CTM BOOM DEPLOYMENT MECHANISM WITH INTEGRATED BOOM ROOT DEPLOYMENT FOR INCREASED STIFFNESS OF THE BOOM-TO-SPACECRAFT INTERFACE

Marco Straubel(1), Christian Hühne(2)

(1) Composite Design Department, DLR Institute of Composite Structures and Adaptive Systems, Braunschweig, Germany, marco.straubel@dlr.de

(2) Composite Design Department, DLR Institute of Composite Structures and Adaptive Systems, Braunschweig, Germany, christian.huehne@dlr.de

KEYWORDS

deployable, mechanisms, space, composites, solar sails, solar arrays, drag sails, instrument booms

ABSTRACT

CTMs (Collapsible Tube Masts) are well known for small and medium sized solar sails as they can create huge and stiff sail backbone structures out of a very small mass. But one key issue with those masts is the need for a full deployment of the booms cross section in order to generate the full stiffness. Close to the deployment mechanism the stiffness is significantly decreased. Usual mechanisms try to counteract this drawback by guiding rollers or surfaces that support the boom in this weak transition zone.

The underlying paper will present a different approach: The boom spool of the novel deployment mechanism contains a simple but reliable mechanism that is triggered at the end of the longitudinal deployment. This inner mechanism deploys the booms cross section and locks the boom spool into the outer walls of the surrounding structure. The result is a boom deployment mechanism that supports the utilization of the full potential of the CTMs.

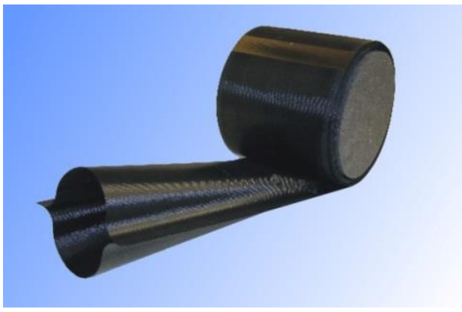

Figure 1 DLR's coilable carbon composite mast during coiling/uncoiling

1. INTRODUCTION

The DLR Institute of Composite Structures and Adaptive Systems is investigating deployable space structures as well as deployment strategies for about two decades. Although different applications like Solar Sails [1, 2, 6, 7], Solar Arrays [3], Drag Sails [4] and Radar Antennas [5] have been investigated, the load carrying backbone structures were always made from coilable CFRP booms of CTM type (see Figure 1).

With the experience of those projects it became clear that from an overall system perspective, a promising candidate for further volume, mass and cost reduction of the current concepts is in the advancement of the interface stiffness and strength between booms and spacecraft. An increase in performance of the interface will allow the usage of booms of smaller cross section and, therefore, smaller and lighter deployment mechanisms.

The following sections will illustrate this claim.

1.1. Transition Length

For a deploying and a deployed boom there is always a specific transition length required to allow the boom to fully evolve its cross section from the stowed to the deployed configuration (see Figure 1). Depending on laminate setup and cross section geometry, this length is ranging from 0.5 to 1.0m. As the deployment mechanisms are not large enough to cover the entire transition length, the booms usually enter/leave the mechanism at a spot, where the transition is not completed, the cross section is not fully evolved and, consequently, the load bearing capacity of this boom section is reduced.

As the majority of booms are deployed from a mechanism that is attached to the spacecraft, this week spot is always at the location which also needs to carry the highest bending moment in case of a tip force with a significant lateral component. This effect is visualized in a purely qualitative manner in Figure 2 and an image of a failing boom under test

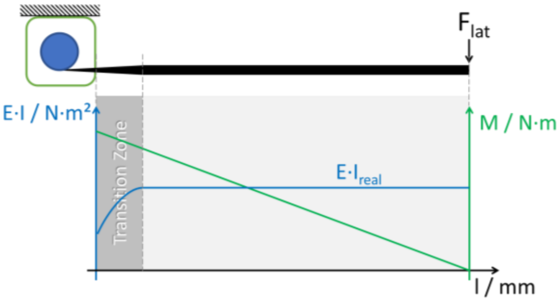

*Figure 2 Generic, qualitative bending moment M and bending stiffness E*I characteristic of a boom under lateral tip load F_{lat} with marked transition zone (light grey).*

Figure 3 Boom failing at the spot it leaves the GOSSAMER-1 deployment mechanism during sail tensioning limit load tests.

in Figure 3. The part of the free transition length (the part outside of the green framed deployer) is marked with a light grey area. While the bending moment decreases constantly over length, the real bending stiffness E^*I_{real} increases in a non-linear manner up until the transition zone has been left and remains constant for the remaining boom length.

1.2. Resulting Boom Oversizing

While the local weakening of the boom in the transition zone seems obvious, the impact on the sizing process is severe. When optimizing the booms cross section and laminate setup to fit the load requirement, the nominal booms needs to be oversized – along its full length – to be able to carry the maximum loads only in a small highly loaded spot with locally reduced bending stiffness. As consequences, the boom deployment mechanism will be larger and heavier than required for an ideal boom with a constant bending stiffness.

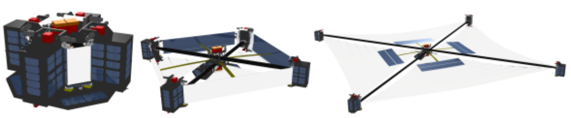

Figure 4 GOSSAMER-1 solar sail in stowed, deploying and deployed configuration (Source: DLR)

1.3. Mitigation Concepts

To counteract the mechanical performance reduction at the highly loaded region close to the space craft, there are three main strategies:

1. Reverse the deployment logic and deploy the booms from its tip
2. Advance the external support of the boom in the weak transition zone by either a longer support length or a more effective support technique.
3. Allow the boom to develop its full cross-section at the root by a dedicated mechanism.

The first approach was used for DLR's GOSSAMER Solar Sail deployment concept (see Figure 4) and was successfully increasing the interface stiffness and strength between spacecraft and boom. However, due to the sail deployment approach of GOSSAMER the sail deployment forces acting on the combined boom and sail deployment mechanism at the boom tip were not in-plane with the boom-cross plane. Consequently, the sail deployment forces and the offset from the boom plane result in a torque acting on the deployment mechanism at the tip that could again result in a collapsing boom (see Figure 3).

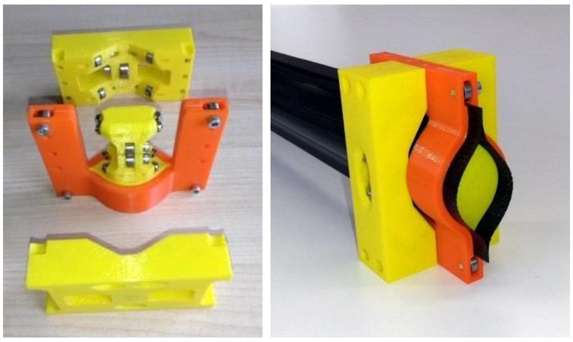

Figure 5 DLR's Floating Core concept with outer guide shells (orange), an inner floating core (inner yellow part) and the core interface frame (larger yellow parts) [8]

The second approach has been successfully pursued by Hillebrandt et al. by a adding a special installation to the spot where the boom leaves the deployment mechanisms. As for the most previous DLR concepts, this development supports the deploying boom at its transition zone from the outside by specially shaped guide shells that mimic the boom natural shape in this zone. In addition, this so-called *Floating Core* concept features an inner core that supports the boom shells from the inside as well. The boom shells can pass the installation only through a very thin boom-shaped gap that doesn't allow the boom shells to buckle. The inner core is kept in place by a patented arrangement of interlocking ball bearing rollers at the outer frame and the core. This setup could be also used to force the boom to open up “earlier” so that the transition zone can be shortened. Hillebrandt et al. also reported on performed non-destructive and destructive bending tests with and without this feature and could proof significantly increased values of bending stiffness (+23%) and of bending strength (+90%)[8].

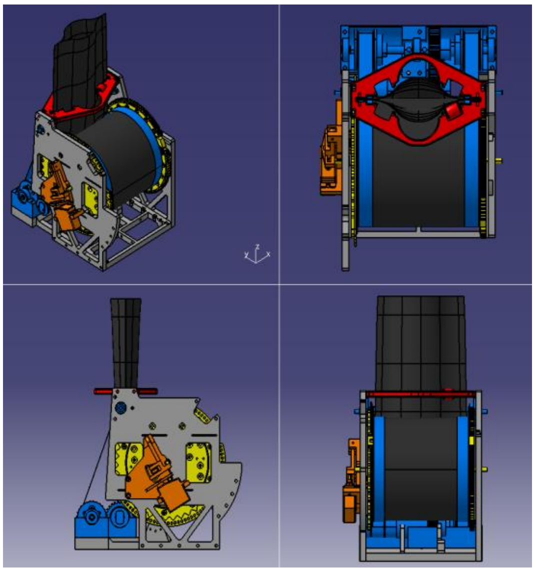

Figure 6 Novel boom deployment mechanism fulfilling all given requirements (Source: DLR)

The third approach is chosen for the here presented development in order to push the bending stiffness and strength to their theoretical maximum values. Such a root deployment of the boom cross section could only be done after the longitudinal deployment has been entirely finished. During deployment, the bending stiffness and strength are reduced significantly. So, this concept is only applicable to deployable structures that require no significant loads on the deploying booms. As the boom cross section undergoes a rapid and significant deformation during the root deployment, a combination with the promising floating core concepts seems unrealistic at this point.

1.4. Resulting Requirements

The following requirements were set for the here presented development. The mechanism shall be able to:

R1. Deploy up to two booms with 180° offset out of the same mechanism.
R2. Perform a sub-deployment of the boom root once the boom is deployed to its full length
R3. Assure, that this deployed boom root is connected to the main structure of the deployment mechanism in a stiff manner
R4. Provide a basic guidance of the boom during deployment (limited load carrying capacity during deployment)
R5. Provide sensor data to confirm completion of all relevant deployment processes
R6. Perform its boom root deployment and latching without any actively driven mechanism in the spool that needs to be powered from outside the spool (try to avoid the use of commutators or slip rings etc.)

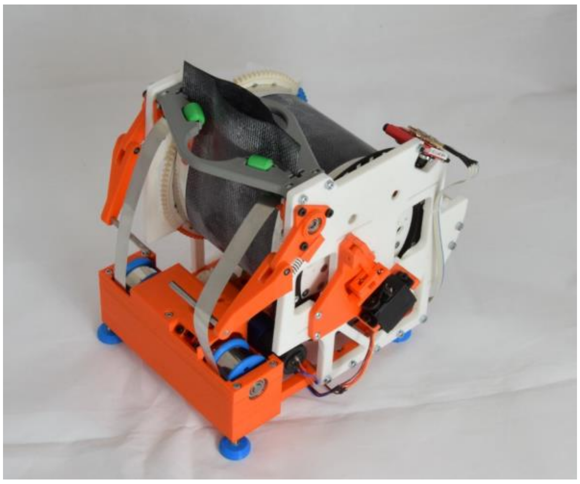

Figure 7 First proof-of-concept prototype

R7. Support easy integration and refurbishment of the mechanism

2. CONCEPT INTRODUCTION

A CAD model of the first resulting prototype mechanism is shown in Figure 6 and an image of the mostly 3D printed hardware in Figure 7. The following subsection will orient along the requirements specified in section 1.4 and will show and explain how this mechanism fits the given requirements.

2.1. Boom Longitudinal Deployment

The longitudinal deployment of the boom is driven with a so far matured concept that hasn't changed much since GOSSAMER-1 (see Figure 8 and [1]).

The deployment is controlled by a well-tuned interaction of a boom spool brake and a metallic tape. The belt is rolled up together with the mast and rests on its outer side. Together with the brake the tape suppresses the inherent tendency of the mast to unfold itself. It presses the mast against the braked boom spool and allows the deployment process to be controlled to the millimetre via its own electrically controlled drive unit.

For the current development, initially, we made use of the same concept but increase the number of co-coiled tapes from one to two. This was done to prevent disturbance of the boom cross-sectional

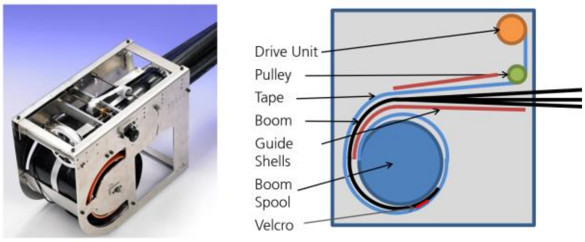

Figure 8 GOSSAMER-1 boom deployment mechanism breadboard (left) and boom deployment drive components (right)

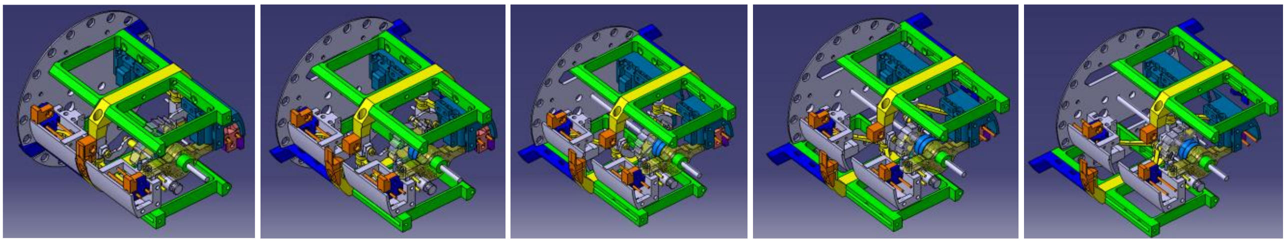

Figure 10 Root deployment mechanism in stowed (left), deploying (three middle images) and deployed (right).

development by the tape. The two tapes are visible as two blue vertical stripes at the left and right end of the boom spool on the two right sub-figures in Figure 6. The drive unit is also visible in the lower left and upper right sub-figure (also in blue).

The pulleys used for the redirection of the tapes is located close the guide ring (red in Figure 6) in order to allow the tape to guide the boom until this ring to further support it in this vital transition zone.

While this boom-deployment-by-tape-retraction concept gives a good controllability of the deployment, it is not sufficient to stop the deployment at a very accurate point. The value of interest here is not the exact deployed boom length but the relative angle between the outer mechanisms body and the boom spool. Both need to be perfectly aligned in order to support the boom spool latching although the boom cross section deployment is a rapid process that results in a shock and that happens in parallel to the boom spool latching. So, the boom spool needs to stay in its position while this shock is impacting.

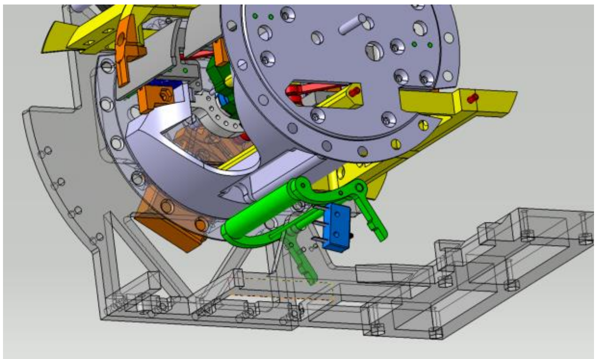

Figure 9 Detailed view on the latching roller lever (green) and end switch (blue)

The result of this combined requirement is surprisingly simple and is shown in Figure 9. A spring driven roller is installed outside the boom spool. The spring pushes the roller towards the centre axis of the boom spool and thereby -before and during deployment - slightly pressing the still coiled layers of the boom against the spool. Once the deployment is nearly finished and the last layer of the coiled boom unspooled, the roller finds a mating grove in the boom spools outer shell that it will be pushed in by the spring.

Thereby, the geometries of roller lever and cavity are chosen in a way that the boom spool cannot continue its rotation and is stopped at a very precise angle. This latching is however acting in deployment direction. For the stowage procedure no special care needs to be taken, the roller will jump out of the pocket once the hub is rotating backwards. To precisely hold the boom spool in place for cross section deployment and boom spool latching, the deployment driving tapes need to be pretensioned.

2.2. Boom Root Deployment

Figure 11 depicts both relevant cross section extremes to allow an understanding of the geometrical morphing that the boom cross section undergoes during deployment and stowage.

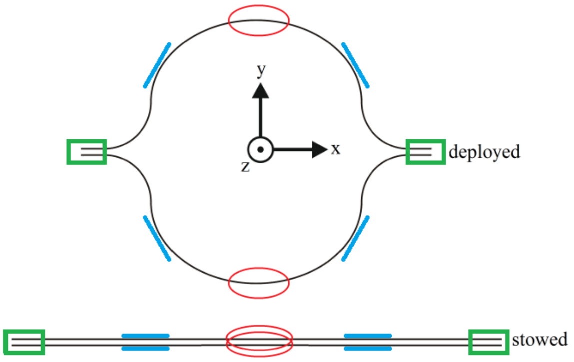

Figure 11 Schematic boom cross sections in deployed and stowed configuration with marked possible interface spots at the flange (green rectangles), the upper boom shells (red ellipses) and side boom shells (blue lines)

Before concentrating on deployment of the root the question on a hypothetical ideal boom root interface for a deployed boom needs to be answered. For a cross-section like the one shown in the upper part of Figure 11, an all-encompassing clamping of the entire cross-section over a few millimetres would certainly be close to the optimum. For generic tests on mast stiffness, such ideal clamping conditions have been created either with specially machined clamping blocks or the use of potting compounds.

For a morphing interface we cannot support the entire cross section but need to concentrate on attractive point at the cross section that are:

I. Equally distribute over the cross section in

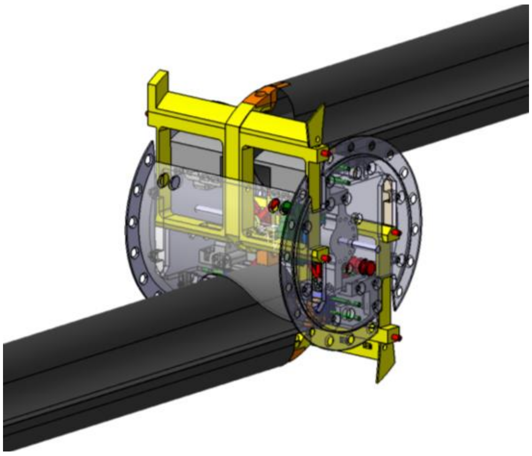

Figure 12 Boom spool equipped with two opposing booms and with already triggered boom root deployment mechanism

II. order to allow moments of different orientation and compression loads to be transferred efficiently.

III. Located at spots where the interfacing portion of the boom shells is
   a. not deforming too much between stowed and deployed shape and
   b. only performing in-plane translative movements without any rotation across the z-axis (please refer to Figure 11 for a reference coordinate system)

While requirement I. is mandatory, the requirements II.a. and IIb are considered are considered to be of a softer nature.

For the here presented cross root interface we decided to concentrate on the spots marked with read ellipses and blue rectangles in Figure 11. Both spots fulfil the requirements I. and II.b. of the list. The top and bottom I/F (red circles), however, do not fulfil requirement II.a. This lack was mitigated by limiting the width of the interfaces at this point to not significantly restrict the overall cross section deformation.

On a first glimpse, the new mechanism depicted in Figure 6 may look familiar and not to different from previous DLR concepts. Figure 12, however, reveals how the concept is different. It shows the extracted boom spool with 2 attached booms attached with an 180° offset with deployed cross section.

Figure 12 allow an insight into the innards of this concept in deployed configuration while Figure 10 illustrates the deployment process.

Figure 11 and Figure 13 use of the same markings for boom flange interfaces (green rectangles) and the top- and bottom shell interfaces (red circles).

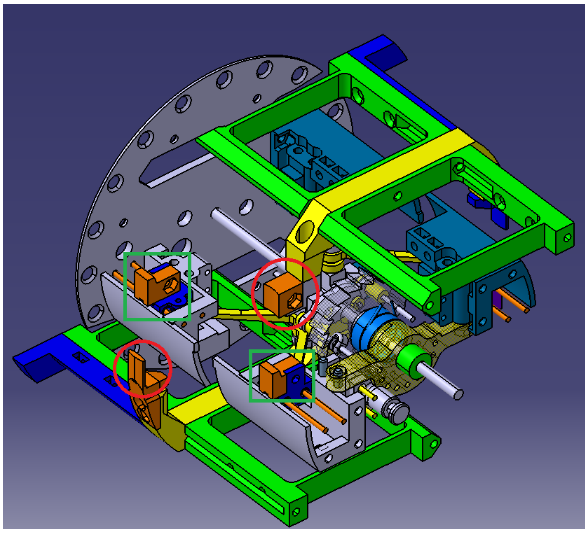

Figure 13 Boom spool internal mechanism used for boom root deployment with two larger sliders (yellow-green) and the two boom flange interfaces (green framed orange parts) and the two boom shell interfaces (red circled orange parts) in deployed configuration.

The key elements of this principle are two large sliders (yellow in Figure 12, green-yellow in other figures) that perform a synchronised but opposing movement. Each slider has two boom interface points directly attached to it. The clue here is that those two interfaces do not belong to the same boom. This is visible in Figure 13 where the top-shell interface of the boom (lower left red circle) is attached to the lower slider while the bottom-shell interface (red circle in the middle) is attached to the upper slider. The same logic applies to the second boom facing downwards.

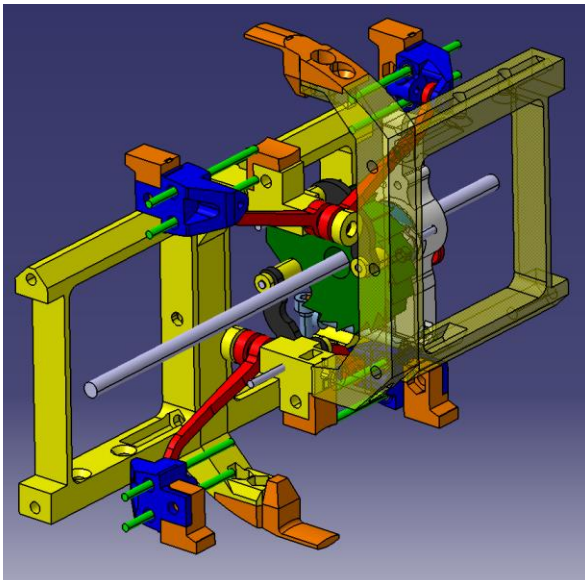

Figure 14 Detailled view on inner mechanisms driving the flange interfaces

Figure 14 visualized how the boom flange interfaces are also indirectly driven by the large sliders due to

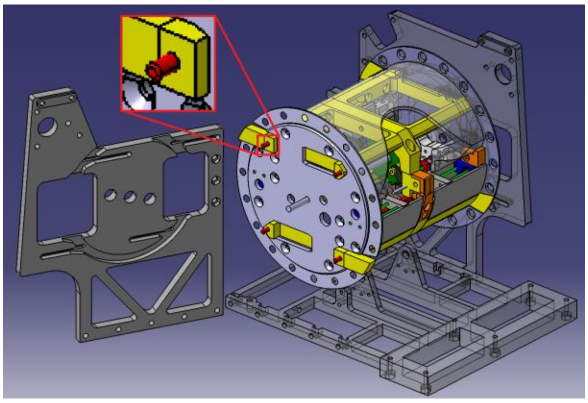

Figure 15 Components required for boom spool latching like main body side plate with straigth and circular groves as well as bolts(red) installed in the larger sliders of the spool.

the connection with piston-rod (red). The flange interface blocks (orange) are screwed into small individual slider blocks (blue) that are able to slide on a pair of 2mm diameter smooth rods (green) by use of the small plain bearings. The geometries and relative position of piston-rods, large and small sliders are optimized in a way that all boom interfaces rest in their ideal spots for deployed and stowed configuration.

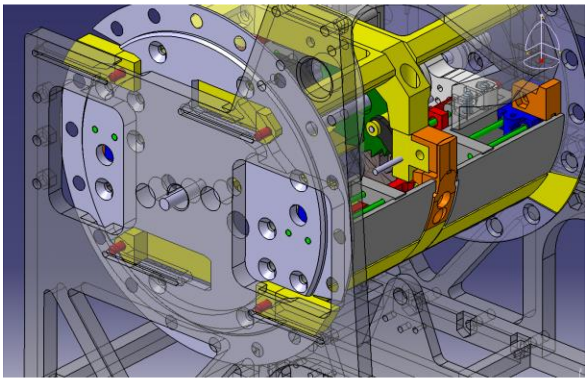

Figure 16 Spool latching system in stowed (upper image) and deployed (lower image) configuration

2.3. Boom Spool Latching

Figure 15 shows important parts of the mechanism that are involved in the latching process. Again, the large sliders play a vital role. They include eight bolts sticking out of the boom spool envelope and intruding into the envelopes of the two main body side plates.

Those side plates featured dedicated circular and straight groves that fit both the bolt positions for an ongoing longitudinal boom deployment with collapses boom root and the configuration with deployed boom root.

During boom deployment, the bolts follow the circular groves (see Figure 16) and allow the boom spool to rotate freely.

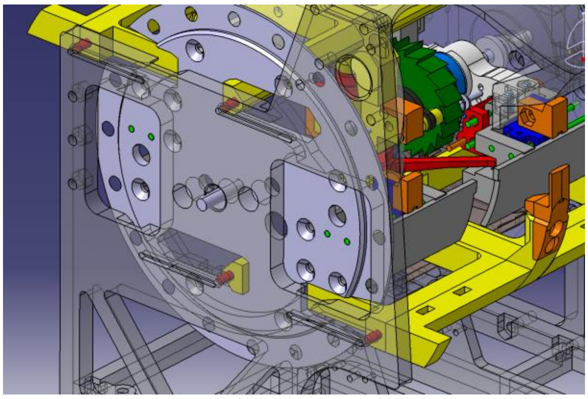

Figure 17 Spool latching system in stowed (upper image) and deployed (lower image) configuration

When the large sliders moved to their deployed position, the bolts are entering the straight groves and follow them until they find the tapered end of those groves that result in in a play-free locking of the sliders into the outer body of the mechanism (see Figure 17).

2.4. Driving actuator

With the active mechanism defined, the question for the driving actuator for the all-triggering large sliders and all depending components needs to be answered. Figure 18 further dismantles the inner mechanism to show the relevant parts. The large sliders are moved by a second set of piston rods (black) that transform the 180° rotation of a cranked shaft wheel (dark green) into a translative motion. The cranked shaft wheel is thereby driven by a pre-tensioned torsion spring (light blue, partially hidden behind the cranked shaft wheel).

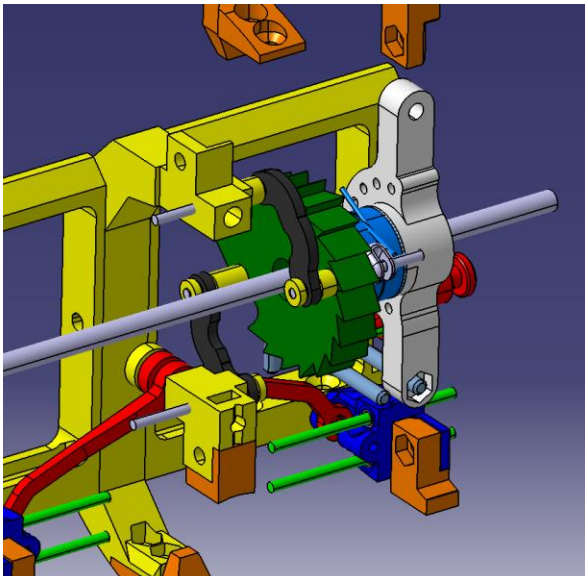

Figure 18 Detailled view on deployment driving components like torsion spring (light blue), cranked shaft (dark green) and smaller piston rods (black) right in the middle of deployment (approx. 60% deployed)

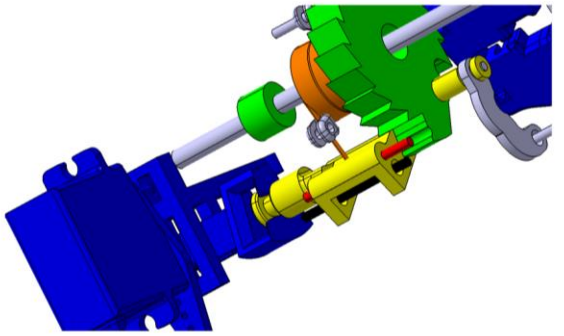

Figure 19 Details on how the locking slider (yellow) with fixed bolt (red) blocks the crankshaft wheel (green) by sliding along two blank rods (black, second one is hidden)

The non-linear characteristics of a cranked shaft and piston rods combination also result in some side effects that were initially not intended but found to be very supportive. Both the deployment starting and end points are in a so-called dead centre of the piston-rod characteristic. From actuation side this results in increased translational forces and reduced velocities that the configuration can induce into the large sliders in proximity to the dead centres. This will support the start of the deployment for a flight hardware mechanism where large forces are usually helpful to overcome initial breakaway torque and forces resulting from friction pairings that haven't been moves for weeks, months or even years.

The end of the deployment is also supported as the high forces ease the full completion of the deployment as well as the final latching while the reduces velocities reduce impact shocks.

Moreover, one should understand the origin of the term *dead centre* which is related to the lack of capability of the cylinder of a steam or gasoline engine to induce a torque into the cranked shaft - at the dead centre positions - because the projected lever has a length of zero. As we basically run this concept backwards here, this effect helps to include an inhering latching of the deployed mechanism. The cranked shaft wheel will be still seeing a residual actuation torque generated from the torsion spring. Any translative force on the larger sliders that try to push the sliders back into the mechanism will not be able to induce a significant torque into the cranked shaft as the configuration is exactly stopped in one of the two dead centres and hold in place by a combination of end stop and residual torsion spring pre-tension.

2.5. Deployment Trigger

With the mechanism and driving actuator defined, a trigger was required to unleash the power of the torsion spring.

Figure 19 visualizes how the torsional spring is prevented from performing its task. A small slider with a fixed bolt is blocking the cranked shaft. To trigger the deployment, the slider needs to be pulled away from the cranked shaft. Once this is done, the spring performs its task and the root deployment is triggered immediately.

As requested in requirement R6, it was intended to trigger the deployment without any electrical actuator inside the boom spool to prevent the wiring of such component inside a rotating system. Hence, it was decided to introduce a concept that could be best described as a mechanical version of an electric commutator ring.

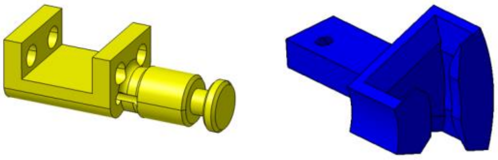

Figure 20 Detailed view on the both interacting key parts; Slider (left) and claw (right)

Figure 20 introduces the two key elements of this concept while Figure 21 and Figure 22 shows their interaction and required main body side plate modification.

The slider that locks the crankshaft wheel features a mushroom head sticking out of the boom spool side plate which is penetrating the envelope of one main body side wall. As for the boom spool locking bolts, there is a dedicated grove in the side plate to allow the head of the slider to pass though while the boom spool is rotating (see Figure 21).

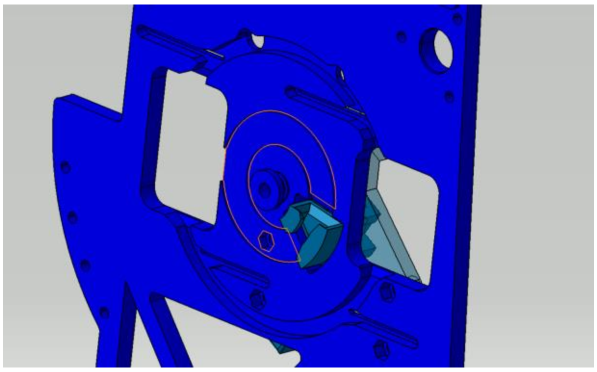

Figure 21 Side wall of the main body with claw and highlighted grove for the slider head.

The mushroom head of the slider passes through a matching claw that is attached to an actuator mounted to the outside surface of the main body side plate, every full boom spool revolution. Both side plate grove and claw are designed and positioned in a way that they allow the mushroom head to freely travel its circular path during longitudinal boom deployment phase while restraining it in its capability to move away from the cranked shaft. So, an unintended trigger during

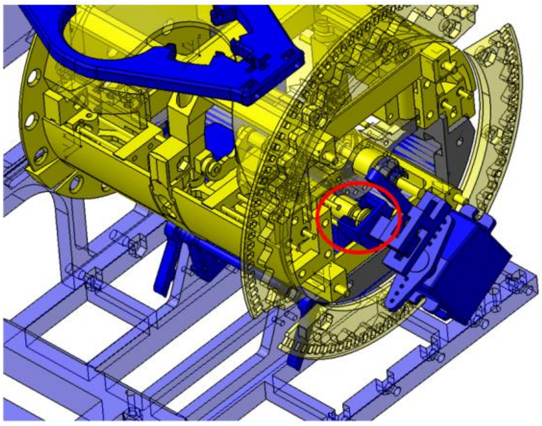

Figure 22 Boom deployment mechanisms with color-coded parts that are eigher stationary (blue) or rotating (yellow) with red-circled interface point between both groups

launch or longitudinal deployment is not possible.

When the boom spool latches at the end of the longitudinal deployment both mating key parts are aligned perfectly (see Figure 22).

To trigger the boom root deployment, the external actuator displaces the claw by only a few millimetres to free the spool-internal cranked shaft wheel.

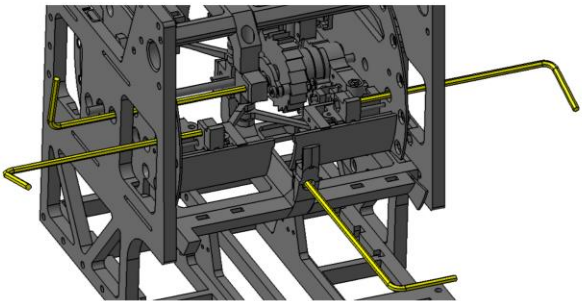

Figure 23 Visualization of the easy access to the four boom interface blocks for boom installation

2.6. Handling and Ground Operations

The fact that basically all internal mechanisms of this concept are driven by the cranked shaft wheel also eases the on-ground operation. To bring the boom root cross section into its flattened shape and unlock to boom spool, one simply need to rotate the cranked shaft wheel by 180° and lock it with the externally driven actuator.

To ease the installation of a fresh boom into the mechanism, the four vital interface block and their mating parts in the mechanism are designed in a way that the can be easily attached and detached from each other (refer to Figure 13 to see orange interface blocks). Therefore, the boom could be equipped with those blocks outside the mechanism using a special rig to align all part perfectly.

Once the adhesive is cured, the boom can be integrated into the mechanism by using four screws that can be reached with usual long Allen keys through dedicated cut-outs in the main body and boom spool side plates (see Figure 23).

2.7. Control and Sensor Electronics

For the first prototypes, only two actuators were included to control it:

1. Tape drive motor for longitudinal deployment (DC-motor)
2. Trigger actuator for boom root deployment (model building servo motor)

For monitoring, the following sensors had been installed as well:

1. End stop switch detection the position of the roller lever
2. Rotary encoder tracking the boom spool relative position
3. Rotary encoder tracking the tape spool relative position

As the prototype was only intended for laboratory functional tests and only our mechanical institute involved in this activity, we had to design our own control electronics. Thanks to the very user-friendly Arduino DIY electronics environment, this task could be fulfilled with reasonable effort.

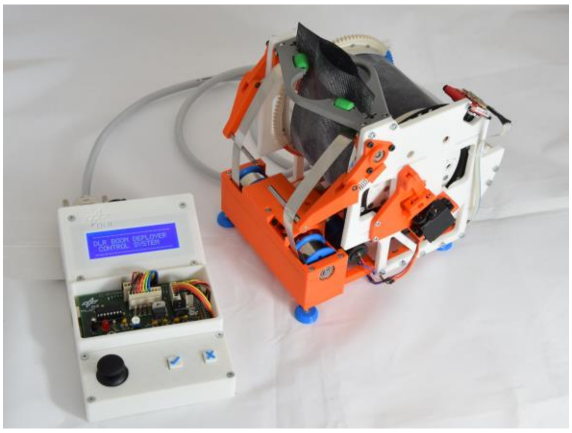

Figure 24 First prototype with control electronics base on 8-bit Arduino Mega and a costom PCB for DC-Motor control

The first version of the control electronics was made in 2017 and was able to control all actuators and show the values of all sensors (see Figure 24) on the attached display. Moreover, there was an mode programmed into the microcontroller that could run a complete deployment fully autonomously incl. automatic stop of the tape driving motor at the end of longitudinal deployment and automatic boom cross section deployment.

However, as the newer 2021 version of the mechanism uses a brushless DC motor for tape drive and will use a SMA based release-nut actuator for triggering of the root cross section deployment, a new control electronics have been used.

Figure 25 Enhanced custom control electronics

Figure 25 shows the more advanced but still Arduino-based system with its case and a custom PCB. It is based on the more powerful 32-bit SAMD21 processor line and provides the following features:

1. Two UART ports for control of external brushless DC motor drivers
2. Input channels for 4 rotary encoders
3. Inputs for 5 end-stop switches
4. Ability to drive and monitor 4 high power parts like HDRs or heaters (up to 36VDC at 2 Amps)
5. 3 thermocouple inputs
6. Battery-backed internal RTC (Real Time Clock)
7. Two SD Card slots and one on-board 16MB flash memory for redundant data logging
8. Intuitive user interface via integrated display, LEDs, jog dial, switches and potentiometers
9. Ports for Bluetooth and WiFi modules for optional wireless remote control by PC, tablet or even smart phone
10. On-board Bosch-Sensortec BNO-055 MEMS IMU sensor for acceleration logging (motivated by parabolic flight test foreseen for summer 2021)

3. BREADBOARDS

3.1. Version 2017

A lot of functional testing has been performed with the prototype shown in Figure 7 which also led to a series of successive design updates eased by the fact, that except of shaft, bearings, actuators and springs, this prototype is entire made with a simple consumer FDM 3D-printer.

As gossamer structures are per definition only lightly loaded, the plastic parts could carry all loads without a risk of braking them. A drawback, however, is the unrealistic stiffness of the entire prototype which allows no clear statement on how much the stiffness of the boom to space-craft interface has been advanced.

On the positive side the deployments always run smooth and well controlled. We never observed unintended deployment of the boom-root during longitudinal deployment. Although relying on a structure made of relatively soft plastic parts, the subjective increase in stiffness and strength of the boom to mechanism interface was remarkable. During and at the end of the longitudinal deployment, the boom reacts with the formation of growing buckles to a higher amount of lateral force. Once the boom root has been deployed, a lateral tip force did not result in any buckle forming but instead allows the operator to tilt over the entire mechanism and turn it back on its feet afterwards.

Moreover, the above described installation and removal of the boom specimen into the mechanisms using the four interface blocks worked flawlessly.

On the negative side, we observed some inaccuracies in the alignment of boom spool and main body at the end of longitudinal deployment. For some deployments the bolts in the larger sliders did not perfectly align with the straight groves in the main body side plates so that the boom root deployment was disturbed. We could compensate this effect by tuning the programmed delay between the detection of the roller lever end-stop triggering and the shutdown of the motor in charge of the longitudinal deployment. This led us to the conclusion that there is no basic bug in the concept but the interaction of the very strong deployment motor with the plastic roller lever and the plastic structure, led to deformations that will not be that severe when using professionally machined Aluminium and composite parts. It must be said, however, that we have always been able to free such a jammed mechanism and motivate it to finish its task by simply running the DC motor back and forth a little manually.

It definitely underlines the importance of tolerance management for this mechanism.

However, one part described in section 0 above did not prove very comfortable: To turn back the crankshaft wheel by 180° in order to collapse the

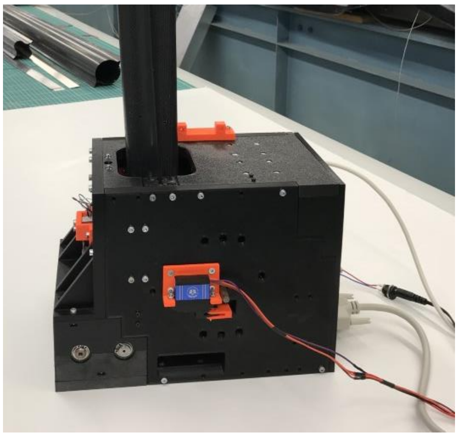

Figure 26 year 2021 version of a boom deployment mechanism with boom root deployment

boom cross section and unlock the boom spool was problematic. There was a tool designed to support this task that should interface with the sawtooth-shaped outer contour of the crankshaft. This tool required a removal of one of the boom spool cover shells and was finally too weak to turn back the crankshaft wheel against the strong torsion spring. We ended up interfacing the sawtooth-shaped contour of the crankshaft with our thumb-nails which proved effective but not comfortable at all.

3.2. Version 2021a

Figure 26 shows the novel version of the mechanism. Advancements in contrast to the former version are:

- Deployment run by brushless DC motor with integrated rotary encoder and motor current/torque sensing
- Tape drive system using one central tape per boom instead of two
- Redesigned boom spool brake
- Tape tension monitoring sensor
- Advanced boom spool locking roller levers
- Additional end-stops switches for confirmation of fully travelled large sliders
- Easy access to the crankshaft rotation via coupling to the main boom spool axle
- General stiffening of highly loaded components to increase system stiffness

Like for the previous version, this mechanism is able to deploy two booms but is only equipped with one.

Figure 27 and Figure 28 show the mechanism with still locked and deployed boom root mechanisms.

4. CONCLUSION

The past pages show a novel deployment mechanism for CTM boom that has been developed in order to maximize the deployed boom to spacecraft interface stiffness and strength. This increased mechanical performance of the interface allows the usage of smaller boom and have a lot of positive upstream effects to other subsystems.

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Figure 27 and Figure 28 show the mechanism with still locked and deployed boom root mechanisms. Conclusion

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However, the increased performance for fully deployed booms is contrasted by reduced performance during deployment. Hence, this concept is only suited for deployable systems that do not required high loads during deployment. Moreover, the current spring driven cross section deployment is a one-shot mechanism that does not allow a boom retraction in space.

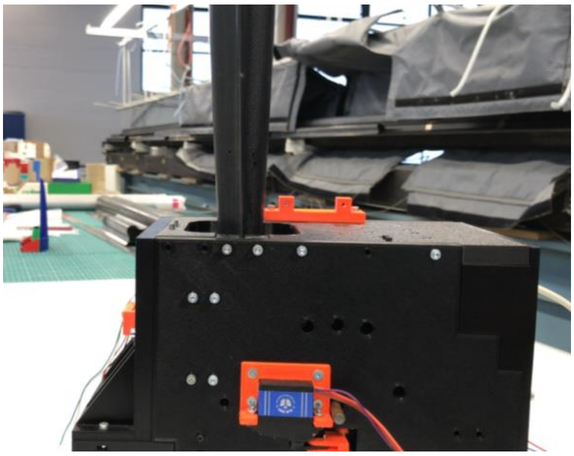

Figure 27 Fully deployed boom with flattened root cross section

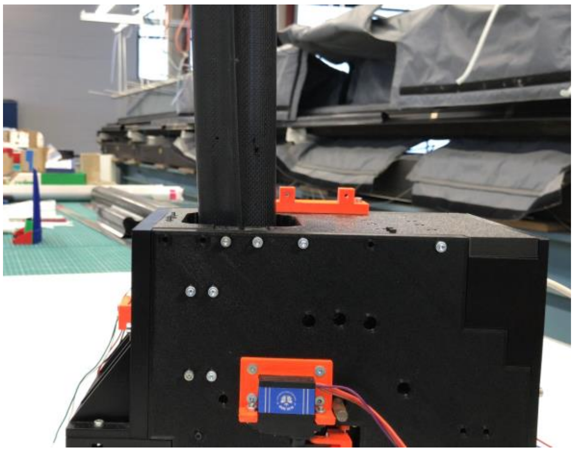

Figure 28 Fully deployed boom with deployed root cross section

Framed by the fact that this development has been a side activity with no dedicated funding during the recent years, the TRL is still low and test-verified

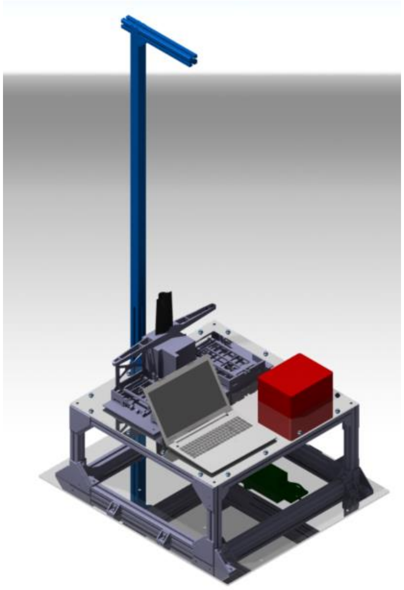

Figure 29 test rack for 0g flight testing

numbers on the level of improvement are so far not available. However, the subjective impression on the two breadboards during functional testing are very promising.

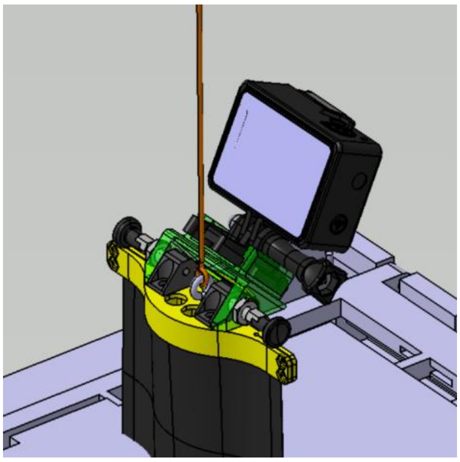

Figure 30 Tip of deploying boom provided with interface to a instrument (here a camera) and safety rope

5. OUTLOOK

Pushed by the recently obtained funding for a parabolic flight test in July 2021, the concept gained some momentum and the advanced second prototype is flight-ready by 99%. It is not required but foreseen by us to substitute some 3D-printed components of the mechanism with aluminium and composite parts in the remaining weeks to the flight.

The test rack is also close to completion (see Figure 29) and will be used to test the 2021 prototype together with different example applications.

One is an attached tip instrument (see Figure 30) that will be represented for the test by a simple camera.

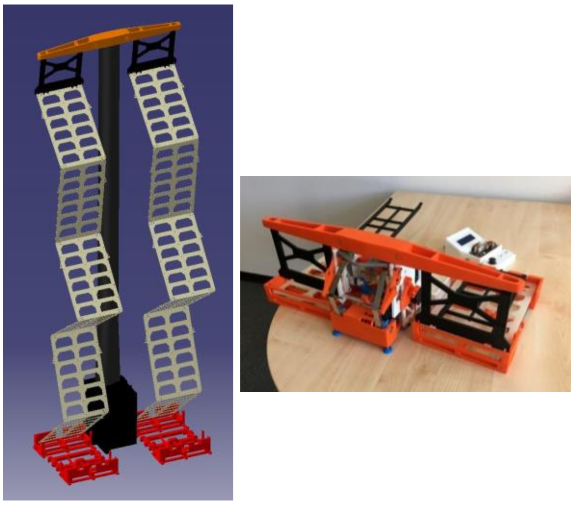

Figure 31 Solar array concept as partially deployed CAD model(left) and attached to the 2017 breadboard (right)

The test plan includes deployment and vibration decay tests.

The most promising application is a solar blanket that has been specially designed to fit the characteristic of the novel deployment mechanism in order to generate a holistically optimized deployable system (see Figure 31). It supports the new boom deployment mechanism by inducing only very small forces and torques on the deploying boom during the entire deployment process. That results in a fully deployed but still intentioned blanket at the end of the longitudinal boom deployment.

The final tensioning of the blanket will be done after the boom cross section deployment has been triggered. It is realized by a dedicated offset mechanism in the blanket container that pull the lower blanket interfaces downwards.

Unless a first prototype already available, it is unfortunately still at a very low development state and is unlikely to be ready by July to join the flight. However, we will continue the development afterwards and plan a test campaign to validate the concepts properly.

REFERENCES

[1] M. Straubel, P. Seefeldt, P. Spietz, and C. Huehne, “The design and test of the gossamer-1 boom deployment mechanisms engineering model,” in *AIAA SciTech*. American Institute of Aeronautics and Astronautics, Jan. 2015, pp. –. [Online]. Available: http://-dx.doi.org/10.2514/6.2015-1837

[2] U. Geppert, B. Biering, F. Lura, J. Block, M. Straubel, and R. Reinhard, “The 3-Step DLR-ESA Gossamer Road to Solar Sailing,” *Advances in Space Research*, vol. 48, pp. 1695–1701, Dec 1 2011. [Online]. Available: http://www.sciencedirect.com/science/article/-pii/S0273117710006332

[3] M. Straubel, M. Hillebrandt, and C. Hühne, “Evaluation of different architectural concepts for huge deployable solar arrays for electric propelled space crafts,” in *14th European Conference on Spacecraft Structures, Materials and Environmental Testing*, Toulouse, France, Sep 27-30 2016.

[4] M. Hillebrandt, S. Meyer, M. E. Zander, and C. Huehne, “Deployment testing of the de-orbit sail flight hardware,” in *AIAA SciTech, 2nd AIAA Spacecraft Structures Conference*, Kissimmee, FL, USA, Jan 5-9 2015. [Online]. Available: http://dx.doi.org/10.2514/6.2015-0434

[5] M. Straubel, “Design and Sizing Method for Deployable Space Antennas,” Ph.D. dissertation, Otto-von-Guericke-Universität Magdeburg, GERMANY, Sep 2012. [Online]. Available: http://elib.dlr.de/81128/

[6] M. Leipold, M. Eiden, C. E. Garner, L. Herbeck, D. Kassing, T. Niederstadt, T. Krüger, G. Pagel, M. Rezazad, H. Rozemeijer, W. Seboldt, C. Schöppinger, C. Sickinger, and W. Unckenbold, “Solar sail technology development and demonstration,” *Acta Astronautica*, vol. 52, pp. 317–326, 2003. [Online]. Available: https://-www.sciencedirect.com/science/article/pii/-S0094576502001716

[7] M. Leipold, C. E. Garner, R. Freeland, A. Hermann, M. Noca, G. Pagel, W. Seboldt, G. Sprague, and W. Unckenbold, “ODISSEE – a proposal for demonstration of a solar sail in earth orbit,” *Acta Astronautica*, vol. 45, no. 4-9, pp. 557 – 566, 1999, third IAA International Conference on Low-Cost Planetary Missions. [Online]. Available: http://-www.sciencedirect.com/science/article/pii/-S0094576599001769

[8] M. Hillebrandt, Martin E. Zander, C. Hühne, “Sliding Core Deployment Mechanism for Solar Sails based on Tubular Shell Masts”, Proceedings of 5th International Symposium on Solar Sailing, Aachen, Germany, Jul 30 - Aug 2, 2019