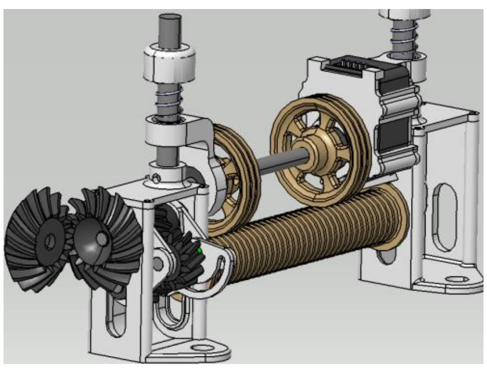

Fig. 13. A CAD representation of a conveying stage with rolls pressing onto the material to provide friction and conveyance speed measurements

3.6 Joining Unit

The joining unit ensures the bonding of the overlapping sections of the CFRP material once it is formed into a tubular shape. It can be broadly divided into two essential parts, the pressure and heat application unit and the forming tube.

3.6.1 Pressure and Heat Application

In the upper section of the joining unit (see Fig. 14), pressure and heat are applied simultaneously to bond the overlapping sections of the CFRP material. The heating element is positioned directly above a corresponding heat sink inside the forming tube to precisely target the bonding area, while the lift mechanism ensures continuous contact for consistent pressure application. The heating element raises the temperature of the thermoplastic, softening the material for bonding, while the pressure applicator evenly distributes the material in the overlap, ensuring a strong and uniform joint. In emergency situations the heating element can be lifted from the forming tube to avoid overheating and therefore damaging the material

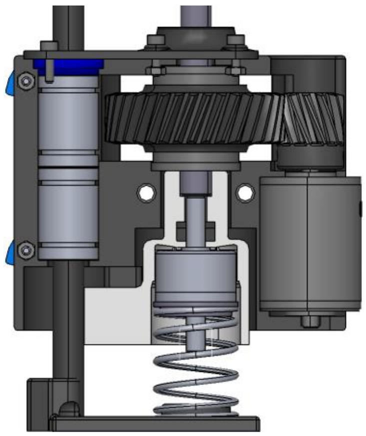

Fig. 14. Crosssection of the Pressure Unit, showing the rod guided by linear bearings (left) and a load cell connected to a trapezoidal rod (middle) being turned by the stepper motor (right).

3.6.2 Forming Tube and Heat Dissipation

The forming tube itself is critical in maintaining the structural integrity of the CFRP during the joining process. Meant to act as a heat sink to both concentrate and dissipate the heat from the above positioned heating as part of a prototype version of a heat dissipation system (as shown with Fig. 15). Due to the required flexibility, a thick 4 AWG cable of copper serves as a preliminary heat pipe replacement to maintain the flexibility.

Multiple thermal sensors (DS18B20) are strategically placed along the tube to monitor the distribution of heat conducted within the material and to assess the effectiveness of heat dissipation measures. These sensors provide data on how heat spreads in the tube, enabling evaluation and adjustment of the thermal management system.

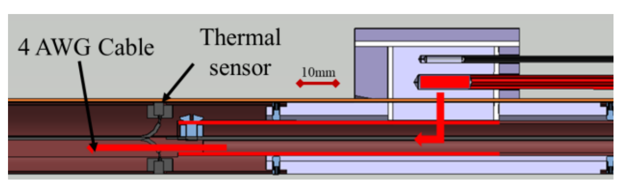

Fig. 15. Cross-Section of the Heating Unit and the Heating tube with

3.7 Electronics and Programming

The electronics and programming for the demonstrator are centered around exact control of heating and motor movements, essential for the accurate production of CFRP tubes. As a preliminary solution for demonstrater, the EinsyRambo[2] control board from Ultimachine was selected, leveraging its compatibility with the Arduino ecosystem and the ATMEGA 2560 microcontroller. This setup allows for robust integration and customization of the demonstrator's functions. Control and monitoring are facilitated through a Python Dash interface, enabling real-time access via a web browser on multiple devices, including smartphones. This interface not only enhances user control and monitoring capabilities but also provides a platform for integrating features such as quality control, optimization algorithms and autonomous readjustments to changing conditions. Additionally, the built-in OLED screen on the control board offers basic, on-site monitoring and process management (see Fig. 16).

Fig. 16. Builtin OLED Screen providing basic monitoring and control

4. Testing

The performance and functionality of the demonstrator have been evaluated through a series of tests designed to verify key aspects of the manufacturing system. These conducted tests focused on material forming, heating, pressure control, and material conveyance to ensure operation and different units.

4.1 Fit Check

The Fit Check was conducted to assess the material forming process. The objective was to verify that the CFRP material can be shaped and aligned correctly during the forming stage. The test ensured that the CFRP maintained the desired curvature as it passed through the forming and conveying stages, establishing a baseline for further testing of material integrity and shape retention (see Fig. 17).


Fig. 17. Fit-Check to prove tubes can be formed with the production demonstrator

4.2 Heat Check

The Heat Check involved a standalone assessment of the heating control system. This test was divided into two stages:

<u>Slow controlled heating and cool down:</u> The heating system was tested with a gradual increase in temperature (as shown in Fig. 18), followed by a controlled cool-down phase, to ensure precise temperature control without exceeding safe thresholds.

<u>Modified fast heating:</u> A fast heating approach was tested with steep temperature gradients, idling temperature, and adjusted heating rates to simulate dynamic conditions.

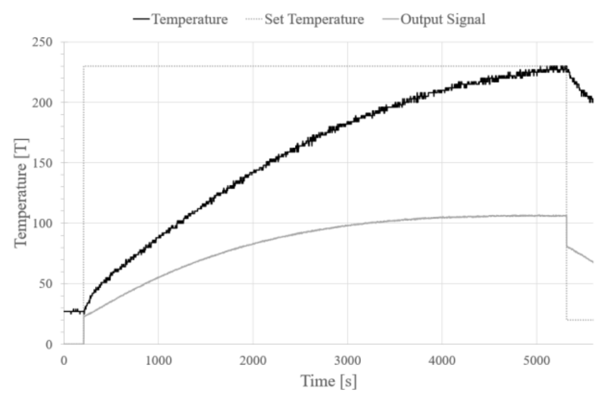

Fig. 18. Temperature readings of the slow controlled heating and cool down test

4.3 Pressure Check

The Pressure Test focused on validating the pressure application system and the calibration of the load cell. This test ensured the unit could move and apply pressure in a controlled manner:

- <u>Load cell calibration:</u> The load cell was tested and calibrated to accurately measure and control the pressure applied during the material bonding process.
- <u>Controlled movement:</u> The pressure unit was tested to ensure it could move precisely and apply a predefined pressure, confirming its ability to handle variable loads and adjust based on material thickness and bonding requirements.

4.4 Conveyance Check

The Conveyance Check involved testing the motorized conveyance system to ensure smooth material movement throughout the entire process. The CFRP material was conveyed with all components fully mounted, verifying the system's ability to transport material effectively across different stages.

Roll modification: The rolls were modified to further optimize the material formation process. Adjustments were made to reduce the formation length to the minimum required, improving the efficiency and precision of the conveying system.

Conveying speed: As part of the test, multiple conveying speeds were evaluated to determine the optimal speed for material transport. After testing various rates, the optimal speed was identified, balancing efficiency and material integrity.

5. Conclusions and Outlook

This study highlights the potential of in-space manufacturing (ISM) and the advantages that the AMoCSiS system offers within this field. Notable advancements have been made in the development of CFRP tube manufacturing, laying the groundwork for constructing large-scale structures in space. However, there are still several challenges to address and more testing to be done.

In summary, the AMoCSiS approach shows promise as a foundational technology for future ISM initiatives. It provides a flexible and scalable solution for constructing robust structures in space. Collaborative efforts with other ISM providers could further enhance this potential by integrating different technologies and methodologies, accelerating the development of comprehensive and scalable space infrastructures.

5.1 Outlook

The future development of the AMoCSiS system will focus on three primary areas: further development and testing, functionality expansion, and ensuring compliance with space-specific requirements.

5.1.1 Development and Testing

Future work will concentrate on refining the demonstrator's performance under various conditions, with a particular emphasis on testing and optimizing the joining process. Iterative testing and optimization of joining parameters—such as heat and pressure—will be conducted to ensure reliable bonding between materials, particularly in the challenging conditions of space. This will include extensive testing in Thermal Vacuum (TVAC) chambers to simulate the harsh environment of space, including extreme temperature fluctuations and vacuum conditions. Such tests are crucial for evaluating the mechanical properties, stability, and durability of the joined structures, ensuring that they maintain their integrity and performance over extended periods.

Further software enhancements will be made to improve the user interface, enable autonomous production, and increase system reliability.

The scalability of the manufacturing process will be explored to support the production of larger diameter tubes, while further investigating the forming length required for tube production. Mitigation could for example be achieved by using multiple material reels or by exploring alternative fibers and materials which are not as stiff such as GFRP.

5.1.2 Functionality Expansion

Expanding the system's capabilities involves integrating continuous quality control measures to ensure the quality necessary to maintain the structural integrity of manufactured structures. This could include techniques such as line cameras to detect defects and ensure proper bonding or using X-ray with opaque thermoplastics[3] on samples to monitor the distribution and bonding.

Adaptive parameter adjustments using machine learning will enable the system to adapt to varying environmental conditions, enhancing production stability and efficiency.

Automated generation of truss structures and nodes will optimize resource utilization and enable the creation of custom designs tailored to specific mission requirements. Exploring the use of materials beyond CFRP could expand the system's versatility, accommodating a broader range of applications. Research into self-healing CFRP materials is also underway, with the potential to significantly enhance the longevity and resilience of space structures, reducing the need for repairs and maintenance.

5.1.3 Space Compliance

To prepare the system for space deployment, optimizations will focus on minimizing dimensions and weight, using space-proven materials and electronics, and incorporating redundancies for increased reliability. A launch-lock system will be developed to secure moving parts during launch and mitigate vibration risks.

Acknowledgements

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