Structural Concept for a Lightweight, Compactly Packaging and Highly Scalable Solar Sail

Martin Hillebrandt[1] and Marco Straubel[2] and Christian Huehne[3]
German Aerospace Center (DLR), Lilienthalplatz 7, 38108 Braunschweig, Germany

The paper describes a structural concept for a square solar sail whose main structural elements are deployable booms that are stowed through reeling. The concept features a highly integrated design through focusing on the harmonization of the stowage concepts of booms and sails. Thereby compact stowage, high scalability and low mass are achieved which makes this concept suitable for a variety of solar sail missions and launch options. The design is based on a cylindrical hub that is used on the outside as a stowage cylinder for the reelable booms and on the inside as a stowage compartment for the sail. However, this concept requires deployment of the sail in two stages. In the first stage the booms are unreeled and latched through a locking root interface. In the second stage the sail quadrants are unfolded through a rigging system. The concept is compatible with several types of reelable boom architectures ranging from tapesprings to trusses and results together with the selected stowage and deployment concepts in a highly scalable solar sail design.

I. Introduction

Solar Sails consist basically of a large reflective surface to gain momentum from the sunlight. To stretch this surface and maintain its flatness either centrifugal forces or additional support structures are used. Although support structures add mass and thereby reduce the sails propulsion capabilities, most solar sails utilize this concept as it possesses advantages regarding maneuverability, deployment control and ground testability. The main elements of the support structure are deployable booms. Their folding principle largely defines the sails deployment concept and stowed form and is thereby a decisive factor for the solar sail's overall complexity, stowage volume and mass. Hence, the selection of the boom technology and the harmonization with the sail membrane's stowage concept are crucial decisions within the early design process. In the following a solar sail concept is presented that is developed under particular consideration of these design steps in order to gain a lightweight, compactly packaging and highly scalable solar sail design. The concept is thereby based on previous solar sail developments such as the ESA-DLR solar sail ground demonstrator [1] and cubesat based sails such as Nanosail-D [2], Lightsail [3] and De-Orbit Sail [4]. It can be seen as an design advancement of the ESA-DLR solar sail ground demonstrator and De-Orbit Sail which are displayed in Figure 1.

[1] Research associate, DLR Institute of Composite Structures and Adaptive Systems.
[2] Research associate, DLR Institute of Composite Structures and Adaptive Systems.
[3] Head of Department Composite Design, DLR Institute of Composite Structures and Adaptive Systems.

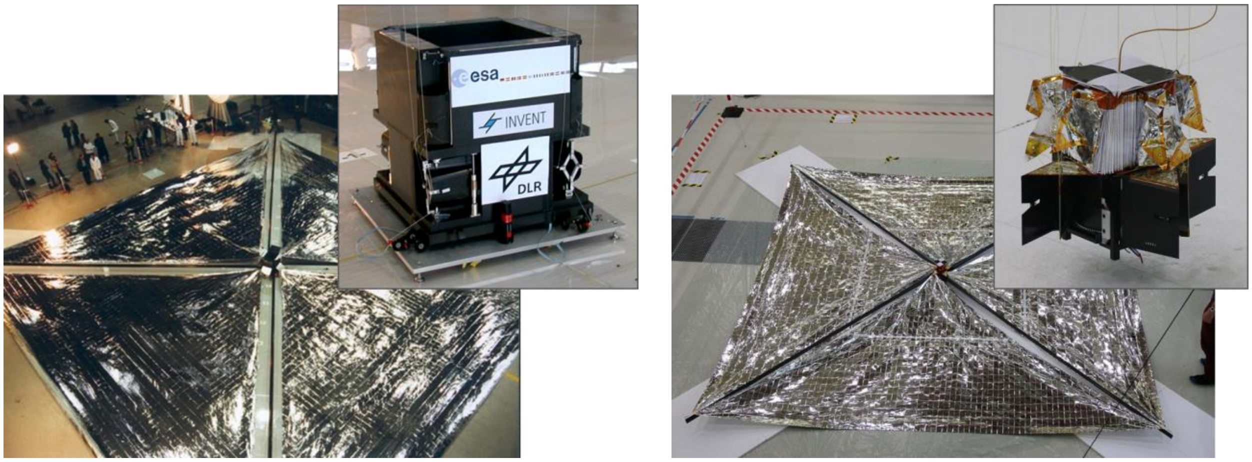

Figure 1: ESA-DLR solar sail ground demonstrator [1] (left) and De-Orbit Sail [4] (right) as examples for solar sails based on reelable booms and zigzag folded sail membranes.

II. Boom Technology, Stowage and Deployment Concept

The solar sails overall structural architecture consists – as for most solar sails – of four deployable booms that are running crosswise along the diagonals of a square sail membrane. The membrane is thereby split into four segments that are attached to the boom tips and the central support structure in the three corners of the triangular sail quadrants.

The development of the sail concept starts with the selection of a specific boom technology and sail folding method. Key criteria for both selections are small individual stowage volumes and the compatibility of their stowage concepts and stowed forms. Harmonization of these properties is essential to achieve the goals of a small overall volume and low system mass.

Figure 2: Reelable double omega boom developed by DLR in partly stowed configuration (left) and boom samples with surface coating (right) [Courtesy: DLR].

The dominating boom technology where compact packaging is the primary design driver are reelable booms. An example for this type of booms is the Collapsible Tube Mast (CTM) [5] displayed in Figure 2 which is the baseline boom technology for the solar sail design presented in the following. Reelable shell booms such as the CTM reach stowage volumes that can get close to the pure material volume as the spacing between coils is small. However, although a high stowage efficiency is reached for the boom itself, there always remains a dead space in the center of the hub that compromises the overall stowage efficiency. To minimize this dead space, in general a small inner reeling radius is desired as is done particularly for cubesat based sails such as Nano-Sail D, Lightsail and De-Orbit Sail. This is achieved by maximizing the allowable reeling strain in the flattened boom shells. However, this causes contradictions in the boom design goals regarding material selection. To reach a high overall stiffness, high buckling strength and low mass, high (HM) and ultra-high modulus (UHM) carbon fiber materials are favored. But the elastic strain limits of these fibers decrease with the modulus. Hence, the selection of materials that are beneficial for the booms mass specific mechanical properties is opposed to the goal of achieving a small stowage volume through minimization of the reeling radius.

The approach chosen here is to use the dead volume inside the boom hub for stowage of the sails as is shown in Figure 3. Thereby the dead volume inside the hub is utilized and also rather large inner reeling radii are ensured. This enables the use of HM or even UHM carbon fibers as boom material as only small strains are induced during reeling of the booms. For containing the sails the hub is segmented into four compartments that are utilized as stowage containers. Each container possesses the form of a quarter-circle and together they act as a spool core for the booms. For the sail quadrants a double-zigzag folding pattern is selected. This folding pattern is adaptable to a variety of stowed forms through variation of the fold length and thereby efficiently fills up the available space inside the containers.

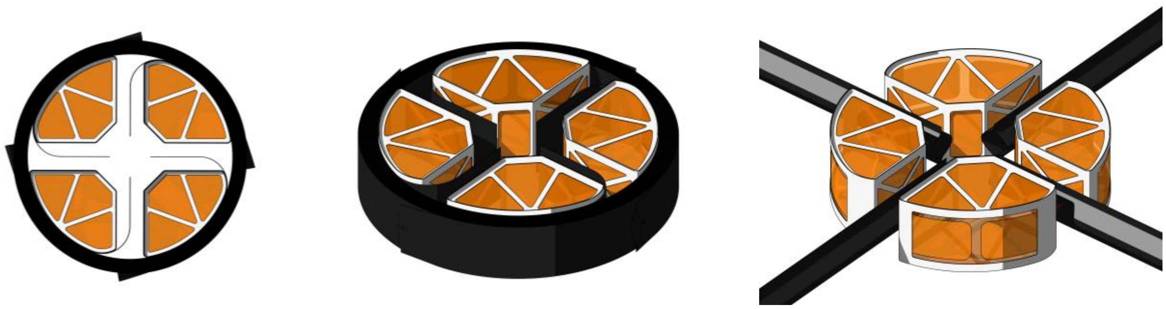

Figure 3: Stowage concept of booms and sails with the four sail containers located inside the reeled boom package and acting as coiling hub.

The deployment concept of the solar sail largely results from the selected stowage concept of booms and sail quadrants. In a first step the booms which are wrapped around the sail containers are deployed. Once the booms are fully unreeled and latched the sail compartments are accessible and the sail quadrants can be pulled out. This is done through a rigging system that is co-coiled and deployed together with the booms. The design of the corresponding mechanism components is described more in detail in the next section.

The advantage of the two-phase deployment is that the booms are unfolded free of any loading. When the sails are deployed, the booms possess already their full load-carrying capability and hence can be designed to the actual loading during operation instead of the deployment process where the reduced mechanical properties of the deploying boom need to be taken into account. Furthermore the two-phase deployment sets only low requirements to the boom deployment mechanism regarding deployment support, control and generated deployment force. Thereby a boom deployment mechanism that is rather simple in its functionalities is applicable. However, the rigging system necessary for sail deployment adds complexity to the system.

In consequence, through harmonization of the folding principles of booms and sails a compact stowed form and low stowage volume is gained. Furthermore the small stowed dimensions are beneficial for the overall system mass as the support structures dimensions are small as well.

III. Description of the Main Modules

In the following the main modules of the solar sail concept are described individually regarding their general design and design dependencies.

A. Boom Spool, Support Structure and Sail Compartments

The spool contains the stowed booms, provides the space for stowage of the sails and acts as the primary support structure of the stowed sail. The spool is composed of two circular sandwich plates that are interconnect by the framework structure of the sail containers. To reduce the mass of the spool, large cut-outs are introduced in the sandwich plates where the sail containers are located. To avoid slippage of the booms off the spool the sandwich plates possess a slightly higher radius to provide end-plates.

The housing of the sail containers possess on the inside a liner made of a thick polyimide membrane for containment of the packaged sail quadrants. A large opening on the outside enables pulling the sails out for deployment. To apply a small retaining force, lids made of thick Kapton foil partially close this opening and cause a sequential sail deployment process.

The assembled sail spool and the sail container are displayed in Figure 4.

Figure 4: Assembled booms spool composed of two sandwich plates and four sail containers which also form the hub for boom coiling (left); detailed view of a single sail container with framework structure and inner Kapton liner (right).

B. Boom Deployment Unit

The deployment principle for the booms is based on steel belts that are co-coiled with the booms. Instead of applying the deployment forces directly to the booms, they are pulled off the spool through these belts. Therefore an electric motor drives four spools with 90 degree offset which each reels one of the belts. The belt spools are mounted to a rotor-frame that encloses the boom spool and is displayed in Figure 5. The rotor consists of two rectangular frames of carbon fiber rods which are connected by aluminum fittings. Attached to these fittings are the axles that drive the belt spools. The drive moment is generated by an electric gear motor and distributed to the belt spools through gear rings on the edges of the boom spools sandwich plates. These gear rings also act as rails for the rotor frame. The gear motor itself is attached to one of the eight rotor frame fittings and directly drives one of the four belt spool axles. The other three are kinematically coupled through the gear rings of the boom spool.

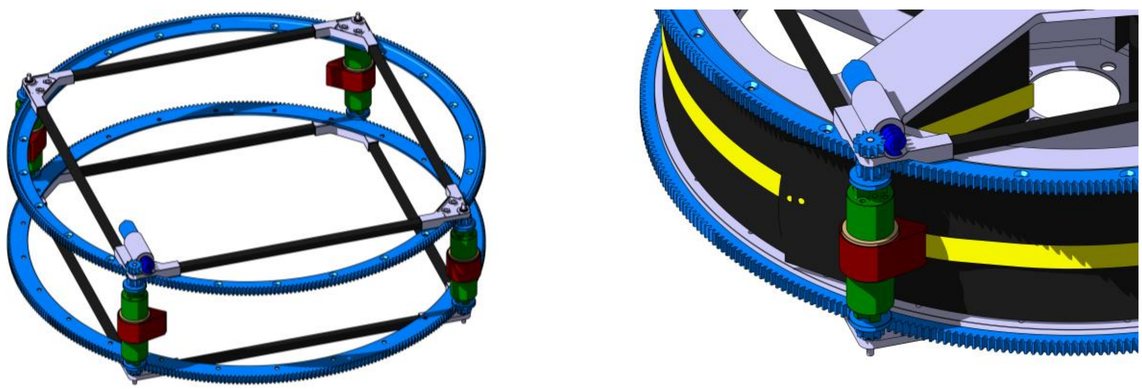

Figure 5: Rotor frame with four belt spools running on two gear rings (left); detailed view on a single belt spool (inside red case) with drive axle, constant moment clutches (green) and rectangular mounted gear motor (right).

The deployment of the booms through the steel belts requires consideration of the changing gear ratio between the boom spool and the belt spools. During deployment the radius of the boom spool decreases through uncoiling of the booms while the belt spool radius increases through coiling of the belts. Thereby the gear ratio between boom and belt spool changes throughout the deployment. However, the gear ratio between the drive motor and the belt spools is fixed and is not adjusted accordingly. As a result the steel belts can become slack or overly tensioned throughout the deployment process. To avoid slackness and excessive tension loads the axles of the belt spools are driven with a higher number of revolutions than necessary for the boom deployment. To compensate for the mismatch a constant torque clutch is installed between each belt spool and its driving axle which is shown green in

Figure 5. Thereby a constant torque is transmitted and the belts are held under constant tension throughout the deployment process.

For small sails a passive deployment mechanism driven only by the booms strain energy can be realized and would significantly reduce the system complexity. However, some means of deployment control such as a damping mechanism may be required.

C. Boom Root Interface

The boom roots are joined in the center of the sail. As the booms undergo a transition in their cross-sectional shape during deployment, this form transition needs to be followed by the root interface. Therefore each boom is attached to the interface by four brackets, two at the flanges and two at the outermost point of the curved middle shell. Two opposing brackets slide on two perpendicular axes to match the change in cross-section. To synchronize the movement of the brackets, they are interconnected by four arms that are kinematically coupled through gear connections at their ends. The principle design is displayed in Figure 6.

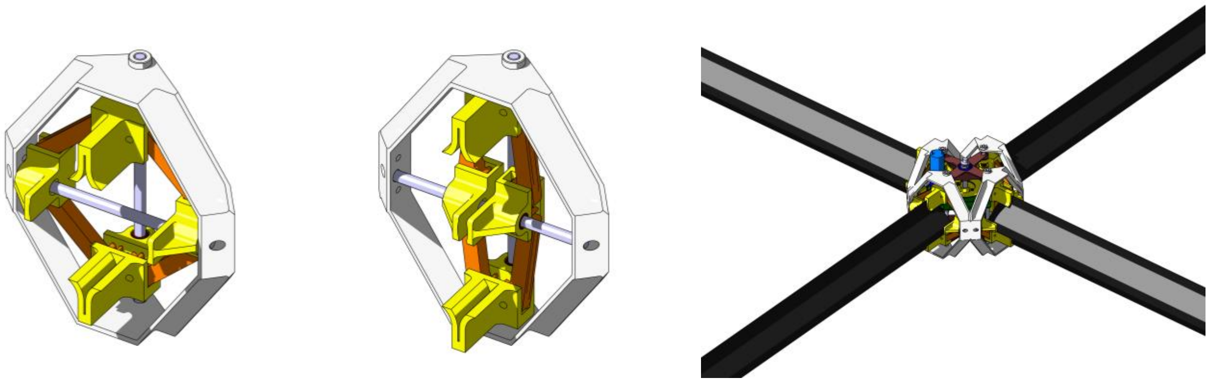

Figure 6: Boom root interface with four brackets for boom attachment (yellow) sliding on two perpendicular axes (left and middle) and assembled state with attached booms and inner mechanism components for actuation (right).

The motion of the boom root interface is actuated by an electric motor. The motor drives a thread-bar that moves two cross-bars which interconnect the vertical attachment points of all four interfaces. For the transition between flattened and deployed state the cross-bars are moved towards each other whereby the boom's cross-section open up. The motions of the interface and cross-bars are displayed in Figure 7 for two opposing booms. Latching of the boom roots is achieved when the cross-bars are in their lowermost position and the brackets for boom attachment are in contact with the surrounding frame.

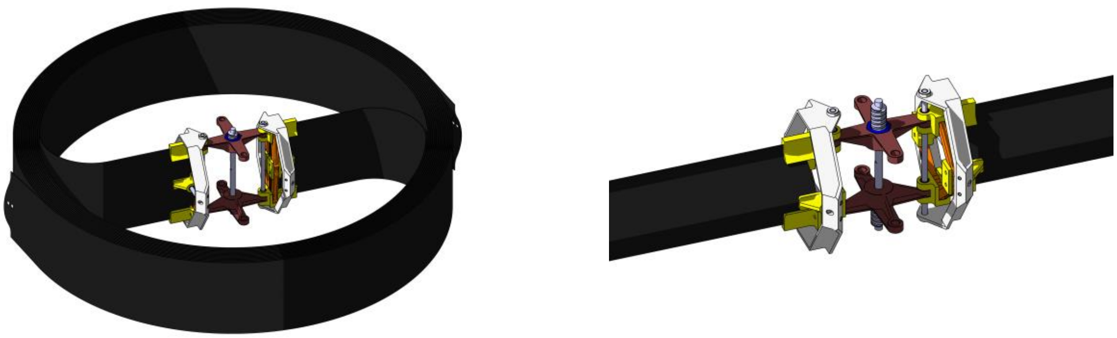

Figure 7: Boom root interface with two of four booms in stowed (left) and deployed configuration (right).

D. Sail Deployment Unit

The sail deployment unit is basically a rigging system that pulls the sails out of their stowage containers after boom deployment and latching of their roots in unfolded state. The rigging system consists of belts that are running from the corners of the sails through deflection pulleys at the boom tips and back to a spool in the center of the sail.

Thereby the belts are running from the deflection pulleys to the central spool inside the tubular masts. The spool is driven by the same electric motor that actuates the opening of the Boom Root Interface. The rigging belts are stowed in the same way as the belts of the boom deployment unit through co-coiling with the booms. Figure 8 displays the stowed boom tip with the co-coiled belts and the pulley cage. Furthermore it shows the rigging spool with the motor which simultaneously actuates the unfolding of the booms roots through the thread shaft which coincides with the spool axle.

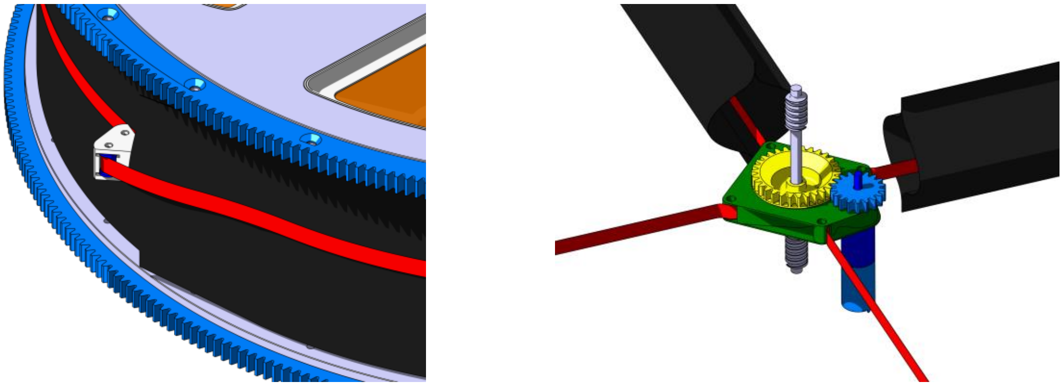

Figure 8: Stowed rigging belt with pulley cage mounted at the boom tip (left) and rigging spool with thread shaft axle and drive motor (right).

IV. Application to a 100 m² Solar Sail

The previously described solar sail concept is further realized in the design of a 100 m² class solar sail. The chosen boom technology is a tubular mast of type CTM that is already used within the De-Orbit Sail project [6]. To assess the maximum sail size realizable with this type of mast, an estimate of the realizable boom length L is gained through use of Euler's buckling load P_{crit}:

$$P_{crit} = \frac{\pi^2 k_{EI,IF} E_{ax} I}{(k_L L)^2}$$

Thereby the parameter $k_{EI,IF}$ describes a knockdown factor to account for stiffness losses at the Boom Root Interface, E_{ax} the axial material modulus, I the second moment of area of the deployed cross-section and k_L the buckling length factor. The required compression strength of the boom results from the sail tension load P and is calculated according to Murphey [7] as follows:

$$P = \sigma_{Sail} t_{Sail} L$$

Here the parameter σ_{Sail} describes the tension stress in the sails center and t_{Sail} the thickness of the sail membrane. Equating Euler's buckling load with the loading applied by the sail considering a safety factor k_P for buckling and solving the expression for the boom length L allows calculating the realizable sail dimensions:

$$P_{crit} = k_P P$$

$$\frac{\pi^2 k_{EI,IF} E_{ax} I}{(k_L L)^2} = k_P \sigma_{Sail} t_{Sail} L$$

$$L = \left(\frac{\pi^2 k_{EI,IF} E_{ax} I}{k_L^2 k_P \sigma_{Sail} t_{Sail}} \right)^{\frac{1}{3}}$$

The values chosen for the parameters are as follows:

- A critical component for the mechanical performance of the booms and thereby realizable length L is the Boom Root Interface. It consists of several moving parts and the attachment of the booms is done in discrete points. Hence considerable losses in stiffness are expected wherefore the loss-factor $k_{EI,IF}$ is set to a value of 0.7.
- For calculation of the booms bending stiffness the material selection is decisive. Due to the low strains induced during reeling of the booms, high or even ultra-high modulus carbon fibers such as Torayca M40J [8] and M55J [9] are applicable. Considering an axial material fraction within the laminate of 50%, this results in an axial modulus E_{ax} of 115 GPa and 170 GPa.

- The second moment of area I is derived from the booms deployed cross-section. For a shell thickness of 0.1 mm the De-Orbit Sail boom possesses a second moment of area I around its "weak" axis of $1.4 \cdot 10^{-9}$ m^4.
- The buckling length factor k_L depends on the type of boom root support and tip suspension. For a boom in a solar sail application loaded in axial compression the length factor k_L is 1.7 [7].
- The safety factor for column buckling k_P is set to 3.
- The required sail center stress σ_{Sail} is chosen with reference to Murphey [7] to 69 kPa.
- As sail membrane an aluminized Kapton sail with a thickness t_{Sail} of 5 µm is selected.

With these values the realizable boom length can be calculated. For the Torayca M40J fiber a length of 7.2 m is achievable and for the M55J fiber a length of 8.2 m. This corresponds to a sail side length s of 10.2 m and 11.6 m. Depending on the spacing between the sail quadrants and their edge design an effective sail area in the order of 100 m² can be realized.

The size of the stowed solar sail is now determined for booms with a length of 7.45 m each. The sail size results to 100 m² taking a loss of 10% sail area into account. For the calculation of the required stowed volume of the sail quadrants a stowage ratio (ratio of the actual stowage volume towards the pure material volume) of 6:1 is assumed while for the booms an ratio of 2:1 is estimated. Thereby the stowed system reaches a diameter of 360 mm and a height of 98 mm. The thereby sized solar sail is displayed in its stowed and deployed configuration in Figure 9 and Figure 10.

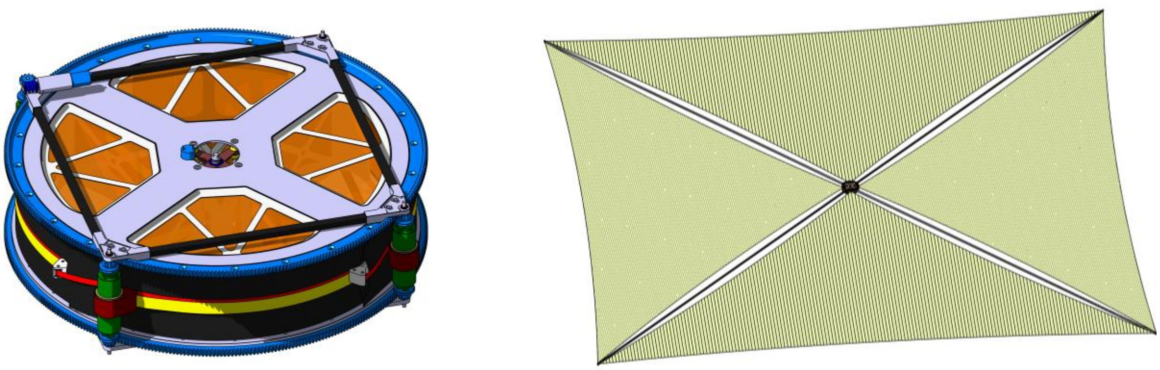

Figure 9: The 100 m² solar sail design example in stowed (left) and deployed configuration (right).

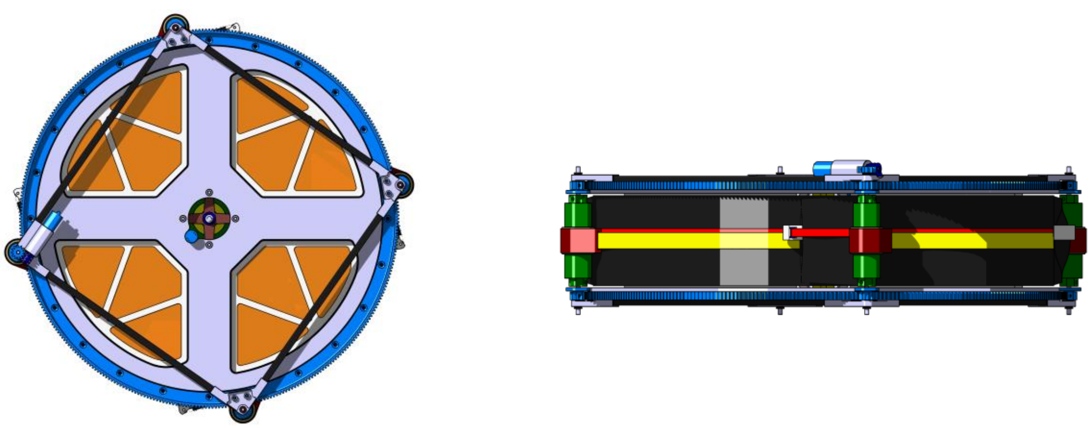

Figure 10: Top (left) and side view (right) of the stowed solar sail.

To evaluate the packaging efficiency of a solar sail, the percentage the sail membrane adds to the stowage volume of the overall system can be used. The higher the sails relative contribution, the higher is the overall packaging efficiency.

The volume contributions of the sails, booms, deployment mechanisms and of the support structure of the 100 m² solar sail are displayed in Figure 11. One can see that a rather large percentage, of almost one-third of the volume is occupied by the stowed sail. However, the largest part still is void space. This void space results primarily from volume required for moving mechanism parts such as the rotor frame of the boom deployment unit or the deploying boom roots that are joined in the sails center and require same space for full opening. Hence, there is still potential for further improvements.

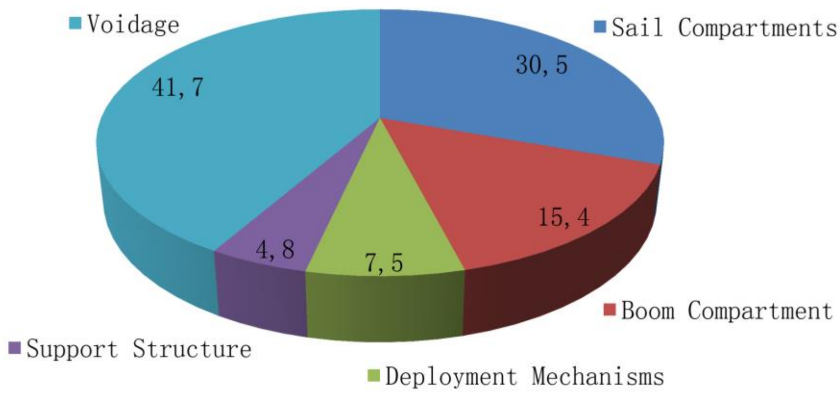

Figure 11: Volume fractions of the sails, booms, deployment mechanisms, support structure and voids of a 100 m² solar sail in relation to the total stowage volume.

V. Scalability Options towards Meter- and Hundred-Meter-Class Sails

A particular design goal is to create a solar sail design that is highly scalable. The scalability of a solar sail depends on the scalability of its stowage and deployment concepts and component designs. The stowage concept depends on reelable booms and double-zigzag folded sail quadrants. As introduced above, both concepts have already been applied in small and mid-size solar sails (see Figure 1).

Of particular importance for the sails overall scalability are the booms. In the small scale region primarily minima in their cross-sectional dimensions are limiting factors such as the wall thickness of a shell boom. A boom design well suited for small solar sails is the TRAC (Triangular Rollable and Collapsible) boom [10]. Like the STEM (Storable Tubular Extendable Member) boom it belongs to the shell booms with an open cross-section and features excellent stowage efficiency and high bending stiffness. With increasing sail size and boom length an increase in structural hierarchy is required. Slender masts with open cross-sections have the tendency for flexural torsional buckling. Hence in the mid-size region a change-over to shell booms with closed cross-sections is beneficial as they possess a considerably higher torsional stiffness. For even larger solar sails trusses are utilized as their large cross-sectional dimensions enable superior bending stiffness and strength in relation to their mass. Trusses are composed of longerons, battens and diagonals which can again become subjects of increasing structural hierarchy. One example is the CTT (Collapsible Tape Truss; see Figure 13) [11] which utilizes thin carbon fiber tapes similar to the TRAC booms as longerons and thin-walled tubes as battens.

Figure 12 shows an approximate size diagram for the field of application of different boom architectures and their change-overs in structural hierarchy for a solar sail application.

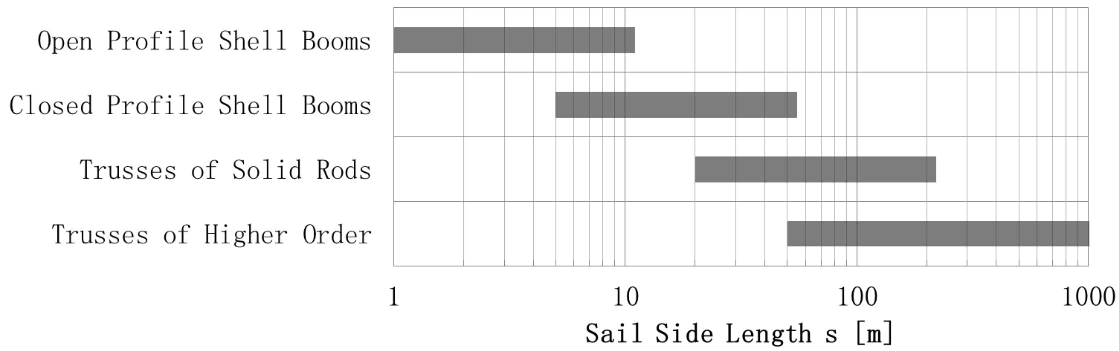

Figure 12: Field of application in terms of sail size of reelable booms with different architectures for a solar sail.

Examples for boom types compatible with the presented solar sail concept are open profile masts such as STEM [12], TRAC and BOWL (Bi-Stable Over the Whole Length) [13] booms, tubular masts like the CTM and CRT (Collapsible Rollable Tube) [14]and trusses like Superstring [15] and CTT. Figure 13 shows samples of the TRAC boom applicable to small sails and the CTT that is utilized for large sails with sail side length in the order of hundred of meters.

Figure 13: Examples of applicable reelable booms: TRAC (Triangular Rollable and Collapsible) [2] boom for small, meter-class sails (left) and CTT (Collapsible Tape Truss) [11] for hundred-meter class solar sails (right).

VI. Conclusion and Outlook

The paper describes a structural concept for a solar sail that features a low stowage volume, low mass and high scalability from meter to hundred-meter class solar sails. The concept is developed with a primary focus on the harmonization of the stowage concepts and stowed forms of booms and sails and according selection of boom technology and sail folding method.

As boom technology reelable booms are selected and the sail quadrants are stowed inside the boom hub through double-zigzag folding. Thereby void space inside the hub is efficiently used and the resulting large hub diameter induces only small strains into the booms during reeling. Thereby despite their low elastic strain limits, high and even ultra-high modulus carbon fibers can be utilized as boom material which contributes to the booms structural performance. The compact stowed form of the overall sail assembly is further beneficial to minimize the dimensions of the solar sails central support structure and mechanism components. The small component dimensions further contribute to a low overall mass.

A second aspect that contributes to a high, mass related structural performance is to conduct the deployment in two phases. Thereby significant loading is applied to the booms only after their full deployment and latching when they possess their full load-carrying capabilities. To enable designing the booms for the actual operational loads, the stowage concept of the sails aims on a minimum of sail deployment loads. This is achieved through large openings in the sail containers which enable easy pull-out. Only small restraining forces are applied through lids of a thick

Kapton foil. However, although the design loads for the booms are kept low, the two-phase deployment also adds complexity as it requires a rigging system for sail deployment.

The high scalability of the presented solar sail concept results from the flexibility regarding the boom architecture while the stowage and deployment concepts and the main mechanism designs remain unchanged. In principle all reelable booms from simple c-shape tapes to trusses composed of rods, tapes or even tubes are applicable. The selected boom technology thereby depends on the sail size and expected boom loading.

Finally the solar sail concept presented in this paper is demonstrator for a 100 m² sail design which shows a volume contribution of the sail of almost one third to the overall stowage volume which indicates the high packaging efficiency of this solar sail concept.

To further advance the development of this solar sail concept, adaptation towards a 6U-cubesat is planned that enables a deployed sail size of up to 8 m x 8 m.

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