A Critical Review of Deployable Truss Masts and Proposal of a New Mast: HiDAM

Yunus Cebeci, Murat Demirel, and Gökhan Kiper

Abstract: This paper investigates the factors which affect the packing ratio of deployable articulated truss masts and investigates the necessary design criteria for new designs with enhanced packing ratio. First, the available deployable articulated truss masts are examined, and the design parameters of these structures are worked out. Then a novel design called HiDAM is proposed with superior packing ratio compared to similar ones in the literature.

Keywords: Satellite components, Deployable structures, Deployable mast.

1. Introduction

Small cargo volumes of space crafts are a big limitation in space applications. This restriction is the main design parameter for structures requiring larger aperture diameters and longer focal lengths, because it inherently affects the functionality of these structures such as their resolutions and working spaces (Puig et al., 2010). Deployable structures are used when compactness is required during transportation and storage. Packing ratio of these structures is an important design parameter. Several studies address the compactness problem for space applications (Darooka and Jensen, 2001; Hanaor and Levy, 2001; Jensen and Pellegrino, 2001; Tibert, 2002; Kiper and Söylemez, 2009; Puig et al., 2010; Straubel, 2012).

This study is on deployable masts (DMs), which are commonly used in satellites and other space structures. DMs can be classified as coilable booms and articulated masts which are truss-like structures containing rigid components (Straubel, 2012). Generally, masts have larger cross-section compared to booms (Ihle et al., 2016). In choosing a DM, the length of the mast and the quantity of payload necessary for the application are critical factors. While the coilable structures are preferred where low endpoint positioning accuracy (mm-cm level) and less load bearing capacity are needed, articulated and telescopic masts are suitable for the applications requiring higher load-bearing capacity (up to 100 kg) and high endpoint accuracy (μm-mm level) (Puig et al., 2010). Telescopic masts have a higher folding rate compared to articulated masts, but articulated masts are more convenient for space applications that require higher bearing capacity, deployment reliability and positioning accuracy. Deployable truss masts (DTMs) usually have similar parts such as longerons for longitudinal elements and battens for transverse elements (Fig.1A).

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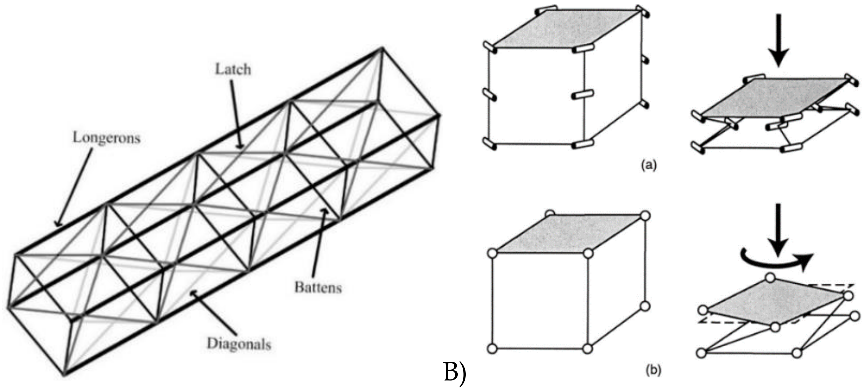

A) B)

Fig.1. A) DTM terminology B) DM folding principles a) translational type, b) screw type (Pellegrino, 2014)

The polygonal structures formed by battens can also be called as platforms. There may be hinges at the ends of the longerons and battens. Also, these structures may require diagonal cables and latch mechanisms to increase stiffness. Pellegrino (2014) describes two folding principles for deployable masts (Fig.1B) which can be named as translational-type folding and screw-type folding. Obviously, these folding principles directly affect the motion of the DMs. For instance, a mast performs a synchronous deployment if its folding principle is based on the screw type, but if it is the translational type, it executes a sequential deployment.

In this paper, first a critical review for DTMs is presented. Then a new design with higher packing ratio compared to existing structures is introduced.

2. Existing Deployable Truss Masts

Several types of articulated masts have been patented (Mauch, 1969; Benton and Robbins Jr, 1986; Hedgepeth and Adams, 1986; Kitamura et al., 1990). ATK/ABLE Engineering Company designed the Folding Articulated Square Truss (FAST) to support the solar arrays on the International Space Station (ISS) (Warden, 1987). Able Deployable Articulated Mast (ADAM) was designed as an improved version of the FAST and it has been flight proven with many applications such as Shuttle Radar Topography Mission (Ramirez, 1998; Gross and Messner, 1999). Xue et al. (2018) studied the influence parameters of the ADAM in detail as well. Since these masts have longer focal lengths and higher payload capacity, they are mainly used in applications requiring baseline extension with a radar at the tip of the mast or high-resolution optical systems. Additionally, while FAST realizes translational type of folding principle, ADAM has screw type folding principle.

Working on the parametric modelling of the open and closed states of DTMs, Deng et al. (2011) designed a tapered DM with low mass and increased stiffness, for which the height of the DTM can be determined with the given geometrical analysis with no regard to its constructional design. In their study, it is shown that the mechanical properties of the tapered design are improved compared to DTMs with identical cross-sectional areas. Guo and You's (2012) DTM design with serially connected Bennett linkages has single degree-of-freedom (DoF) and its open and closed dimensions can be calculated parametrically. Another novel DTM is proposed by Lu et al. (2014) using Hoekens linkage as a deploying unit and they determined appropriate actuation systems according to static analysis and structural behaviour.

In most space applications, a constant orientation of the tip of the mast is desired during the motion. For instance, deploying the solar panels of the ISS requires only translational motion and most components to be located at a distance out of the satellite body such as cameras and sensors should not rotate during deployment. To achieve this, Borel-Bricard motion was used (Bricard, 1896; Borel, 1905). It is a spatial motion in which all point paths are spherical curves. It is used in design of a DTM based on Wren platforms by Kiper and Söylemez (2011), where over-constrained single-DoF mechanisms with Borel-Bricard motion are issued. Lee and Hervé (2014) also studied mechanisms with the Borel-Bricard motion in detail.

Based on the work by Kiper and Söylemez, Zhao et al. (2018) proposed a DTM system, which has better stiffness characteristics than ADAM. They designed and made a prototype of the Self-Lockable Deployable Structure (SDS) which comprises reconfigurable extended joint (REJ). Later the design was patented (Wang et al., 2016). This unit also realizes Borel-Bricard motion. Once the mast is fully deployed, singularity occurs due to the self-motion of the longerons. As a result, it becomes self-locked against longitudinal forces. When the mast is fully deployed, only the first two units need to be folded to lock the entire structure completely.

Fig.2 shows the SDS and its configurations. Here, the hinges used to connect the longerons and battens at the corners are called H-joints which have 3-DoF with 2 parallel axes and an axis perpendicular to them. Another DTM based on Wren platforms is proposed by Wang et al. (2022) recently, in which the link lengths are optimized to maximize the packing ratio by replacing universal joints with a pair of skew revolute joints. In other words, the H-joint in SDS is altered by adding an offset. They also developed a mathematical model and proved that this DM has the largest packing ratio of all comparable structures in the literature (Fig.3). By examining these DTMs, it is seen that the packing ratio can be increased by modifying constructional details. In the next section, a new DTM called Highly Deployable Articulated Mast (HiDAM) is introduced and compared with the other DTMs in the literature.

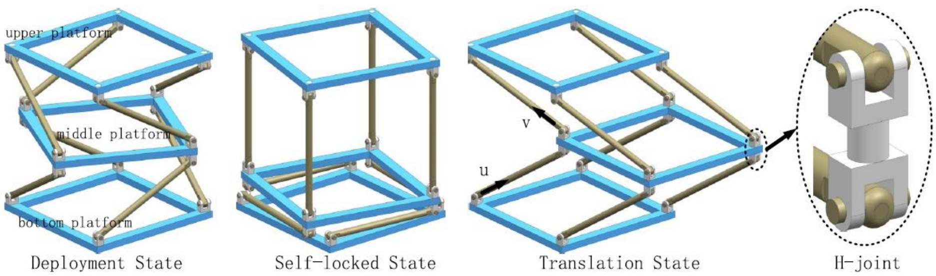

Fig.2. Self-Lockable Deployable Structure (SDS) presented by Zhao et al. (2018).

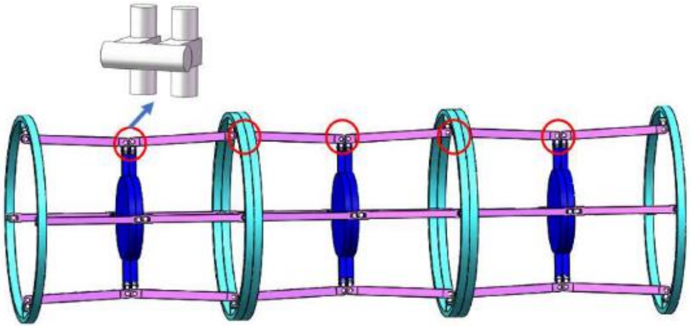

Fig.3. DTM by Wang et al. (2022).

3. Design of Highly-Deployable Articulated Mast

To be able to compare any two DTMs in terms of their packing ratios, their footprint should be equal. Since the canisters used to store these structures are mostly cylindrical (Galvez et al., 2011), the base area covered by the structure is a circle. The polygonal platforms composed of battens and the longerons connecting these platforms at their corners must be circumscribed by this circle.

In Wang et al.'s (2022) study, the joint axis perpendicular to the parallel axes to which the longerons are attached is designed with an offset. With the help of this modification, it is possible to design the platforms to act as the perimeter boundary to avoid overlaps within the allowable volume. Although this design makes it easier to position the parts, it also causes a loss of usable circumference due to the platform wall thickness, so it causes using shorter longerons which adversely affect the packing ratio. Since the goal is to increase packing ratio in the proposed design, we used 3-sided star-shaped platforms, which allows us to locate longer longerons inside the circumscribing circle. As a result, a deployable unit realizing Borel-Bricard motion is constructed.

4. Conclusion and Future Works

The final optimization computations will be carried out for HiDAM after the constructional design is finalized according to the aforementioned design constraints. However, initial results showed that packing ratios larger than 17 can be easily obtained with the proposed model. This is about 12% better than 15.17 which is reported by Wang et al. (2022). The DTMs are have the same circumradius of 45 mm. For larger circumradius values, larger packing ratios can be obtained.

Due to the limitations, the link lengths of a DTM mechanism cannot be determined considering geometrical restrictions only. Therefore, the mechanism design should be performed along with the constructional design. Once the CAD design is finalized along with structural and modal analyses, a prototype of HiDAM will be produced and functional and performance tests will be carried out to check the packing ratio, stiffness and positioning accuracy.

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References

Benton, M. D. and Robbins Jr, W. M. (1986) Extendible Structures. Patent US4599832A.

Borel, É. M. (1905) Mémoire sur les Déplacements à Trajectoires Sphériques. Imprimerie Nationale.

Bricard, R. (1896) 'Géométrie cinématique—sur un déplacement remarquable', Comptes-Rendus de l'Académie des Sciences, Paris, 123(22), 939–940.

Darooka, D. and Jensen, D. (2001) 'Advanced space structure concepts and their development', in 19th AIAA Applied Aerodynamics Conference, 1257.

Deng, Q. et al. (2011) 'Design and analysis of a tapered deployable mast', in Key Engineering Materials. Trans Tech Publ, 31–34.

Galvez, R. et al. (2011) 'The Space Shuttle and Its Operations', in Wings In Orbit Scientific and Engineering Legacies of the Space Shuttle. 3409th Ed. Government Printing Office, pp. 53–73.

Gross, D. and Messner, D. (1999) 'The ABLE deployable articulated mast—enabling technology for the Shuttle Radar Topography Mission', in 33rd Aerospace Mechanisms Symp.

Guo, H. and You, Z. (2012) 'Deployable masts based on the Bennett linkage', in Advances in Reconfigurable Mechanisms and Robots I. Springer, 739–747.

Hanaor, A. and Levy, R. (2001) 'Evaluation of deployable structures for space enclosures', International Journal of Space Structures, 16(4), 211–229.

Hedgepeth, J. M. and Adams, L. R. (1986) Rigid Diagonal Deployable Lattice Column. Patent US4569176A.

Ihle, A. et al. (2016) 'Deployable structures activities at the european space agency's structures section', 14th European Conference on Spacecraft Structures, Materials and Environmental Testing, 1–14.

Jensen, F. and Pellegrino, S. (2001) Arm Development Review of Existing Technologies. Cambridge University.

Kiper, G. and Söylemez, E. (2009) 'Deployable space structures', in 4th International Conference on Recent Advances in Space Technologies, İstanbul, 131–138.

Kiper, G. and Söylemez, E. (2011) 'Modified Wren platforms', in 13th IFToMM world congress, Guanojuato, Mexico, Vol. 1, 1183-1187.

Kitamura, T. et al. (1990) 'Development of a high stiffness extendible and retractable mast 'Himat' for space applications', in 31st Structures, Structural Dynamics and Materials Conference, 1054.

Lee, C.-C. and Hervé, J. M. (2014) 'Bricard one-dof motion and its mechanical generation', Mechanism and Machine Theory, 77, 35–49.

Lu, S. et al. (2014) 'A new family of deployable mechanisms based on the Hoekens linkage', Mechanism and Machine Theory, 73, 130–153.

Mauch, H. R. (1969) Deployable Lattice Column. Patent US3486279A.

Pellegrino, S. (2014) Deployable Structures. Springer.

Puig, L., Barton, A. and Rando, N. (2010) 'A review on large deployable structures for astrophysics missions', Acta Astronautica, 67(1–2), 12–26.

Ramirez, E. (1998) Shuttle Radar Topography Mission. Available at: https://www2.jpl.nasa.gov/srtm/mast_photos.html (Accessed: 11 Sept. 2019).

Straubel, M. (2012) Design and Sizing Method for Deployable Space Antenna. Deutsches Zentrum für Luft-und Raumfahrt eV.

Tibert, G. (2002) Deployable Tensegrity Structures for Space Applications. KTH.

Wang, H. et al. (2016) Reconfigurable Extended Joint. Patent CN104608117B.

Wang, J., Kong, X. and Yu, J. (2022) 'Design of deployable mechanisms based on Wren parallel mechanism units', Journal of Mechanical Design, 144(6), 63302.

Warden, R. M. (1987) 'Folding, articulated, square truss', in 21st Aerospace Mechanisms Symposium, LB Johnson Space Center, Houston, Texas.

Xue, N. et al. (2018) 'The influence parameters of 60m ABLE deployable articulated mast mode', in Proc. Int. Symp. Big Data and Artificial Intelligence, 299–305.

Zhao, L. et al. (2018) 'Sequentially assembled reconfigurable extended joints: self-lockable deployable structure', Journal of Aerospace Engineering, 31(6), 4018103.