IN ORBIT BONDING (IOB) OF LONG DEPLOYABLE STRUCTURES

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ABSTRACT

A number of space missions in the coming years will base on evolving technologies for large structural members. Application scenarios reaching from solar sail missions over solar array structures to tethered spaceships for building up large instruments are focussed. Extensive activities have been performed in the field of in-orbit deployable booms which are the main element of large structures, beside inflatables. These studies have revealed a lot of useful results on boom concepts.
According to experience the length capacity of such deployable booms is driven by the packaging process, packing density and concepts for the pre-manufactured booms, resulting in all cases in limited boom length and locally overloaded areas (e.g. by buckling). Solutions which successfully developed to overcome the packing problem possess lower stiffness and load capability. Therefore, a novel solution by in orbit assembly of semifinished parts is proposed, allowing higher packing density and therefore greater boom length (the goal is 100m), in combination with active curvature control for obtaining not only straight booms (by controlled feed and active correction if needed) but also slightly curved booms with predefined shapes.
HTS has performed a conceptual design study with the purpose to select a practicable solution and demonstrate the functional feasibility of such a solution. A hardware demonstration model (Fig. 5) was manufactured for process visualisation and testing of the implemented functions.

1 INTRODUCTION

A survey of recent technologies for deployment of long booms performed at the beginning of the work was especially focussed on coilable solutions pointing out advantages and shortcomings. The BI-STEM (Storable Tubular Extendible Member, see RD 1) and CTM (Collapsible Tube Mast, see RD 2) were found to be very interesting and promising concepts as reference for the development of an in orbit bonding facility.

The CTM can be seen as an extension of the principle of Bi-STEM where the two members were bonded at the edge and coiled together with the advantage of higher stiffness and load capability. The new approach of in-orbit bonding shifts the assembly activities of the easily coilable boom components from ground into orbit with obviously two major advantages:

- Breaking the length limitations of the recent solutions by allowing a much higher storage capacity of semi-finished parts instead of finished assemblies
- Having influence on the shape of the boom during deployment by active control of the feed and bonding of the semi-finished sections assuring accurate alignment of the resulting boom .

In cooperation with ESA a requirements specification covering the most probable application scenarios was elaborated and a specification of a demonstrator was derived.

2 REQUIREMENT SPECIFICATION

The basic functions of the in-orbit bonding facility were determined as follows:

- Storage of boom section segments
- Feed and expansion of stored boom segments
- Positioning and alignment of boom segments
- Assembly of boom sections
- Deployment of boom
- Boom alignment and length control

Supplementary to the basic functions optional functions were investigated and assessed. The additional functions of interest are:

- Curvature control
- Grappling of the remote end of the boom with other booms or payloads
- Wiring of power and data
- Power supply options including the possibility of using the boom as substrate for solar cells
- Facility separation and jettisoning to remove unnecessary masses
- Active length/alignment control to compensate thermal distortions
- Retraction of the deployed booms

3 BOOM CROSS SECTIONS

One of the first activities was the trade-off and selection of a suitable cross section. Provided that every boom should have the same mass per length a multitude of reasonable concepts was evaluated (Fig. 1). Besides mechanical properties also aspects of a simple technical solution for the main process steps were driving criteria (e.g. access to the joining area, low complexity of alignment for proper bonding). Taking into account the desired ability for a multidirectional curvature control the triple reel candidate number 8 was evaluated to be the most suitable solution.

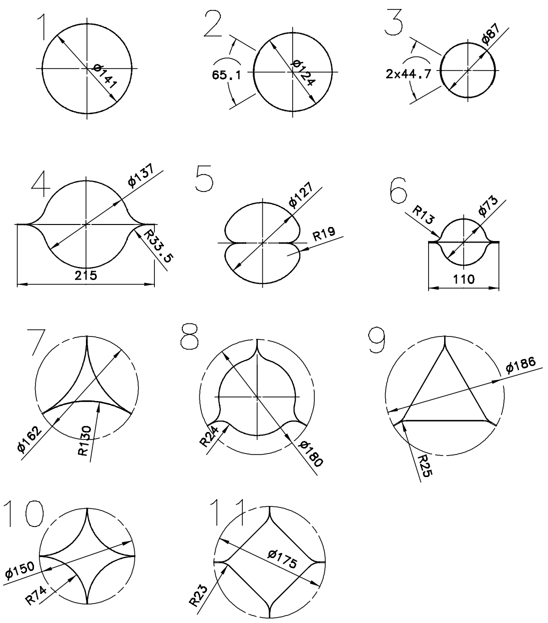


Fig. 1 possible boom sections

With respect to a simple design of the breadboard model section number 9 (Fig. 1) was chosen for the technology demonstration. The main drawback of section type no. 8 compared to no. 9 is a reduced buckling stability because of its plane side surfaces.

Carbon fibre reinforced plastic (CFRP) is the most suitable material for the manufacturing of the shells because of their low CTE and mass and the low thickness of the layers, which is needed for coiling of the semi-finished boom segments. On the other hand is a high performance concerning stiffness and strength.

4 PROCESS DEFINITION AND ASSOCIATED DESIGN

4.1 Storage

Considering that bonding is a continuous process a winding up of the CFRP bands on a drum is the preferable way of storage. The inner coil diameter is limited by allowable bending of the fibre material. Design criteria was a acceptable strain level of 0,4%. (Typical values of failure strain for CFRP are from 0,5%-1%.)

The coil thickness for a given boom length of 100 m can be estimated as follows:

$d_{i\text{-}coil}$	inner coil diameter
$d_{o\text{-}coil}$	outer coil diameter
ε	allowable strain
p	layer pitch on drum (≈shell thickness)
n	number of layers on drum
L	boom length

$$d_{i\text{-}coil} = p / \varepsilon = 0{,}3\text{mm} / 0{,}004 = 75\text{mm}$$

$$d_{o\text{-}coil} = d_{i\text{-}coil} + 2 \cdot p \cdot n$$

and

$$L = \pi \cdot n \cdot (d_{o\text{-}coil} + d_{i\text{-}coil}) / 2$$

result in

$$n = \sqrt{\left((d_{i\text{-}coil} / 2 / p)^2 + L / \pi / p \right)} - d_{i\text{-}coil} / 2 / p = 224$$

and

$$d_{o\text{-}coil} = 209 \text{ mm}$$

This is surely an idealised value for the coil diameter because the pitch will be greater than the shell thickness, especially when the bonding flanges will be pre-curved. A tension force in the up-winding procedure also plays an important roll to prevent a loose coil.

For the determination of a compact configuration for the three storage drums several concepts have been compared. Besides space saving aspect a symmetrical layout was aspired to guarantee identical conditions for each CFRP segment. Therefore the storage drums were arranged in a circular pattern (120° rotated) around the boom axis (Fig. 2).

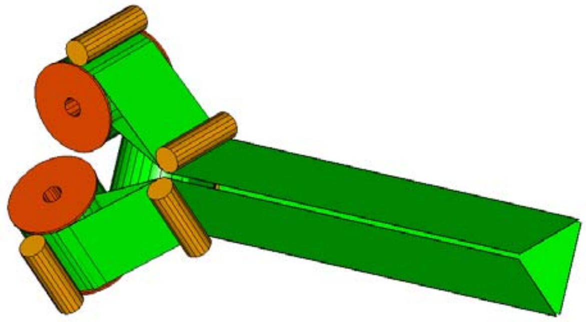


Fig. 2 storage drum configuration

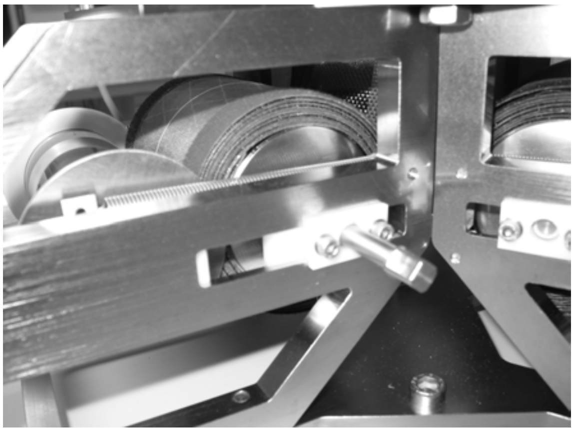


Fig. 3 demonstrator storage unit

The storage unit has been designed as a compact modular unit. This allows to connect different storage volumes depending on the needs of the application foreseen. Another goal is to facilitate jettisoning of the storage unit after deployment of the booms in-orbit when it is no more needed and would only be a handicap with respect to accelerated motions, e.g. as generated by attitude control. In particular for solar sail missions the total mass of the spacecraft has a major impact on the solar sail performance. Therefore the possibility of separation of the unnecessary mass of the facility after successful deployment of the booms has been analysed. (Fig. 4).

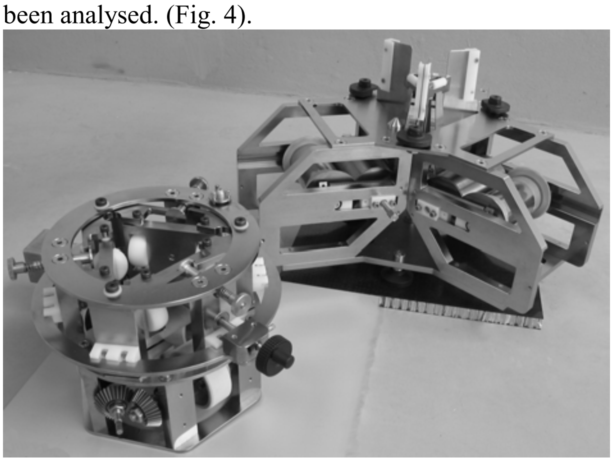


Fig. 4 jettisoning of storage unit

4.2 Feeding

For the feeding process three general aspects were investigated:

- the location of the drive in relation to the CFRP band to transport (pulling, pushing)
- the type of drive (motor, spring, pressured gas)
- principle of force transmission (friction, positive transmission)

The proposed technical solution is a geared DC-Motor pulling the CFRP-Segments with controlled speed by friction wheels. Besides the simplicity of this design the decisive reason for a drive in pulling configuration was a prioritised deployment process and the aim to keep the risk of jamming or buckling low. A retraction and winding- up of the boom is feasible . On the demonstrator the boom can be stored again by hand wheels during inward transport.

Concerning the slippage that may occur a bevel gear was used to equalise the transmission speed on every friction wheel and compensate potential slippage. The force of the assigned pressure roll was optimised to provide sufficient friction for proper transport.

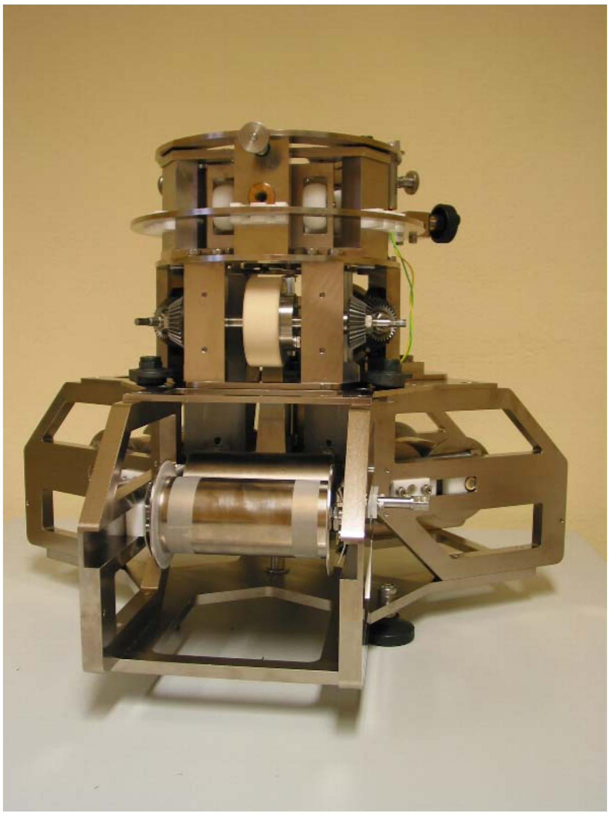


Fig. 5 IOB- demonstrator

4.3 Alignment and curvature control

Recent solutions of deployable structures possess defined dimensions with their specific tolerances. The deployable booms are manufactured to their nearly perfect shape, being typically a straight boom. During their storage on coils they are permanently stressed and creep may occur. This typically results in a shape error after deployment, without a possibility of curvature correction, only the possibility to align the tip of the deployed boom remains.

A new quality for deployment of booms will be established if the shape or the relative position of the boom ends is assessable. A first step in this direction was implemented with an alignment mechanism. This is becoming feasible with the approach in that way that the boom is assembled in space in a controlled way.

The selected method for curvature control is introducing a displacement at two of the three bonding seams of the boom segments for a certain deployment distance. This is supposed to shorten the total length of these two bonds and result in a slight deviation from the nominal curvature.

The mechanism provides 3 support brackets each bearing 2 guiding rolls for the section alignment. They are interconnected by forked hinge elements simply supported and staggered at 120° on base ring. One of three bending directions can be chosen by turning a lock ring with an attached spindle in operational position. The opposite hinge will be locked. By using the spindle the selected support bracket will be pushed towards the middle of the section and the two adjacent brackets rotate outwards (Fig. 7). This results in a displacement of the bonding seams and a modified cross section shape.

Fig. 6 Alignment mechanism - disabled

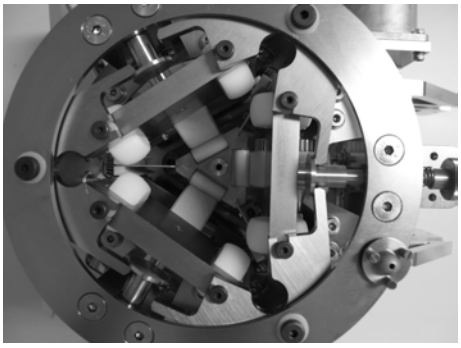
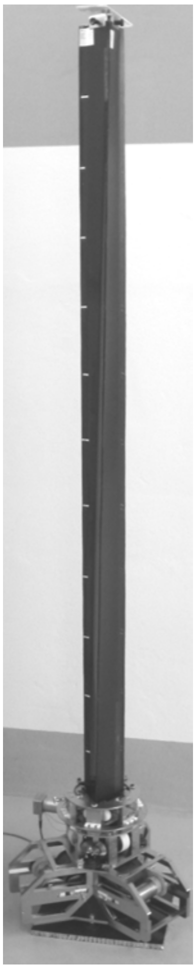


Fig. 7, Alignment mechanism – enabled

4.4 Deployment

A number of deployment tests have been performed after assembling the IOB hardware. Functional tests revealed few problematic points that could be solved. (e.g. in the alignment of the segments to each other). After providing additional adjustable guiding elements misalignments of the CFRP-segments edges were reduced. Starting point of the process demonstration is a configuration were all 3 Segments are wound-up on the storage drum and the ends are threaded through the drive unit to a position where the target can be mounted on top of the boom sample (Fig. 8). This target is focussed by a laser beam and allows monitoring of the boom deflections. The results in this early stage of testing and optimisation are very promising with respect to straightness of the booms and the operation of the facility.



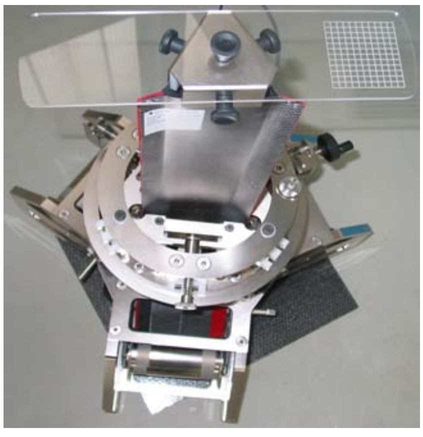


Fig. 8 Boom extension

5 CFRP- SPECIMEN MANUFACTURING

For testing and demonstration a number of sets of boom segments were manufactured in a hand laminating process. Although these samples are not intended to built state of the art booms it was possible to gain experiences on the procedures and fibre layout of the specimen.
The segments possess a length of 3m and a width of 125mm. The later assembled boom has an inscribed circle diameter of 54mm. A shell thickness of approximately 0,30-0,35 mm was achieved with this process. This allows a reasonable storage drum diameter of 80 mm. To facilitate multiple use of the segments for demonstration a reversible bonding technique was used.
After cutting and cleaning the CFRP-bands Velcro® strips were attached lengthwise at the bonding area. Hook & Loop side of the strips was applied in a alternating sequence in order to equalise the drum diameter on the storage roll. (Fig. 9)

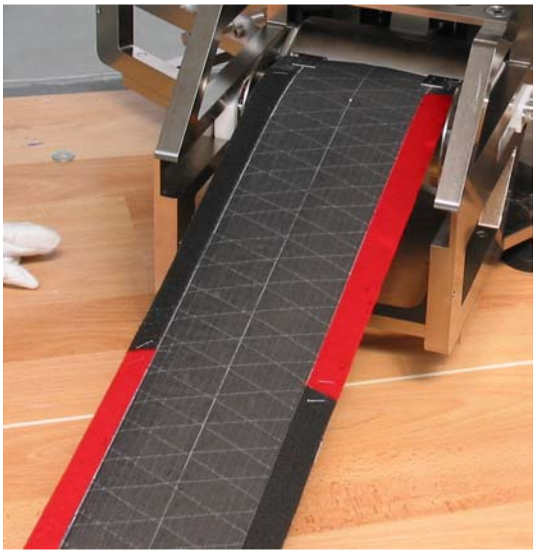


Fig. 9 CFRP-Segment ready for winding up

A point of great interest is the data and power transfer within structures. A smart concept is the embedding of conductor lines into the segments. One of the produced samples provided two undulating wires embedded in the middle of the ply stack. Winding tests revealed that the minimum drum diameter has to be larger to prevent cracks due to increased CFRP layer thickness. A local attachment of the wire at small flatable CFRP-levers may be one considerable concept for further improvements.

6 APPLICATION SCENARIOS

Solar sailing is recognised as a future technology for planetary to interstellar flight. Presently a lot of research and development programs including in-orbit demonstrations are ongoing. Unfortunately the pressure of this solar wind is very low and efficient propulsion can only be achieved for great sail areas. The length of the deployable booms is in the range of about 20 meters to 200 meters where IOB offers a concept that is breaking recent length limitations.
Also the mass allocation will be in favour of the payload and the solar sail and deployable booms shall have only a fraction of the total mass. In a solar sail mission it will therefore be useful to separate after boom deployment all unnecessary masses from the in orbit bonding facility as discussed before. The strength and shape accuracy on the other hand is of lower importance than in other applications.

Another potential application of deployable space frames composed of several deployable booms is discussed with reference to the XEUS mission under the aspect of firmly tethered mirror spacecraft (MSC) and detector spacecraft (DSC), held at a distance of 50m with an accuracy of 1mm.
Additional Benefits could be:

- Accurate length adjustment can occur through the bonding facility. This provides also the possibility to correct the position of the detector module relative to the mirror module even after full deployment. Possible are not only focal length corrections but also tilt and lateral movement, if the length of individual booms will be changed. This would allow also the compensation of any thermally induced de-focussing.
- The AOCS can somehow be simplified, because there is effectively only one spacecraft left, composed of 2 modules. The mass moment of inertia of the entire telescope, and therefore also its stability, is much higher than of the single spacecrafts before.
- Electrical connection of both modules by integrated harness and power generation by solar cells attached to the surface of the booms are conceivable.

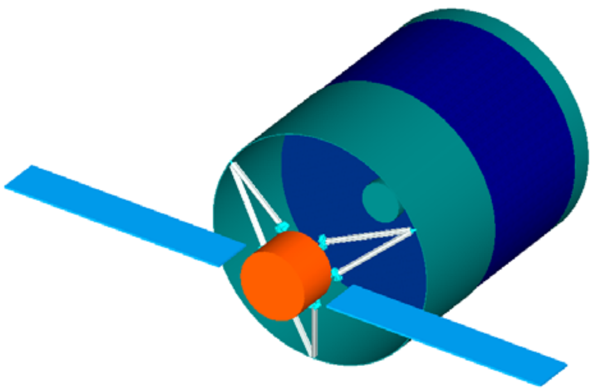


Fig. 10 XEUS scenario – e.g. service mode

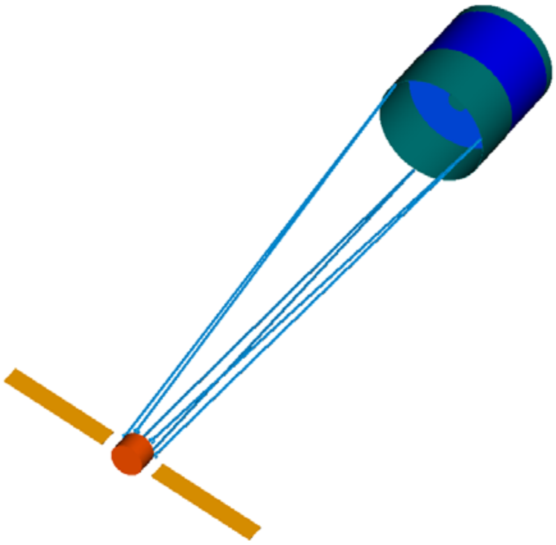


Fig. 11 XEUS scenario - operational mode

In order to simplify the AOCS and especially reduce the risk of the detector drifting outside the x-ray focus, a scenario as shown in Fig. 10 and Fig. 11 may be considered. In this example the DSC is connected with the MSC by means of 3 bipods, 1 every 120°. This arrangement provides an isostatic mounting condition. It is often used for the attachment of big mirrors, is reasonably stiff and free of unknown forces disturbing the optical quality. This arrangement will lead to a total of 6 booms, 50 m long each.
The list of reasonable application scenarios could be supplemented with reflector areas or sun shields.

7 CONCLUSIONS AND ROADMAP

The in orbit bonding principle investigated in the study has the potential for a wide field of applications. The winding of semi-finished materials and the assembling in space resulting in a well defined straight and stiff boom of a big length is a beneficial method of storage for long structural members as needed for example in solar sail structures, solar arrays or sun shields for the next generation space telescopes.

The further development of the IOB concept should be focussed on three main steps:

- Detailed investigation of an automated bonding technology including the selection of suitable adhesives,
- Definition of all subsystems of the facility including power supply, motor drive, latching, remote control and sensing and detailed analysis of the facility with respect to a potential space application, and
- Design of a full size space compatible demonstrator as a first step towards a demonstration mission (mass budget, lubrication).

After the successful completion of these activities the application of the in-orbit bonding facility in a real or demonstration mission can be envisaged.

8 REFERENCES

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RD 2. The CTM family of masts and the CTM engineering model; M.Aguirre, R. Bureo, F. del Campo, M. Fuentes; Proceedings of the 3rd ESMATS; Madrid 1987

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