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(54) **DEPLOYABLE SHEET MATERIAL SYSTEMS AND METHODS**

(56) **References Cited**

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U.S. PATENT DOCUMENTS

3,144,104 A *	8/1964	Weir .....	E04C 3/005 182/41
3,169,725 A *	2/1965	Berglund .....	B64G 1/12 244/155 R
3,213,573 A *	10/1965	Bohr .....	B21C 37/10 174/DIG. 11
3,300,910 A *	1/1967	Isaac .....	B64C 27/50 137/355.26
3,362,656 A *	1/1968	Wyatt .....	B64G 1/32 244/167
3,363,857 A *	1/1968	Vilbig .....	B64G 1/10 244/1 R
3,387,414 A *	6/1968	Adams .....	E04C 3/005 206/216

(Continued)

OTHER PUBLICATIONS

Pappa et al, "Solar Array Structures for 300 kW-Class Spacecraft," Space Power Workshop, Manhattan Beach, CA, Apr. 24, 2013.

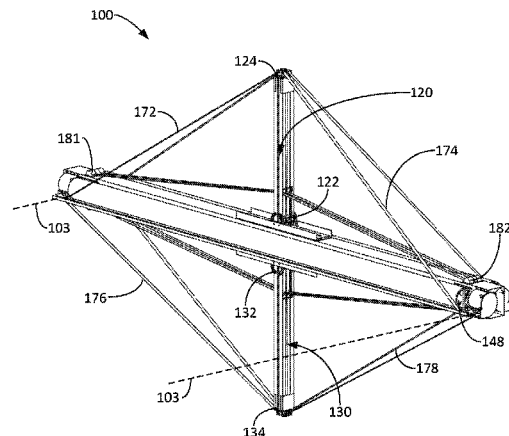
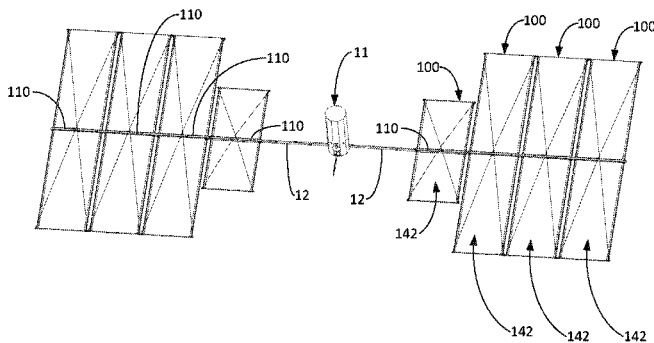
(Continued)

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(57) **ABSTRACT**

Exemplary deployable sheet material systems may be configured to stow and deploy sheet material. The systems may include one or more masts, one or more extendable booms, and one or more guys wires configured to function in conjunction with each other to deploy the sheet material and then to maintain the sheet material in the deployed configuration.

**20 Claims, 12 Drawing Sheets**



(56)

References Cited

U.S. PATENT DOCUMENTS

3,480,232	A *	11/1969	Theodore	B64G 1/32 244/167	5,833,176	A *	11/1998	Rubin	B64G 1/222 244/172.7
3,499,610	A *	3/1970	Hamlin	B64G 9/00 138/166	5,865,905	A *	2/1999	Clemens	H01L 31/0547 126/624
3,508,587	A *	4/1970	Mauch	F16L 11/121 138/119	5,961,738	A *	10/1999	Benton	B64G 1/44 136/245
3,521,290	A *	7/1970	Hossein	B64G 1/22 244/1 R	6,016,999	A *	1/2000	Simpson	B64G 1/1007 244/159.5
3,528,543	A *	9/1970	Robinsky	B65D 81/03 428/178	6,017,002	A *	1/2000	Burke	B64G 1/222 136/245
3,532,299	A *	10/1970	Baker	B64G 1/222 136/245	6,051,775	A *	4/2000	Brown	B64G 1/222 136/245
3,589,632	A *	6/1971	Rew	B21C 47/003 188/82.84	6,206,327	B1 *	3/2001	Benedetti	B64G 1/10 244/159.4
3,608,844	A *	9/1971	Tumulty, Jr.	B21C 47/18 242/373	6,217,975	B1 *	4/2001	Daton-Lovett	B29C 61/0608 156/161
3,690,080	A *	9/1972	Dillard	B64G 1/222 136/245	6,256,938	B1 *	7/2001	Daton-Lovett	F16H 19/064 138/119
3,696,568	A *	10/1972	Berry	E04C 3/005 52/108	6,286,787	B1 *	9/2001	Fleeter	B64G 1/007 244/110 D
3,735,943	A *	5/1973	Fayet	B64G 1/222 136/245	6,343,442	B1 *	2/2002	Marks	B64G 1/222 244/172.6
3,749,133	A *	7/1973	Bochory	F16L 11/121 138/119	6,374,565	B1 *	4/2002	Warren	B64G 1/222 138/119
3,785,590	A *	1/1974	Wentworth	B64G 1/222 244/1 R	6,423,895	B1 *	7/2002	Murphy	H02S 30/20 136/245
3,809,337	A *	5/1974	Andrews	B64G 1/222 136/245	6,437,232	B1 *	8/2002	Dailey	B64G 1/222 136/245
3,811,633	A *	5/1974	Cummings	B29C 53/20 226/172	6,478,261	B2 *	11/2002	Laraway	B64G 1/222 244/172.6
3,817,481	A *	6/1974	Berks	B64G 1/222 136/245	6,508,036	B1 *	1/2003	Cadogan	B64G 1/222 52/108
3,848,821	A *	11/1974	Scheel	B64G 1/222 135/115	6,543,725	B1 *	4/2003	Meurer	B64G 1/443 136/245
3,862,528	A *	1/1975	Meissinger	B64G 9/00 242/390.2	6,547,190	B1 *	4/2003	Thompson	B64G 1/443 244/172.7
4,018,397	A *	4/1977	Rusch	B21C 37/10 242/388.6	6,550,720	B2 *	4/2003	Fleeter	B64G 1/641 244/110 D
4,030,102	A *	6/1977	Kaplan	H01Q 15/161 136/245	6,568,638	B1 *	5/2003	Capots	B64G 1/10 244/159.4
4,047,339	A *	9/1977	Smith	E04C 3/005 52/108	6,637,702	B1 *	10/2003	McCandless	B64G 1/222 244/172.6
4,133,501	A *	1/1979	Pentlicki	B64G 1/443 136/245	6,843,029	B2 *	1/2005	Breitbach	B64G 1/222 52/108
4,225,871	A *	9/1980	Ramari	H01Q 1/087 343/877	6,888,513	B1 *	5/2005	Graham	B64G 1/222 343/880
4,265,690	A *	5/1981	Lowenhar	H01P 3/00 156/148	6,942,186	B1 *	9/2005	Levin	B64G 1/648 244/158.2
4,384,163	A *	5/1983	Rauschenbach	B64G 1/222 136/245	7,104,506	B1 *	9/2006	Goodzeit	B64G 1/222 244/168
4,426,053	A *	1/1984	Chenin	B64G 1/222 136/245	7,211,722	B1 *	5/2007	Murphy	H02S 20/00 136/245
4,579,302	A *	4/1986	Schneider	B64G 9/00 136/292	7,617,639	B1 *	11/2009	Pollard	B64G 1/222 343/915
4,630,791	A *	12/1986	Chapman	B64G 1/14 136/245	7,694,486	B2 *	4/2010	Murphy	B64G 1/222 52/645
4,991,784	A *	2/1991	Schmid	B64G 9/00 242/390.3	7,895,795	B1 *	3/2011	Murphey	B64G 1/222 52/108
5,228,644	A *	7/1993	Garriott	B64G 1/443 136/245	8,167,247	B2 *	5/2012	Daily	G02B 26/02 244/158.1
5,235,788	A *	8/1993	Maimets	B64G 4/00 244/172.6	8,292,232	B1 *	10/2012	Andrews	B64G 1/62 244/159.1
5,296,044	A *	3/1994	Harvey	H02S 30/20 136/245	8,356,774	B1 *	1/2013	Banik	B64G 1/407 244/159.5
5,314,146	A *	5/1994	Chicoine	B64G 1/10 244/159.4	8,616,502	B1 *	12/2013	Stribling	B64G 1/44 244/172.7
5,520,747	A *	5/1996	Marks	B64G 1/222 136/245	8,636,253	B1 *	1/2014	Spence	B64G 1/222 136/245
5,720,452	A *	2/1998	Mutschler, Jr.	B64G 1/222 136/245	8,683,755	B1 *	4/2014	Spence	B64G 1/222 136/245
5,779,195	A *	7/1998	Basuthakur	B64G 1/007 244/173.1	8,770,522	B1 *	7/2014	Murphey	B64G 1/222 244/159.4
					8,816,187	B1 *	8/2014	Stribling	H02S 30/20 136/245
					8,893,442	B1 *	11/2014	Spence	E04C 3/005 52/108

(56)	References Cited					
	U.S. PATENT DOCUMENTS					
8,894,017	B1 *	11/2014	Baghdasarian	B64G 1/443	2012/0012154	A1 * 1/2012 Keller ..... B64G 1/222 136/245
8,905,357	B1 *	12/2014	Harvey	B64G 1/007 244/168	2012/0025750	A1 * 2/2012 Margo ..... H01M 10/465 320/101
9,004,410	B1 *	4/2015	Steele	B64G 1/443 244/172.7	2012/0090660	A1 * 4/2012 Keller ..... B64G 1/222 136/245
9,016,635	B2 *	4/2015	Hoyt	B64G 1/007 244/158.2	2012/0167943	A1 * 7/2012 Blanchard ..... B64G 1/222 136/245
9,120,583	B1 *	9/2015	Spence	H02S 30/20	2012/0167944	A1 * 7/2012 Blanchard ..... B64G 1/222 136/245
9,156,568	B1 *	10/2015	Spence	B64G 1/44	2013/0061541	A1 * 3/2013 Taylor ..... B29C 67/0014 52/108
9,550,584	B1 *	1/2017	Harvey	B64G 1/222	2013/0186011	A1 * 7/2013 Keller ..... E04H 12/00 52/108
9,580,190	B1 *	2/2017	Spence	B64G 1/222	2013/0233371	A1 * 9/2013 Rodin ..... H02S 30/20 136/245
9,605,430	B2 *	3/2017	Baudasse	E04C 3/005	2014/0042275	A1 * 2/2014 Abrams ..... B64G 1/222 244/172.6
9,611,056	B1 *	4/2017	Spence	B64G 1/443	2014/0123575	A1 * 5/2014 Bobbio ..... E04H 12/185 52/108
9,718,639	B2 *	8/2017	Baudasse	B64G 1/222	2014/0151485	A1 * 6/2014 Baudasse ..... B64G 1/222 242/375
9,856,039	B2 *	1/2018	Abrams	B64G 1/222	2014/0230949	A1 * 8/2014 Daton-Lovett ..... B64G 1/222 138/177
9,919,815	B2 *	3/2018	Steele	B64G 1/443	2014/0263844	A1 * 9/2014 Cook, Jr. .... B64G 1/222 244/164
9,975,652	B2 *	5/2018	Blanchard	B64G 1/222	2015/0102172	A1 * 4/2015 Thurn ..... B64G 1/40 244/158.2
10,059,471	B2 *	8/2018	Steele	B64G 1/44	2015/0144740	A1 * 5/2015 Turse ..... B64G 1/44 244/172.6
2002/0096603	A1 *	7/2002	Bauer	B64G 1/222 244/172.7	2015/0259911	A1 * 9/2015 Freebury ..... E04C 3/005 52/108
2002/0112417	A1 *	8/2002	Brown	B64G 1/222 52/108	2015/0284955	A1 * 10/2015 Adams ..... E04C 3/005 52/108
2003/0000569	A1 *	1/2003	Zwanenburg	B64G 1/222 136/251	2015/0368903	A1 * 12/2015 Turse ..... B65H 75/4402 242/407
2003/0015625	A1 *	1/2003	McGee	B64G 1/222 244/172.6	2016/0010333	A1 * 1/2016 Freebury ..... E04C 3/005 52/646
2003/0057330	A1 *	3/2003	Deel	B64G 1/222 244/172.8	2016/0023781	A1 * 1/2016 Baudasse ..... B65H 75/28 52/108
2003/0164186	A1 *	9/2003	Clark	B64G 1/222 136/245	2016/0024790	A1 * 1/2016 Baudasse ..... E04C 3/005 52/108
2003/0182878	A1 *	10/2003	Warren	B64G 1/222 52/108	2016/0032609	A1 * 2/2016 Kucinski ..... B21C 37/0818 52/108
2005/0178921	A1 *	8/2005	Stribling	B64G 1/222 244/172.7	2016/0122041	A1 * 5/2016 Abrams ..... B64G 1/222 244/172.6
2006/0185277	A1 *	8/2006	Quincieu	B64G 1/10 52/265	2016/0137319	A1 * 5/2016 Steele ..... B64G 1/443 52/745.2
2006/0207189	A1 *	9/2006	Pryor	B64G 1/222 52/1	2016/0311558	A1 * 10/2016 Turse ..... B64G 1/222
2007/0145195	A1 *	6/2007	Thomson	B64G 1/222 244/172.6	2016/0332752	A1 * 11/2016 Abrams ..... B64G 1/222
2007/0262204	A1 *	11/2007	Beidleman	B64G 1/222 244/172.6	2017/0021947	A1 * 1/2017 Pellegrino ..... H02S 10/40
2008/0143636	A1 *	6/2008	Couchman	B64G 1/66 343/915	2017/0063296	A1 * 3/2017 Crujssen ..... H02S 40/22
2009/0057492	A1 *	3/2009	Harris	B64G 1/222 244/164	2017/0158357	A1 * 6/2017 Hart, III ..... B64G 1/222
2009/0173831	A1 *	7/2009	Roseman	B64G 1/12 244/159.6	2017/0297749	A1 * 10/2017 Steele ..... B64G 1/44
2009/0184207	A1 *	7/2009	Warren	B64G 1/222 244/172.6	2017/0298628	A1 * 10/2017 Rakow ..... B64G 1/222
2009/0218448	A1 *	9/2009	Peypoudat	B64G 1/007 244/158.7	2017/0320600	A1 * 11/2017 Crujssen ..... H01L 31/041
2010/0163684	A1 *	7/2010	Dando	B64G 1/222 244/172.6	2018/0111703	A1 * 4/2018 Hensley ..... B64G 1/222
2010/0187364	A1 *	7/2010	Kutter	B64G 1/1078 244/171.7		
2010/0187365	A1 *	7/2010	Kutter	B64G 1/1078 244/171.7		
2011/0162690	A1 *	7/2011	Workman	H02S 30/20 136/245		
2011/0204186	A1 *	8/2011	Keller	B64G 1/222 244/172.6		
2011/0210209	A1 *	9/2011	Taylor	B64G 1/222 244/172.6		
2011/0253193	A1 *	10/2011	Korman	H01L 31/048 136/245		
2011/0253614	A1 *	10/2011	Curran	H02S 30/20 210/239		
2011/0253827	A1 *	10/2011	Watanabe	B64G 1/222 242/370		

## OTHER PUBLICATIONS

Dhere et al., "CIGS2 Thin-Film Solar Cells on Flexible Foils for Space Power," NASA/CP-2002-211831, 91-100.

Hopkins, "Stepping Stones: Exploring Increasingly Challenging Destinations on the Way to Mars," Lockheed Martin, 2012.

NASA, "Combination Methods for Structural Deriving Design Loads Considering Vibro-Acoustic, etc., Responses," NASA PD-ED-1211, Lesson Date: Feb. 1, 1999, Lesson No. 652, 1-4.

Penson et al., "Hypervelocity Impact Studies on Space Tethers," 54<sup>th</sup> International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law, Bremen, Germany, *International Astronautical Federation*, Sep. 29-Oct. 3, 2003.

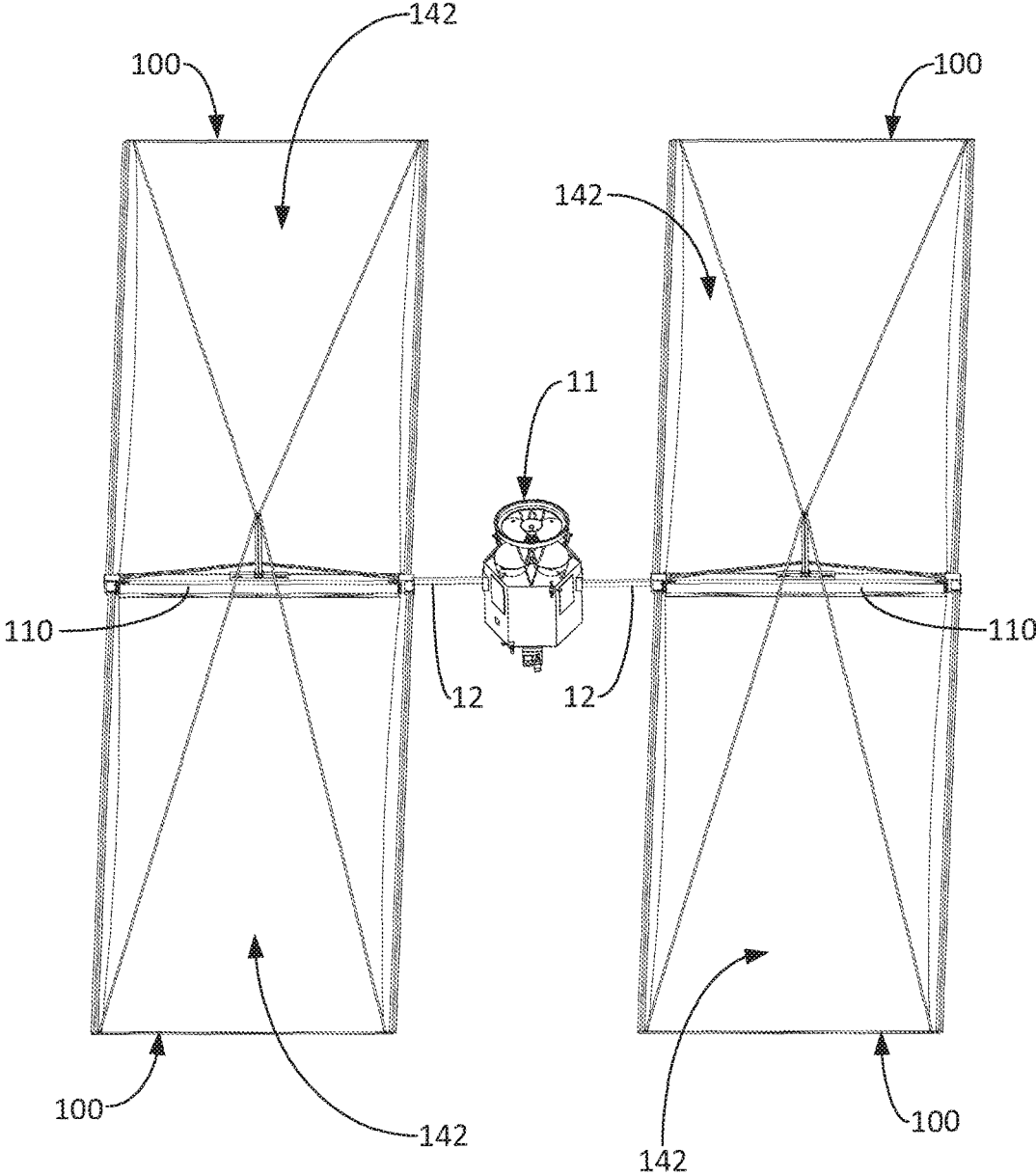
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**References Cited**

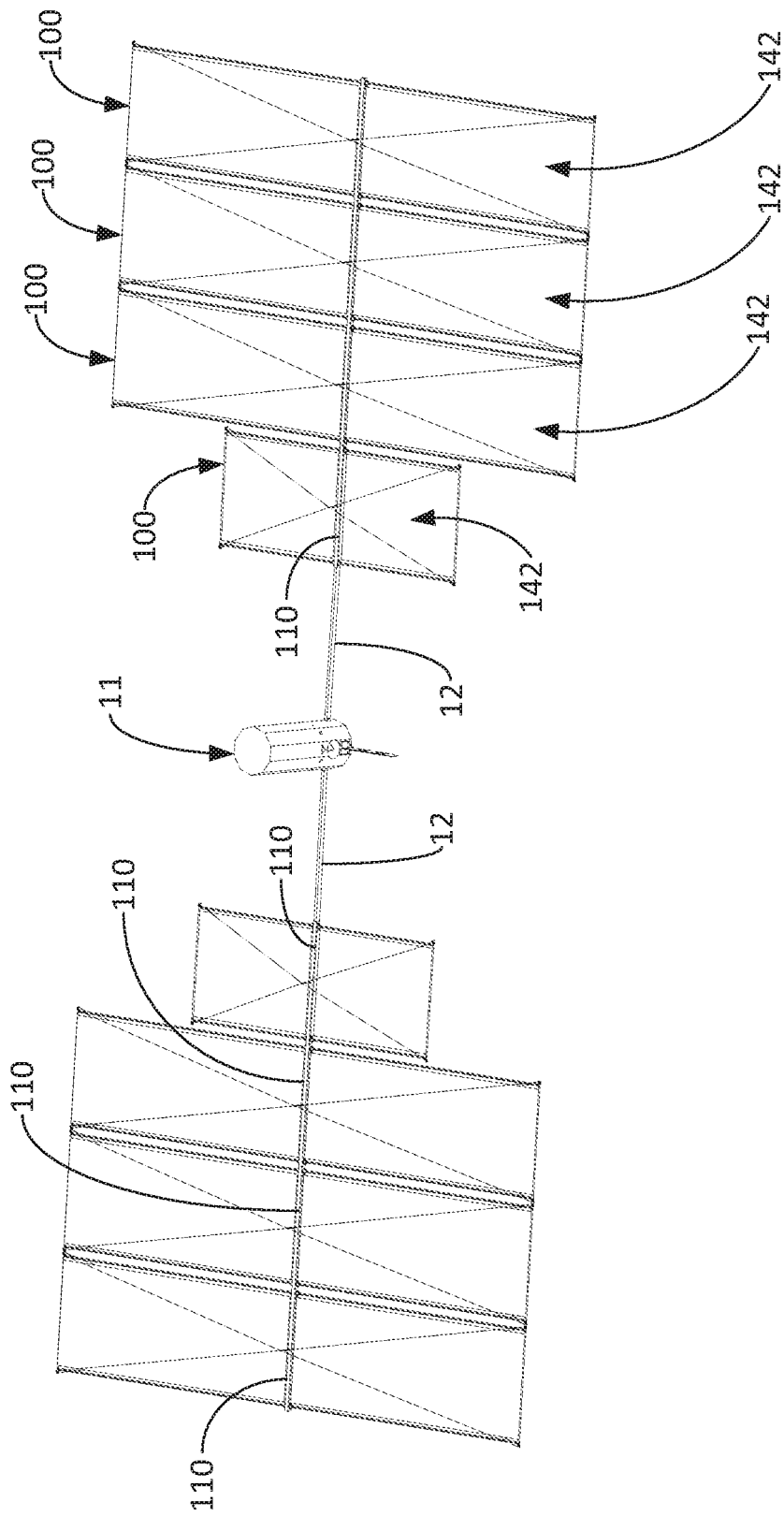
OTHER PUBLICATIONS

Vanguard Space Technologies, 2014. [Online]. Available: <http://vst-inc.com/satellite-components/solar-power-systems/flexible-solar-panels/>.

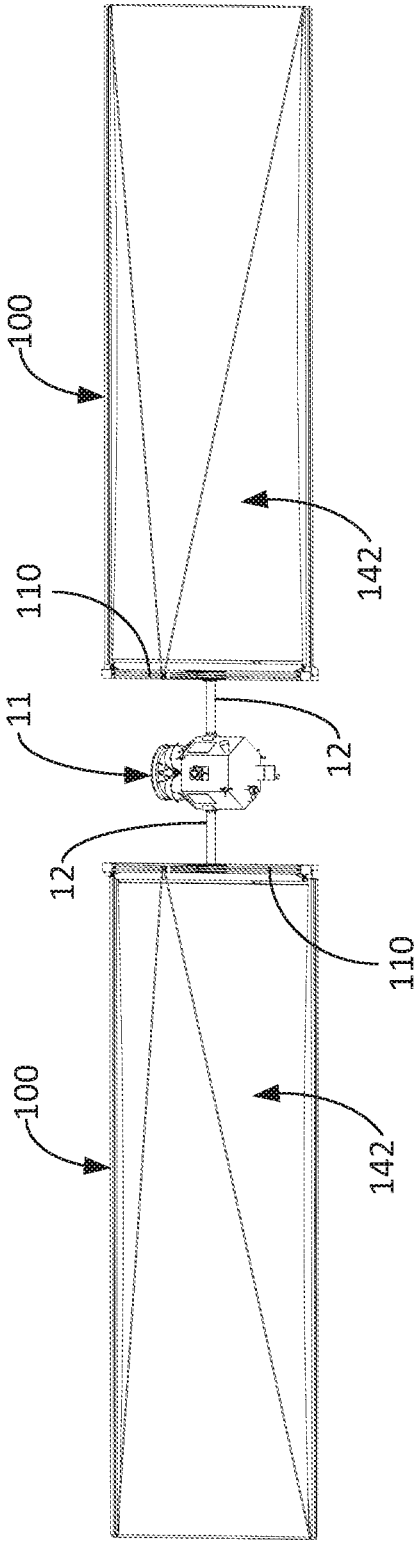
\* cited by examiner



**Fig. 1A**



**Fig. 1B**



**Fig. 1C**

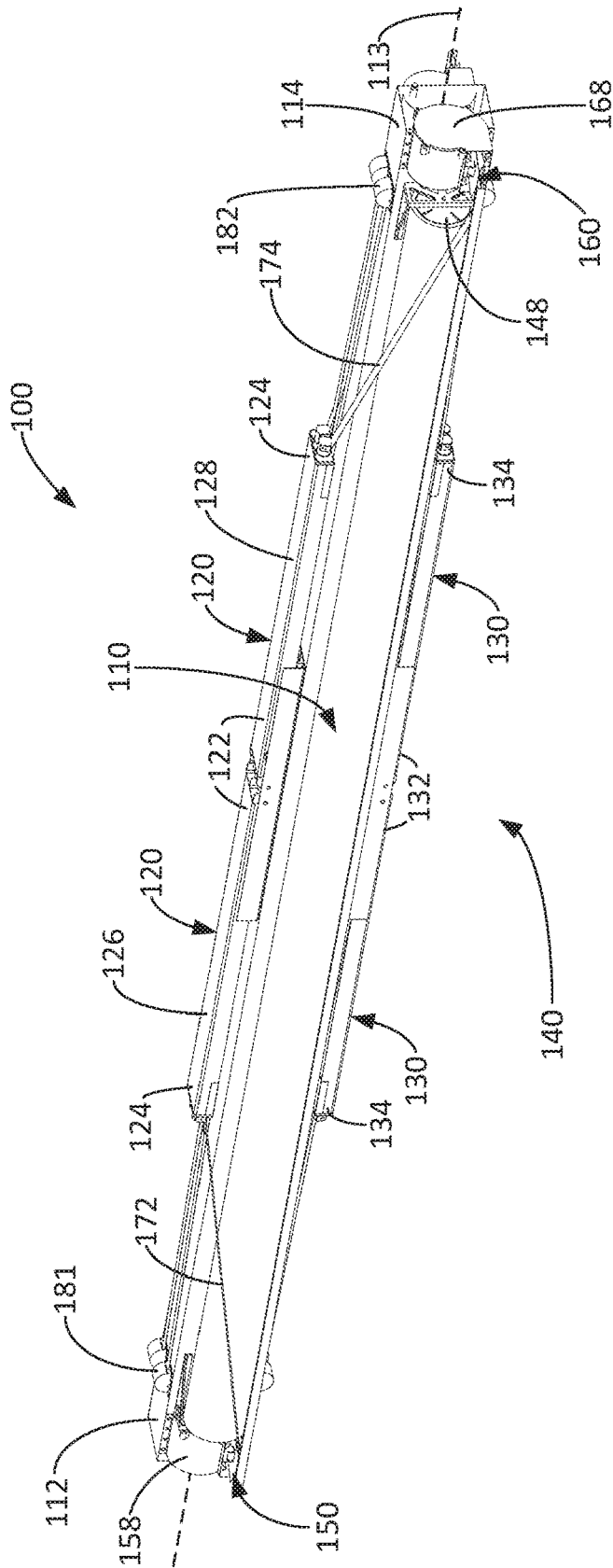


Fig. 2



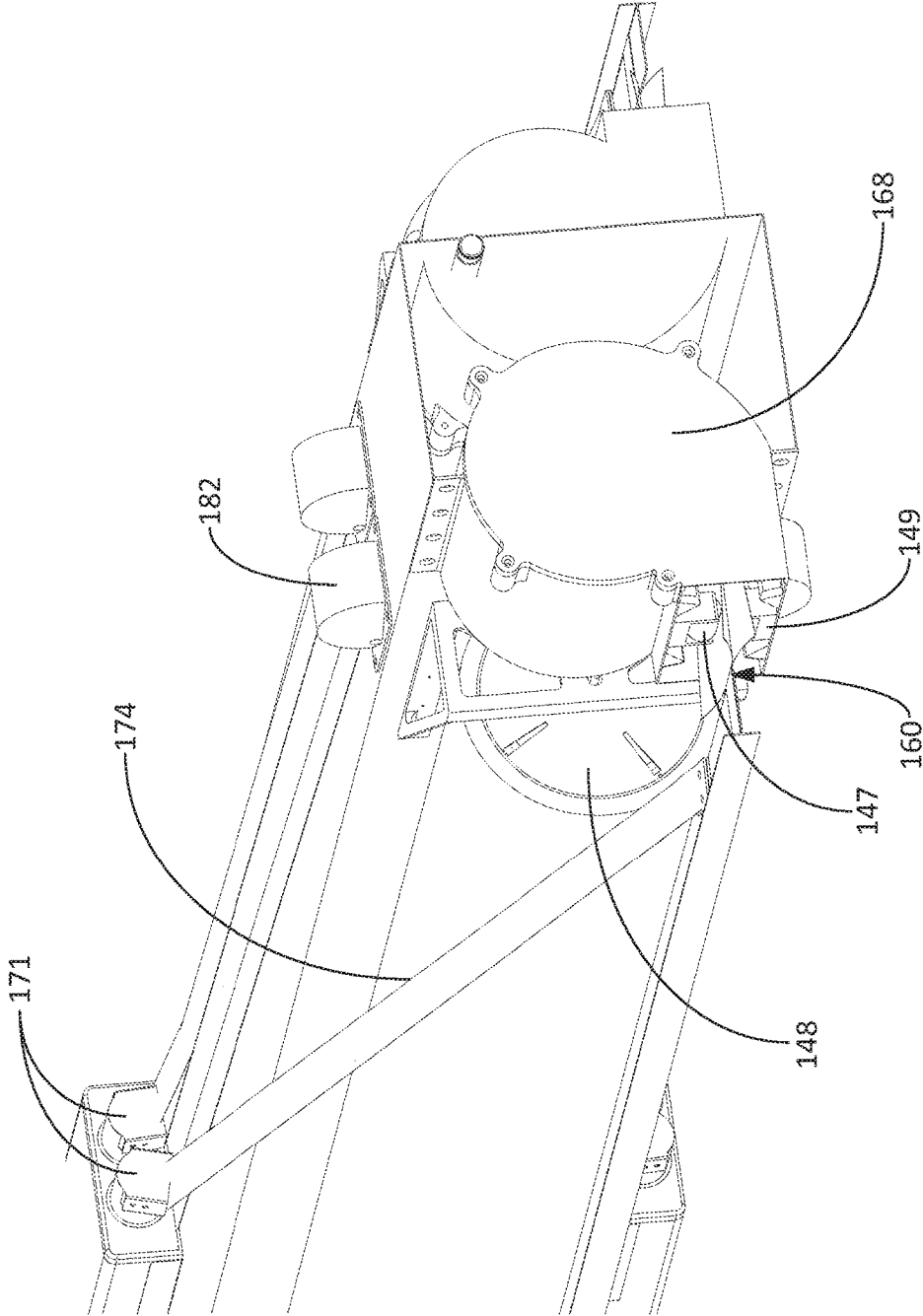
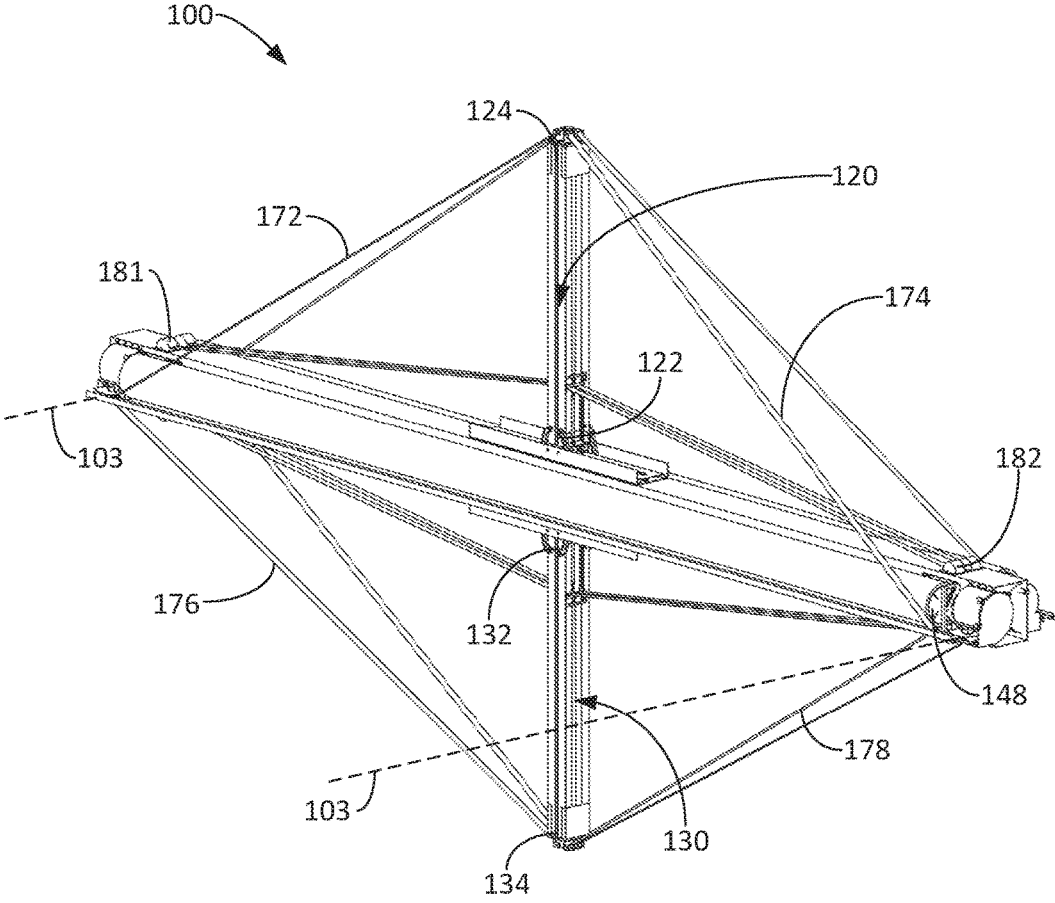


Fig. 3



**Fig. 4**

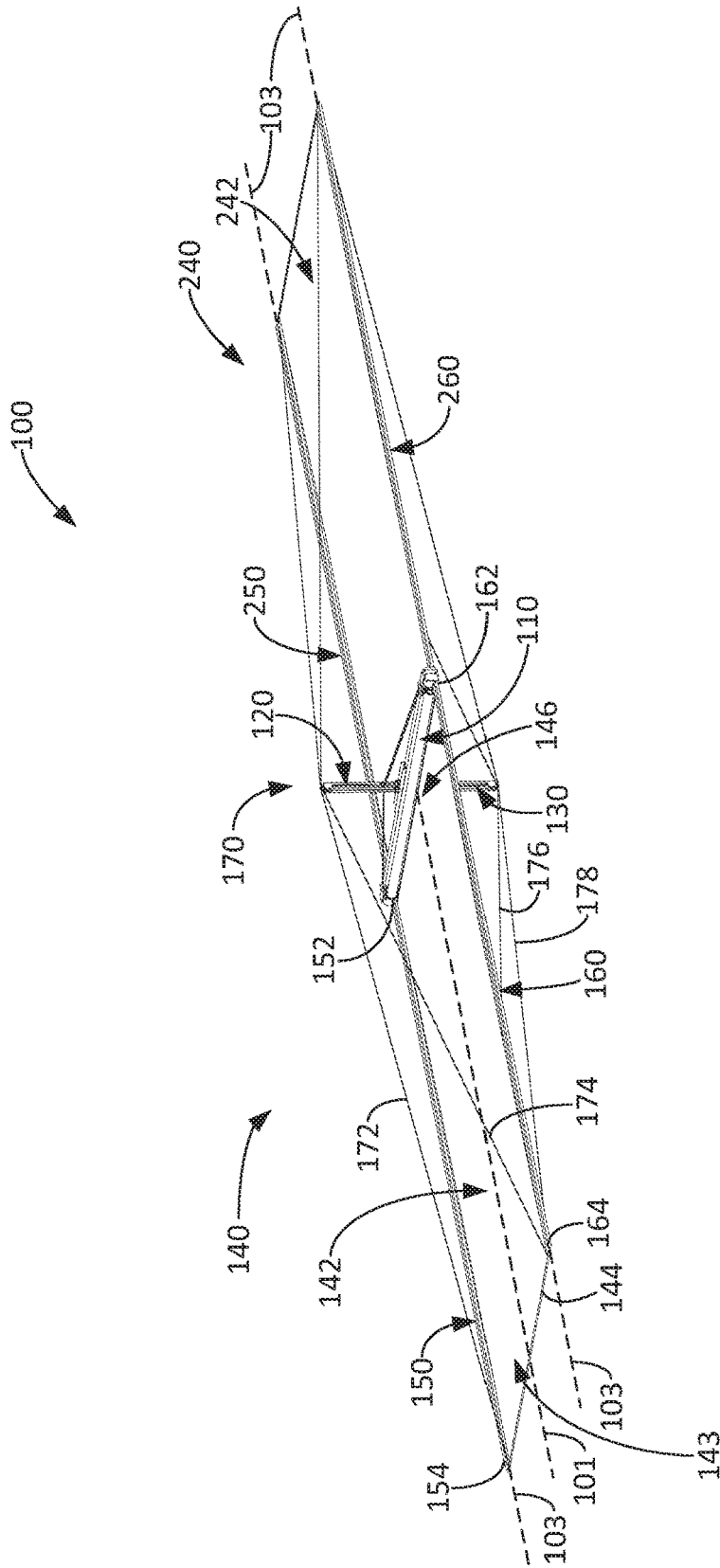
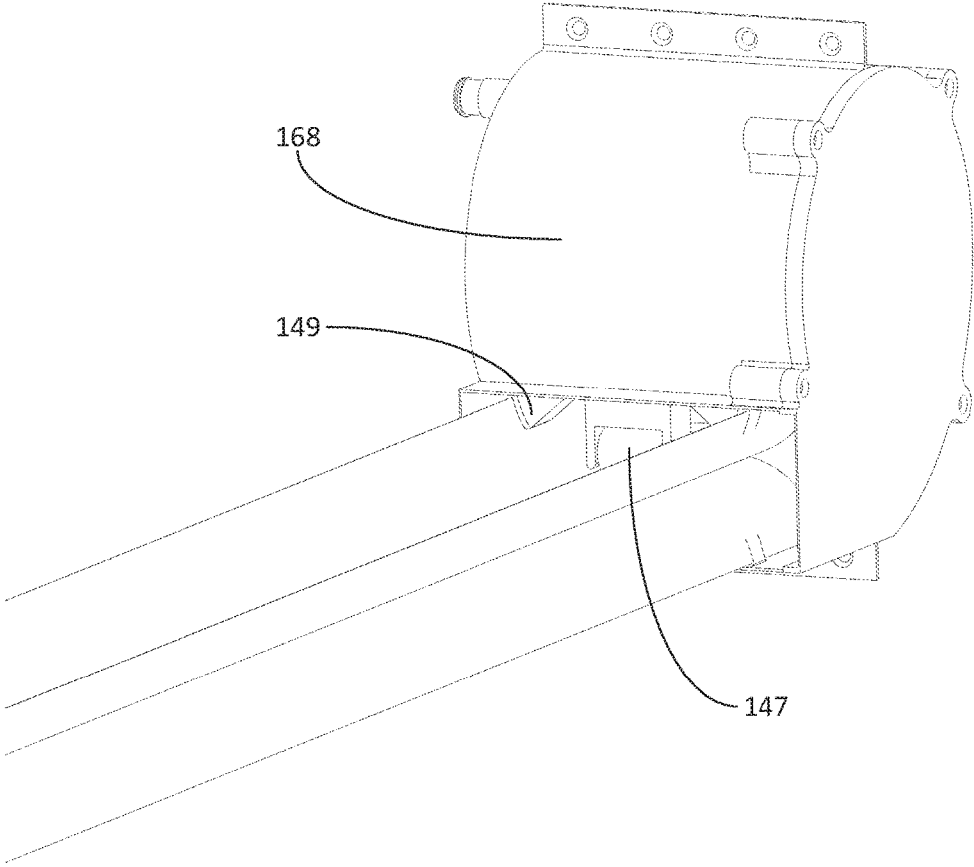


Fig. 5



**Fig. 6**

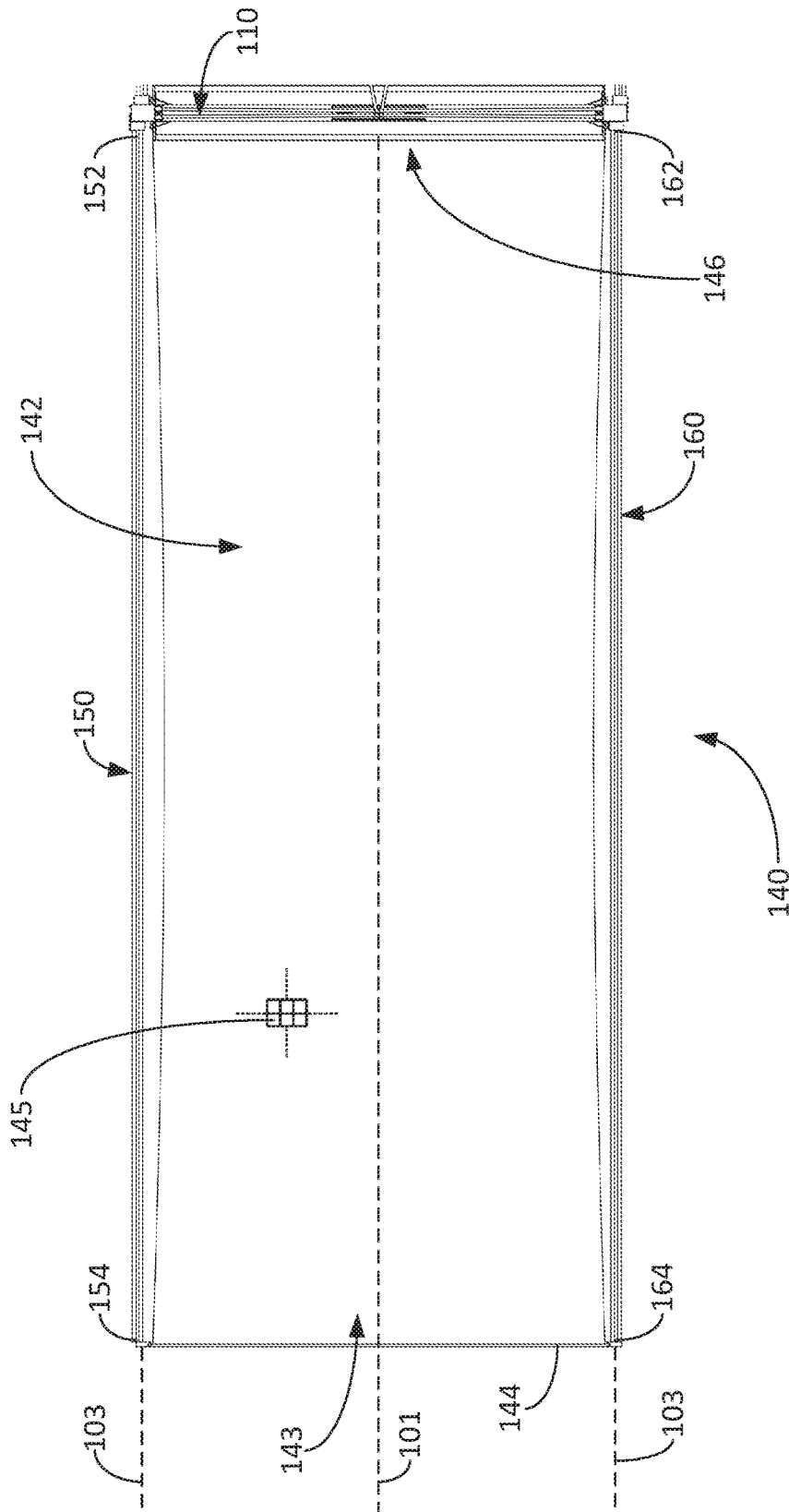
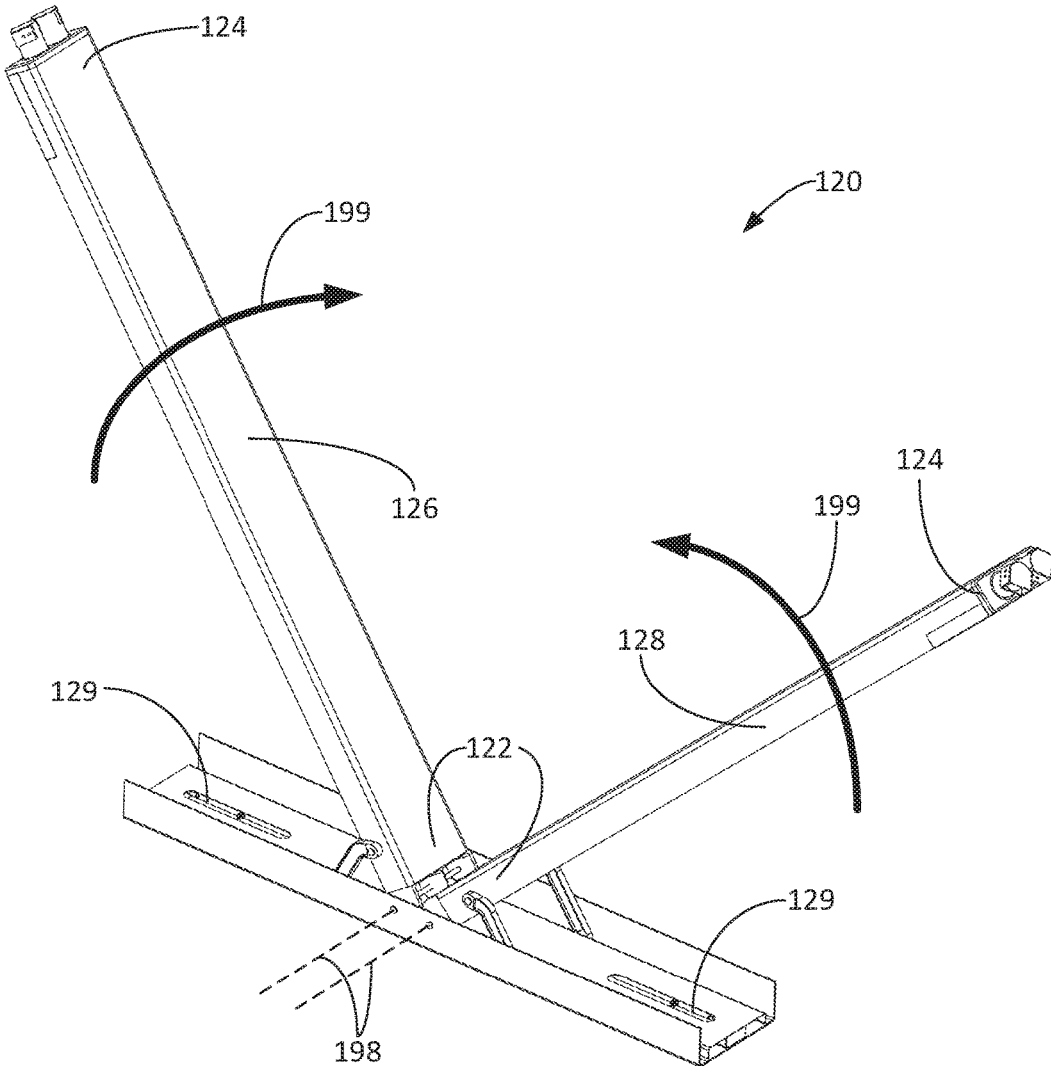
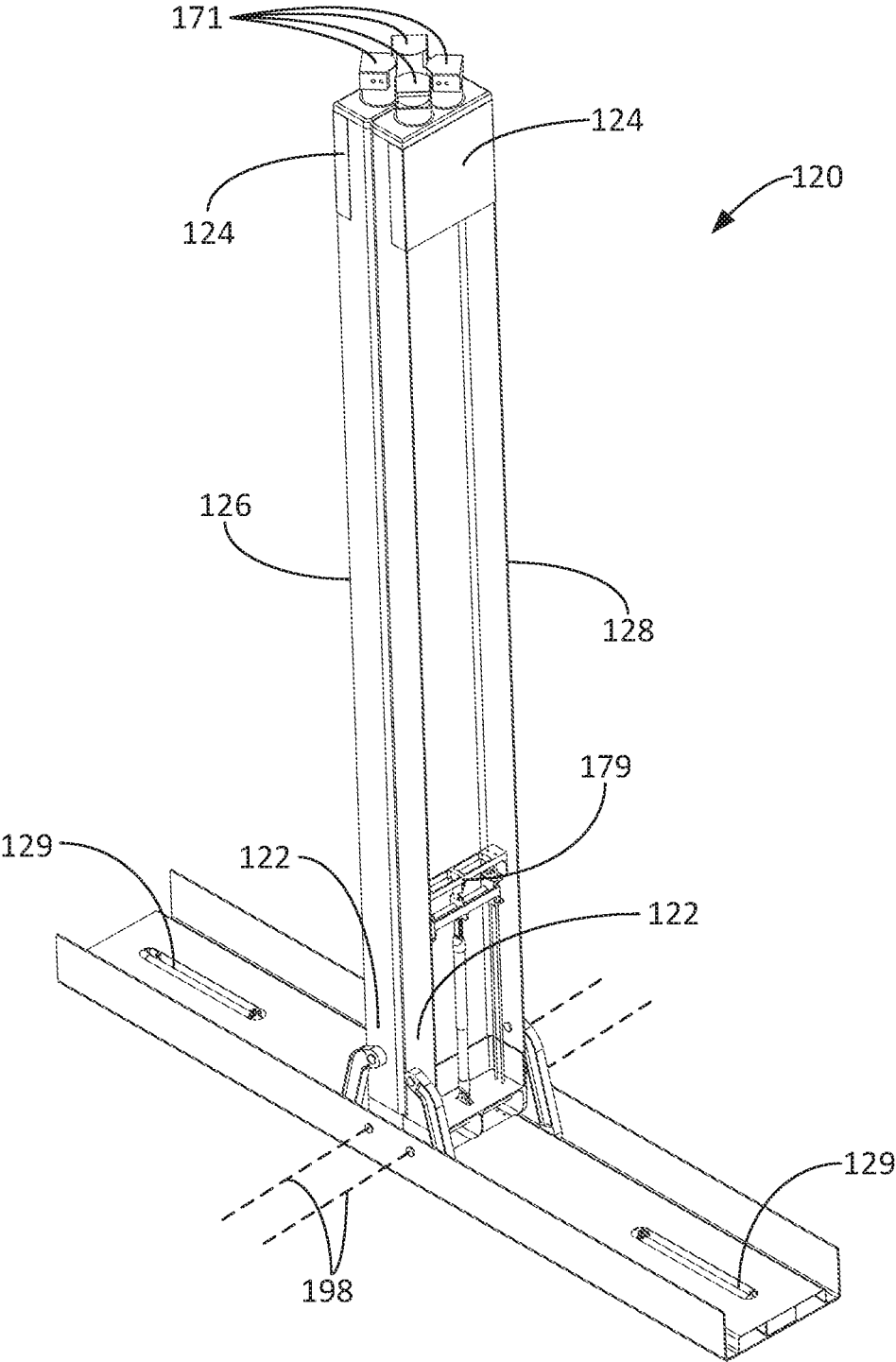


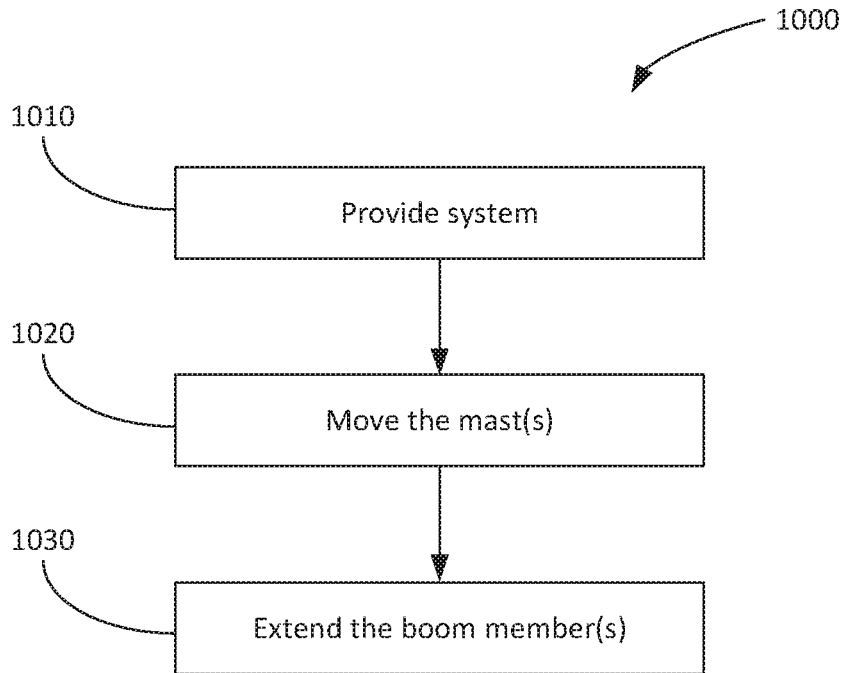
Fig. 7



**Fig. 8**



**Fig. 9**



**Fig. 10**



## DEPLOYABLE SHEET MATERIAL SYSTEMS AND METHODS

### CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application Ser. No. 62/160,965 filed 13 May 2015, entitled "DEPLOYABLE TENSIONED SYSTEM," which is incorporated herein by reference in its entirety.

This invention was made with Government support under contract NNX14CL64P awarded by NASA. The Government has certain rights in the invention.

### SUMMARY

The present disclosure relates generally to exemplary deployable sheet material systems for use in stowing and deploying sheet material such as, e.g., solar arrays to provide solar power to spacecraft, solar sails to provide propulsion to spacecraft, drag apparatus to de-orbit spacecraft, etc. The exemplary deployable sheet material systems may be further used with non-spacecraft systems and apparatus. For example, the exemplary deployable sheet material systems may be used with, or in conjunction with, terrestrial apparatus and systems for stowing and deploying sheet material (e.g., solar arrays, polyimide films, etc.) for use with military and research outposts, rapid disaster relief, and/or outdoor recreation.

An exemplary spacecraft system for deploying sheet material described herein may include a primary beam member extending from a first end region to a second end region, a first mast coupled to the primary beam member, and a second mast coupled to the primary beam member opposite the first mast. Each of the first and second masts may extend from a proximal region coupled to the primary beam member to a distal region. The distal region of the first and second masts may be positioned farther from the primary beam member when the system is in a deployed configuration than when the system is in a stowed configuration. The exemplary spacecraft system may also include a spoolable apparatus coupled to the primary beam member. The spoolable apparatus may include a first boom member proximate the first end region of the primary beam member, a second boom member proximate the second end region of the primary beam member, and a sheet material extending from a proximal sheet region to a distal sheet region and located between the first and second boom members. The first boom member, second boom member, and the sheet material may be in a spooled state when the system is in the stowed configuration and the first boom member, second boom member, and the sheet material may be unspooled into an extended state when the system is in the deployed configuration. The exemplary spacecraft system may further include a plurality of guy wires. The plurality of guy wires may include a first guy wire extending from at least the distal region of the first mast to the first boom member, a second guy wire extending from at least the distal region of the first mast to the second boom member, a third guy wire extending from at least the distal region of the second mast to the first boom member, and a fourth guy wire extending from at least the distal region of the second mast to the second boom member.

In one or more embodiments, each of the first and second boom members may extend from a proximal boom region located proximate the primary beam member to a distal boom region when in the extended state. The first and third

guy wires may extend to the distal boom region of the first boom member and the second and fourth guy wires may extend to the distal boom region of the second boom member. In one or more embodiments, the first and second boom members of the spoolable apparatus may be biased to extend along extension axes to deploy the first and second boom members and the sheet material from the spooled state to the extended state. In one or more embodiments, the spoolable apparatus may also include a spoolable apparatus actuator to restrict movement of the first and second boom members into the extended state along the extension axes and to release the first and second boom members to extend along the extension axes to deploy the first and second boom members and the sheet material from the spooled state to the extended state.

In one or more embodiments, the first mast may be biased to move relative to the primary beam member to move from the stowed configuration to the deployed configuration. The spacecraft system may also include a mast actuator to restrict movement of the first mast and to release the first mast such that the distal region of the first mast moves from proximate the primary beam member to a distance away from the primary beam member. In one or more embodiments, the sheet material may include one or more photovoltaic arrays. In one or more embodiments, the system may also include one or more tensioners to tension one or more of the plurality of guy wires.

In one or more embodiments, the first mast may include a first mast portion and a second mast portion. Each of the first and second mast portions may extend from a proximal mast portion region pivotably coupled to the primary beam member to a distal mast portion region. The proximal mast portion region of the first mast portion may be proximate the proximal mast portion region of the second mast portion. The proximal mast portion regions of the first and second mast portions may be located between the distal mast portion region of the first mast portion and the distal mast portion region of the second mast portion when in the stowed configuration. The distal mast portion region of the first mast portion may be proximate the distal mast portion region of the second mast portion when in the deployed configuration.

Another exemplary system for use in deploying sheet material described herein may include a primary beam member extending from a first end region to a second end region, one or more masts coupled to the primary beam member, a first boom member, and a second boom member. Each of the one or more masts may extend from a proximal region pivotably coupled to the primary beam member to a distal region. The first boom member may extend from a proximal first boom end region coupled to the first end region of the primary beam member to a distal first boom end region located farther away from the primary beam member than the proximal first boom end region. The second boom member may extend from a proximal second boom end region coupled to the second end region of the primary beam member to a distal second boom end region located farther away from the primary beam member than the proximal second boom end region. The exemplary system may also include a sheet material extending from a proximal sheet region proximate to the primary beam member to a distal sheet region located farther away from the primary beam member than the proximal sheet region. The sheet material may be further located between the first and second boom members. The exemplary system may further include one or more guy wires extending from at least the

distal region of the one or more masts to the first boom member and the second boom member.

In one or more embodiments, the one or more masts may include a first mast pivotably coupled to the primary beam member and a second mast pivotably coupled to the primary beam member opposite the first mast. In one or more embodiments, the one or more guy wires may extend to the distal first boom end region of the first boom member and the distal second boom end region of the second boom member. In one or more embodiments, the one or more masts may be biased to move relative to the primary beam member. The system may also include one or more mast actuators to restrict the one or more masts from moving relative to the primary beam member and to release the one or more masts to move such that the distal region of the one or more masts is located farther away from the primary beam member than the proximal region of the one or more masts.

In one or more embodiments, the sheet material may include one or more photovoltaic arrays. In one or more embodiments, the system may also include one or more tensioners to tension the one or more of guy wires. In one or more embodiments, each of the one or more guy wire may extend from one of the first and second end regions of the primary beam member to one of the first and second boom members through the distal region of one of the one or more masts. In one or more embodiments, each of the one or more guy wires may extend from at least the distal region of the one or more masts to one of the distal first boom end region and the distal second boom end region.

An exemplary method of deploying sheet material from a spacecraft described herein may include providing a deployable system. The deployable system may include a primary beam member, one or more masts extending from a proximal region pivotably coupled to the primary beam member to a distal region, and a deployable apparatus coupled to the primary beam member and configurable in a stowed configuration and a deployed configuration. The deployable apparatus may include a plurality of boom members, and a sheet material extending between at least two of the plurality of boom members. The plurality of boom member and the sheet material may be located proximate the primary beam member when in the stowed configuration and extend from the primary beam member when in the deployed configuration. The deployable system may also include a plurality of guy wires extending from the distal region of one or more masts to the plurality of boom members. The method may also include moving the one or more masts relative the primary beam member to position the distal region of the one or more masts farther away from the primary beam member than when in the stowed configuration. Further, the method may include extending the plurality of boom members and the sheet material away from the primary beam member to deploy the sheet material.

In one or more embodiments, the deployable apparatus may be biased to extend into the deployed configuration and the method may also include releasing the deployable apparatus to extend away from the primary beam member. In one or more embodiments, the one or more masts may be biased to move relative the primary beam member to position the distal region of the one or more masts farther away from the primary beam member than when in the stowed configuration and the method may also include releasing the one or more masts to move relative the primary beam member to position the distal region of the one or more masts farther away from the primary beam member than when in the stowed configuration. In one or more embodiments, the method may further include tensioning the plurality of guy

wires after the plurality of boom members and the sheet material are extended away from the primary beam member.

The above summary is not intended to describe each embodiment or every implementation of the present disclosure. A more complete understanding will become apparent and appreciated by referring to the following detailed description and claims taken in conjunction with the accompanying drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a perspective view of a plurality of exemplary deployable sheet material systems coupled to a spacecraft.

FIG. 1B is a perspective view of another plurality of exemplary deployable sheet material systems coupled to a spacecraft.

FIG. 1C is a perspective view of yet another plurality of exemplary deployable sheet material systems coupled to a spacecraft.

FIG. 2 is a perspective view of an exemplary deployable sheet material system in a stowed configuration.

FIG. 3 is an expanded perspective view of an end portion of the exemplary deployable sheet material system of FIG. 2.

FIG. 4 is a perspective view of the exemplary deployable sheet material system of FIG. 2 when between the stowed configuration and a deployed configuration.

FIG. 5 is a perspective view of the exemplary deployable sheet material system of FIG. 2 when in the deployed configuration.

FIG. 6 is a perspective view of an exemplary boom member housing and a portion of an exemplary boom of the deployable sheet material system of FIGS. 2-5.

FIG. 7 is a top plan view of the exemplary deployable sheet material system of FIGS. 2-6 when in the deployed configuration as shown in FIG. 5.

FIG. 8 is a perspective view of an exemplary mast of the deployable sheet material system of FIGS. 2-7 between a stowed configuration and deployed configuration.

FIG. 9 is a perspective view of the exemplary mast of FIG. 8 when in the deployed configuration.

FIG. 10 is a block diagram of an exemplary method of deploying an exemplary deployable sheet material system.

#### DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

In the following detailed description of illustrative embodiments, reference is made to the accompanying figures of the drawing which form a part hereof, and in which are shown, by way of illustration, specific embodiments which may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made without departing from (e.g., still falling within) the scope of the disclosure presented hereby.

Exemplary embodiments shall be described with reference to FIGS. 1-10. It will be apparent to one skilled in the art that elements (e.g., apparatus, structures, parts, portions, regions, configurations, functionalities, method steps, materials, etc.) from one embodiment may be used in combination with elements of the other embodiments, and that the possible embodiments of such apparatus and systems using combinations of features set forth herein is not limited to the specific embodiments shown in the figures and/or described herein. Further, it will be recognized that the embodiments described herein may include many elements that are not necessarily shown to scale. Still further, it will be recognized

that the size and shape of various elements herein may be modified but still fall within the scope of the present disclosure, although certain one or more shapes and/or sizes, or types of elements, may be advantageous over others.

Systems (e.g., spacecraft, terrestrial, etc.) including exemplary deployable sheet material systems are described herein. The deployable sheet material systems may be used to deploy and stabilize one or more portions of sheet material for use by the spacecraft (e.g., using tension). In one example, the sheet material may include a solar array capable of receiving incident solar radiation, converting the solar radiation into electrical power, and providing the electrical power to the spacecraft. Sheet material such as, e.g., flexible solar arrays, thin polyimide film (e.g. MYLAR or KAPTON blanket), metallic foil, scrim cloth, etc. may not have enough rigidity to maintain a deployment position by itself. Thus, the exemplary deployable sheet material systems may provide apparatus and structure to deploy such sheet material and to maintain such material in the deployed configuration. In at least one embodiment as described herein, the sheet material (e.g., rollable/spoolable solar array) may be deployed in a substantially-planar deployment configuration (e.g., the sheet material may substantially lie in a plane when deployed). To maintain the sheet material in the deployment configuration, the exemplary deployable sheet material systems described herein may place the sheet material under tension to extend the sheet material into, or lying substantial within, a plane.

Further, it may be described that the exemplary deployable sheet material systems described herein may define a “truss”-based structure to support any resultant loads from the deployed sheet material (e.g., a photovoltaic array). For example, one or more load-bearing members of the exemplary system may form, or define, a “truss”-based structure, and internal loads of such load-bearing members may be substantially in compression or tension, with bending loads within a member that may be marginal.

One or more deployable sheet material systems described herein may be configurable between a stowed configuration and a deployed configuration. When in the stowed configuration, the sheet material and other structure may be described as being stored into a relatively-compact space (e.g., the sheet material and other structure may “take up” less space than when in the deployed configuration). When in the deployed configuration, the sheet material may be extended to provide a large surface area (e.g., larger than when in the stowed configuration) and may be supported by the “truss”-based structure described herein.

The exemplary “truss”-based structure of the deployable sheet material systems may be described as helping evenly distribute resultant loads and decreasing the mass typically used (e.g., without using the “truss”-based structure) to support such resultant loads. In other words, the exemplary systems described herein may be able to support the same amount of sheet material as other systems by using structures having less mass than such other systems. Further, the exemplary deployable sheet material systems may also be described as increasing reliability by using the passive deployment of components and by distribution of internal loads.

Various exemplary deployable sheet material systems **100** coupled to a spacecraft **11** and configured in a deployed configuration to deploy one or more portions of sheet material **142** (e.g., solar arrays, solar sails, drag structures, etc.) are shown in FIGS. 1A-1C. As shown, the exemplary deployable sheet material systems **100** may be arranged in various configurations which respect to the spacecraft **11**.

For example, as shown in FIG. 1A, four deployable sheet material systems **100** may be coupled to the spacecraft **11** on opposing sides from one another. As will be described further herein, each of the deployable sheet material systems **100** may be configured in a stowed configuration in close proximity to the spacecraft **11**, and then may be configured to extend away from the spacecraft **11** into a deployed configuration to deploy the sheet material **142**. Further, for example, as shown in FIG. 1B, multiple deployable sheet material systems **100** are coupled to the spacecraft **11** in series on either side of the spacecraft **11**. In this embodiment, each of the deployable sheet material systems **100** may be configured in a stowed configuration in close proximity to the spacecraft **11**, may be configured to extend (e.g., “fold out”) from the spacecraft **11**, and then may be further configured into a deployed configuration to deploy the sheet material **142**. Still further, for example, as shown in FIG. 1C, two deployable sheet material systems **100** are coupled to opposing sides of the spacecraft **11** similar to the systems **100** of FIG. 1A.

The spacecraft **11** may include various spacecraft components and may be many different shapes and sizes. For example, the spacecraft **11** may include one or more spacecraft structures, propulsion systems, communications systems, avionics, thermal control systems, launch vehicle adapters, payloads (telecommunications systems, science instruments, etc.), etc. As shown in FIGS. 1A-1C, the exemplary deployable sheet material systems **100** may be coupled to the spacecraft **11** in a variety of different configurations. For example, the deployable sheet material systems **100** may release (e.g., fold, slide, extend, etc.) outward from the spacecraft **11** before deploying sheet material **142** (e.g., solar arrays, solar sails, etc.) into a deployed configuration.

The deployable sheet material systems **100** may be configurable between a stowed configuration as shown in FIG. 2 and a deployed configuration as shown in FIG. 5. FIG. 4 illustrates the deployable sheet material system **100** between the stowed configuration and the deployed configuration. The deployable sheet material system **100** may be configured into the stowed configuration to reduce the size and profile of the deployable sheet material system **100**, e.g., during transportation. The deployable sheet material systems **100** may be configured into the deployed configuration to deploy the sheet material **142** of the systems **100** (e.g., extend the surface area of the sheet material **142**). In one or more of the embodiments, the system **100** may include one or more electro-mechanical actuators (e.g., shape-memory alloy, paraffin, pyro-technic, burn wire, etc.) configured to initiate movement of the deployable sheet material systems **100** from the stowed configuration to the deployed configuration as will be described further herein.

Generally, the exemplary deployable sheet material systems described herein include apparatus configured to stow and deploy one or more portions of the sheet material such as a photovoltaic array. One such exemplary deployable sheet material system **100** and parts, or portions, thereof is depicted in FIGS. 2-9. The exemplary deployable sheet material system **100** may include a primary beam member **110** (e.g., a trunk beam, a composite trunk, a primary structure, a housing, etc.) that extends from a first end region **112** to a second end region **114** (e.g., from a first end to a second end, from a location proximate the first end to a location proximate the second end, etc.) along an axis **113**.

The primary beam member **110** may be coupled to the spacecraft **11** such that the primary beam member **110** is spaced away from the spacecraft **11**. In one or more embodi-

ments, for example, as shown in FIG. 1A, the primary beam member 110 may be coupled to and spaced away from the spacecraft 11 through an intermediate coupling member 12. In one or more embodiments, for example, as shown in FIG. 1B, multiple primary beam members 110, each part of, or corresponding to, an independent deployable sheet material system 100, may be coupled to each other and the primary beam members 110 may be configured to fold with respect to each another to reduce the profile of the deployable sheet material systems 100 when in the stowed configuration. As shown in FIGS. 1A-1C, the axis 113 (as shown in FIG. 2) of, or defined by, the primary beam member 110 may be parallel or perpendicular to the intermediate coupling members 12 when deployed or spaced away from the spacecraft 11. The primary beam member 110 may be described as defining the structure to which other components of the deployable sheet material system 100 are coupled to, which, thereby, may be described as coupling the other components of the deployable sheet material system 100 to the spacecraft 11 or other base system.

The exemplary deployable sheet material system 100 may further include one or more masts coupled to the primary beam member 110 that are configured to extend from the primary beam member 110 to locate, or position, one or more guy wires that will be used to stabilize the sheet material 142 as described further herein. As shown in the embodiment depicted in FIGS. 2-9, the exemplary deployable sheet material system 100 includes a first mast 120 coupled to the primary beam member 110 and a second mast 130 coupled to the primary beam member 110 opposite the first mast 120. The first and second masts 120, 130 may be described as being “mirrored structures” of each other because, e.g., the first and second masts 120, 130 are located on and extend from either side, or opposite sides, of the primary beam member 110 as shown in FIG. 4. The primary beam member 110, the first and second masts 120, 130, and/or portions thereof, may include (e.g., be formed of, etc.) one or more materials such as, e.g., carbon fiber reinforced plastic, steel, aluminum, titanium, composite, etc.

Each of the first and second masts 120, 130 may extend from a proximal region 122, 132 coupled to the primary beam member 110 to a distal region 124, 134. Each of the first and second masts 120, 130 may be coupled to the primary beam member 110 at, or proximate, the proximal regions 122, 132 of the corresponding first and second masts 120, 130. Although two masts are included in the embodiment depicted, other embodiments may include a single mast or more than two masts.

The first and second masts 120, 130 may be coupled to the primary beam member 110 between the first end region 112 and the second end region 114 of the primary beam member 110. As shown in FIG. 4, each of the first and second masts 120, 130 are coupled to the primary beam member 110 about halfway (e.g., proximate a center region) between the first end region 112 and the second end region 114 of the primary beam member 110. In one or more embodiments, the first and second masts 120, 130 may be coupled closer to the first end region 112 than the second end region 114 or closer to the second end region 114 than the first end region 112. In one or more embodiments, the first and second masts 120, 130 may be coupled to the primary beam member 110 directly opposite each other (e.g., on opposite sides of the primary beam member 110). In other embodiments, the first and second masts 120, 130 may be coupled to the primary beam member 110 offset from each other (e.g., not directly opposite one another on the primary beam member 110).

As described herein, the exemplary deployable sheet material systems 100 may be configured in a stowed configuration where the sheet material 142 is in storage, and in a deployed configuration, where the sheet material 142 is deployed (e.g., extended, unfurled, unrolled, unspooled, etc.) for use thereof. Likewise, the first and second masts 120, 130 may be configured in the stowed and deployed configurations. More specifically, as shown, the first and second masts 120, 130 are stowed in FIG. 2 and are deployed in FIG. 4.

To allow movement from the stowed configuration to the deployed configuration, the proximal regions 122, 132 of the first and second masts 120, 130 may be movably coupled (e.g., pivotally coupled, rotatably coupled, etc.) to the primary beam member 110. For example, the first and second masts 120, 130 may pivot, or move, about the proximal regions 122, 132 such that the distal regions 124, 134 pivots, or moves, away from the primary beam member 110. For example, when in the stowed configuration as shown in FIG. 2, each of the first and second masts 120, 130 may be stored proximate (e.g., extending along, adjacent to, next to, within, etc.) the primary beam member 110. In this example, the first and second masts 120, 130 may be folded adjacent the primary beam member 110 (e.g., parallel to the primary beam member axis 113). When in the deployed configuration as shown in FIG. 4, each of the first and second masts 120, 130 may have been moved, or pivoted, such that the first and second masts 120, 130 extend away from the primary beam member 110. In this example, the first and second masts 120, 130 may be unfolded to extend away from the primary beam member 110 orthogonally away from the primary beam member axis 113. In other words, the first and second masts 120, 130 may move relative to the primary beam member 110 when transitioning from the stowed configuration to the deployed configuration. In one or more embodiments, the first and second masts 120, 130 may move into position in the deployed configuration as shown in FIG. 4 before the rest of the system 100 is completely configured into the deployed configuration as shown in FIG. 5. Further, the distal regions 124, 134 of each of the first and second masts 120, 130 may be described as being located farther away from the primary beam member 110 when in the deployed configuration as shown in FIGS. 4-5 than when in the stowed configuration as shown in FIG. 2.

The first and second masts 120, 130 may include one or more portions that may interoperate together to form, or define, the first and second masts 120, 130. For example, in the embodiment depicted in FIGS. 2-9, each of the first and second masts 120, 130 include two portions, which will be described in more detail with respect to FIGS. 8-9. As shown, the first mast 120 may include a first mast portion 126 and a second mast portion 128. In FIG. 8, the first and second mast portions 126, 128 are transitioning from the stowed configuration to the deployed configuration by moving as indicated by arrows 199 about pivot axes 198. In FIG. 9, the first and second mast portions 126, 128 are positioned, or configured, in the deployed configuration. For example, each of the first and second mast portions 126, 128 have completely pivoted about the pivot axes 198 such that the first and second mast portion 126, 128 are moved proximate one another and extending substantially orthogonally from the primary beam member axis 113.

It may be described that each of the first and second mast portions 126, 128 may form, define, or be part of, the proximal and distal regions 122, 124 of the first mast 120. For example, each of the first and second mast portions 126, 128 may define, form, or be part of, the proximal region 122

and the distal region **124**. More specifically, the proximal region **122** of each of the first and second mast portions **126**, **128** may be movably coupled (e.g., pivotally coupled, rotatably coupled, etc.) to the primary beam member **110** and the distal region **124** of each of the first and second mast portions **126**, **128** may not be coupled to the primary beam member **110** so as to be able to be moved into the deployed configuration. Although not further described herein, it is understood that the second mast **130** and any other mast of the exemplary systems may also include first and second mast portions similar to those described with regards to the first mast **120**.

In one or more embodiments, the first and second masts **120**, **130** may be biased to move relative to the primary beam member **110** from the stowed configuration shown in FIG. 2 to the deployed configuration as shown in FIG. 4. In other words, the first and second masts **120**, **130** may be predisposed to extend in the position as shown in FIG. 4, but are held in place, or restricted from movement, until released. Still, in other words, the exemplary deployable sheet material system **100** may be described as storing potential energy that is configured to move the first and second masts **120**, **130** from the stowed configuration to the deployed configuration. The potential energy may be restricted from being released by one or more portions or apparatus of the exemplary system **100**. For example, the exemplary system **100** may include one or more mast actuators **129** configurable to release the first and second masts **120**, **130** such that the distal regions **124** of the first and second masts **120**, **130** may move from being proximate the primary beam member **110** to a distance away from the primary beam member **110** (e.g., extending orthogonally from the primary beam member **110**) into a deployed configuration. The biasing element, which is the element that is configured to bias, or predispose the first and second masts **120**, **130** into the deployed configuration, may include one or more elastic materials such as, e.g., metallic springs, composite springs, shape memory alloy structures, etc.

As described, in the embodiment depicted in FIGS. 2-9, each of the first and second mast portions **126**, **128** may be biased to move from the stowed configuration to the deployed configuration. For example, as shown in FIG. 8, each of the first and second mast portion **126**, **128** has been released from the stowed configuration and are pivoting about the pivot axes **198** proximate the proximal regions **122** toward the deployed configuration as indicated by arrows **199**. In FIG. 9, the first and second mast portion **126**, **128** of the first mast **120** have come together, or joined, to define the first mast **120** in the deployed configuration. When the first mast **120** is deployed, it may be described that the potential energy has been expended to move the first mast **120** into the deployed configuration. Further, in one or more embodiments, at least some energy may still be acting on the first mast **120** and/or portions thereof **126**, **128** to maintain the first mast **120** configured into the deployed configuration (e.g., extending orthogonally to the primary beam member axis **113**).

The exemplary deployable sheet material system **100** may further include a plurality of guy wire mast pivots **171** coupled to the distal regions **124** of the masts that are configured to receive and direct guy wires for supporting and stabilizing the sheet material **142** as will be further described herein.

The exemplary deployable apparatus **140** of the deployable sheet material system **100** may be described as one or more portions, or pieces, of apparatus and/or structures configured to move the sheet material **142** away from

primary beam member **110** towards, and ultimately to, the deployed configuration. The deployable apparatus **140** may be described in terms of the various types of motions, or movement, the deployable apparatus **140** may perform when deploying the sheet material **142**. For example, the deployable apparatus **140** may be described as rollable apparatus, spoolable apparatus (i.e., configured to be spooled/unspooled), foldable apparatus, accordion shaped apparatus, winglets, compressible apparatus, etc. In other words, the deployable apparatus **140** may extend in a variety of different ways such as, e.g., rolling, folding, accordion-like, sliding, etc. In the exemplary deployable sheet material system **100** depicted and described with reference to FIGS. 2-9, the deployable apparatus **140** may be described as spoolable apparatus because, e.g., the apparatus, or at least many parts, or portions, thereof may be spooled (e.g., placed or configured into a spooled state) when in the stowed configuration.

The exemplary deployable apparatus **140** of the deployable sheet material system **100** may be coupled to the primary beam member **110** and may be configured such that at least a portion of the deployable apparatus **140** extends away from the primary beam member **110** to position and support the sheet material **142** in an extended, substantially planar status, which in at least one example, is configured to collect solar energy. The deployable apparatus **140** may include a sheet material spool **148** (e.g., mandrel, spindle, reel, shaft, etc.) from which the sheet material **142** extends. For example, the sheet material **142** may be rolled-up or wound-up on the sheet material spool **148** such that increasing portions of the sheet material **142** may be configured to extend, or disperse, from the sheet material spool **148** while the sheet material spool **148** remains in place (e.g., similar to a carpenter's tape) while any remaining portion of the sheet material **142** remains rolled-up on the sheet material spool **148**. The sheet material spool **148** may be coupled to the primary beam member **110** such that, e.g., the sheet material spool **148** may not move relative to the primary beam member **110**. In other words, a portion of the sheet material **142** may move relative to and extend away from the primary beam member **110** while the sheet material spool **148** remains stationary proximate the primary beam member **110**. In contrast, other systems may include a spool that that extends away from (e.g., moves relative to) a primary beam member to dispose sheet material while the spool moves, or rolls, away from the primary beam member. Anchoring or affixing the sheet material spool **148** relative to the primary beam member **110** may avoid the complexity attributed to having to move the sheet material spool **148** as would be the case in systems in which the spool moves, or rolls, away from the primary beam member **110**. Anchoring or affixing the sheet material spool **148** to the primary beam member **110** may also improve the first vibration mode of the system **100** by minimizing the amount of mass far from the primary beam member **110**.

In the embodiment depicted, the deployable apparatus **140** may include a first boom member **150** proximate the first end region **112** of the primary beam member **110**, a second boom member **160** proximate the second end region **114** of the primary beam member **110**, and sheet material **142** located between the first boom member **150** and the second boom member **160**. Each of the first and second boom members **150**, **160** may be configured to extend from the primary beam member **110** parallel to an extension axis **101**, which is perpendicular to the primary beam member axis **113**, to deploy the sheet material **142** when in the deployed configuration as shown in FIG. 5. When in the

stowed configuration, the first and second boom members **150, 160** may be stowed or stored (e.g., “rolled up,” spooled, constrained, contained, etc.) proximate the primary beam member **110** as shown in FIG. 4.

More specifically, each of the first and second boom members **150, 160** may extend from a proximal boom region **152, 162** coupled to the primary beam member **110** to a distal boom region **154, 164**, respectively. When in the deployed state, the first and second boom members **150, 160** may be configured to extend away from the primary beam member **110** with the proximal boom regions **152, 162** remaining coupled and proximate to the primary beam member **110**. For example, it may be described that the distal boom regions **154, 164** of the first and second boom members **150, 160** are positioned closer to the primary beam member **110** when in the stowed configuration than when in the deployed and extended configuration.

As shown in FIGS. 2-6, the deployable sheet material system **100** may include a first boom member housing **158** located proximate and coupled to the first end region **112** of the primary beam member **110** and a second boom member housing **168** located proximate and coupled to the second end region **114** of the primary beam member **110**. The first and second boom member housings **158, 168** may be configured to store at least a portion, or all, of the first and second boom member **150, 160**, respectively, when in the stowed configuration. In one or more embodiments, each of the first and second boom member housings **158, 168** may include a spool that is configured to “spool” the first and second boom members **150, 160** when in the stowed configuration. The first and second boom members **150, 160** may be configured to be unrolled, unspooled, or unfurled, away from the first and second boom member housings **158, 168** when configured in the deployed configuration.

In one or more embodiments, the first and second boom members **150, 160** may be biased to extend parallel to the extension axis **101** into the deployment configuration. In other words, the first and second boom members **150, 160** may be predisposed to be configured in an extended state (e.g., to move outward from the primary beam member **110**) extending along boom axes **103**. In one or more embodiments, the system **100** may include a deployable (e.g., rollable, spoolable, etc.) apparatus actuator **149** that is configurable to release the deployable apparatus **140** (e.g., the first and second boom members **150, 160**) as shown in FIGS. 3 and 6. In other words, the deployable apparatus actuator **149** (e.g., a solenoid) may release the boom member **150, 160** such that the boom member **150, 160** extends from the first and second boom member housings **158, 168** (e.g., extending parallel to the extension axis **101** to deploy along the boom axes **103**) without additional forces (e.g., passively).

In the embodiment depicted in FIGS. 2-9, each of the first and second boom members **150, 160** may themselves be biased, or predisposed, into the deployed configuration, and as such, may be elastically deformed when in the stowed configuration. The strain energy thus stored through elastic deformation may be contributed in part by the shape of the cross-section of the boom members **150, 160**. More specifically, the first and second boom members **150, 160** may include (e.g., be formed of) two or more lenticular springs that may be configured, or oriented, such that the convex surfaces face each other. Additionally, the concave surfaces of each lenticular spring may face away (e.g., in an opposing direction), at least in part, from each other. In at least one embodiment, the two lenticular springs of the first and second boom members **150, 160** may further be connected

along a central region (e.g., the central region may be located between the first and second longitudinal edges regions of the two lenticular springs). Similar exemplary lenticular springs may be described in U.S. Pat. App. Pub. No. 2014/0042275 A1 filed on Aug. 9, 2013 and entitled “Gossamer Apparatus and Systems for Use with Spacecraft” and U.S. Pat. App. Pub. No. 2016/0122041 A1 filed on Oct. 8, 2015 and entitled “Extendable Solar Array,” both of which are incorporated herein by reference in their entireties.

It may be described that the first and second boom members **150, 160** may be configured to store potential energy when the deployable sheet material system **100** is configured in the stowed configuration. The stored potential energy of the first and second boom members **150, 160** may provide the movement of the deployable apparatus **140** from the stowed configuration to the deployed configuration when released. More specifically, for example, the lenticular springs of the first and second boom members **150, 160** may store the potential energy and, when released, generate forces to straighten the first and second boom members **150, 160** to extend along boom member axes **103** (e.g., the way a carpenter’s tape naturally straightens itself out). When bent, or wrapped about the spools of the beam member housings **158, 168**, the lenticular springs of the first and second boom members **150, 160** may store potential energy, which may be subsequently expended, or “spent,” to straighten out the lenticular springs during the transition from the stowed configuration, or state, to the deployed configuration, or state. The lenticular springs of the first and second boom members **150, 160** may be selected and/or configured so as to generate a sufficient force for deploying the deployable apparatus **140** (e.g., to deploy the deployable apparatus **140** in a passive manner based on the first and second boom members **150, 160** own potential energy without the aid or addition of energy from other components such as a motor). In other embodiments, however, the first and second boom members **150, 160** may extend from the first and second boom member housings **158, 168** using, e.g., a motor or any other suitable type of active deployment apparatus.

Additionally, as shown, each of the first and second boom member housings **158, 168** may include one or more rollers **147** configured to guide the first or second boom members **150, 160** away from the primary beam member **110**.

As previously described herein, the deployable apparatus **140** also includes the sheet material **142** (e.g., one or more photovoltaic arrays, solar shield, solar sail, etc.) located between the first and second boom members **150, 160** and an end beam **144** as shown in FIGS. 5 and 7. The end beam **144** may extend from the first boom member **150** to the second boom member **160** and may be coupled to each of the distal regions **154, 164** of the first and second boom members **150, 160**.

As shown in FIG. 7, the sheet material **142** or the portion of sheet material **142** may be described as extending from a distal sheet region **143** to a proximal sheet region **146**. The proximal sheet region **146** may be located proximate to, and possibly coupled to, the primary beam member **110**. For example, the proximal sheet region **146** of the sheet material **142** may be coupled to the primary beam member **110** through one or more elastic members (e.g., proximate the first and second end regions **112, 114**). In other embodiments, the proximal sheet region **146** of the sheet material **142** may be directly coupled to the primary beam member **110**. The distal sheet region **143** may be located away from the primary beam member **110** when in the deployed configuration as shown in FIGS. 5 and 7. When the sheet

material **142** is configured in the stowed configuration such as, e.g., “rolled up” or “spooled up” proximate the primary beam member **110**, both of the distal and proximal sheet regions **143**, **146** of the sheet material **142** are proximate the primary beam member **110**.

The first and second boom members **150**, **160** may be configured to deploy (e.g., extend, unwrap, unfurl, unspool, etc.) the sheet material **142** when the boom members **150**, **160** are released to move into the deployed configuration extending along the boom axes **103**. For example, the sheet material **142** may be coupled to the first and second boom members **150**, **160** at one or more locations and/or through one or more other portions or apparatus of the deployable apparatus **140**. For example, as shown, the sheet material **142** may not be directly coupled to the first or second boom members **150**, **160**. Instead, the distal end region **143** of the sheet material **142** may be coupled to the end beam **144** and the end beam **144** may be coupled to each of the first and second boom members **150**, **160**. As such, in one or more embodiments, there may be a gap between the sheet material **142** and each of the first and second boom members **150**, **160** as shown in FIG. 7. In other embodiments, the distal end region **144** or other side regions of the sheet material **142** may be coupled to the first and second boom members **150**, **160**. No matter how the sheet material **142** is coupled to the first and second boom members **150**, **160** (e.g., coupled directly thereto, coupled through other parts, portions, or apparatus, etc.), when the boom members **150**, **160** are spooled out or extended to an extended state when moving into the deployed configuration, the sheet material **142** may also move along with the first and second boom members **150**, **160** into the deployed configuration.

As described herein, in one or more embodiments, the sheet material **142** may include one or more solar arrays **145** (e.g., one or more photovoltaic arrays) disposed thereon as shown in FIG. 7. For example, in one or more of the embodiments, the sheet material **142** may include a thin-film photovoltaic material (e.g., amorphous silicon, copper indium gallium selenide, inverted metamorphic multi-junction, cadmium telluride, organic photovoltaics, etc.) and/or a crystalline photovoltaic material (e.g., crystalline silicon, multi junction crystalline, gallium arsenide, etc.). In one or more of the embodiments, the sheet material **142** (e.g., thin-film photovoltaic material, crystalline photovoltaic material, etc.) may be combined with additional materials in layers (e.g., scrim cloth, glass, polyimide films, adhesives, encapsulations, circuit wiring, etc.) to form a solar array blanket assembly that may be configured to perform mechanical functions (e.g., blanket tensioning) and electrical functions (e.g., power transfer to the system or spacecraft).

In one or more embodiments, the sheet material **142** may be in tension when in the deployed configuration. Tension on the sheet material **142** may be achieved by the geometry of the sheet, such that the fully deployed boom members **150**, **160** place the sheet material **142** in tension by pushing on the end beam **144** to which the sheet material **142** is coupled. In one or more embodiments, the sheet material **142** may be placed in tension by a sheet tensioning apparatus that may be housed within the primary beam member **110** or within the mandrel, or spindle, upon which the sheet material **142** is stored when in the stowed configuration. In one or more embodiments, the sheet tensioning apparatus may apply tension to the sheet material **142** by using, e.g., springs, elastic materials, etc. The sheet tensioning apparatus may be engaged continuously, or only after the other system elements have reached the deployed configuration. Such acti-

vation of the sheet tensioning apparatus may be achieved using any suitable type of release actuator such as, e.g., shape-memory alloy, paraffin, pyro-technic, burn wire, etc.

The one or more solar arrays **145** may be flexible such that the one or more solar arrays **145** can be stowed and extended along with the sheet material **142** as the system **100** moves between the stowed configuration and the deployed configuration. For example, in one or more of the embodiments, the sheet material **142** (e.g., the solar array blanket assembly) may be pliable such that the sheet material **142** may be spooled into a spooled state, or configuration, when the deployable sheet material system **100** is in the stowed configuration and may be unrolled or unspooled into an extended state, or configuration, (e.g., planar configuration) when the deployable sheet material system **100** is in the deployed configuration.

In one or more of the embodiments, the sheet material **142** may include pliable sections that define fold lines such that the sheet material **142** may be folded into a prismatic shape (e.g. flattened accordion shape) when the deployable sheet material system **100** is in the stowed configuration and may be unfolded into a planar configuration when the deployable sheet material system **100** is in the deployed configuration. In one or more of the embodiments, the sheet material **142** may include a plurality of circuits that wire photovoltaic materials in a variety of series and parallel configurations to achieve desirable voltage and current parameters for the sheet material **142**.

In one or more embodiments, the deployable sheet material system **100** may include an electrical system (e.g., wires, cables, circuit board, etc.) electrically coupled to the sheet material **142** (e.g., the one or more photovoltaic arrays) to, e.g., transfer or transmit solar-generated electricity from the sheet material **142** to an electrical storage system. The electrical system may also electrically couple the sheet material **142** to a harness that passes adjacent to (e.g., along, though, etc.) the primary beam member **110** (e.g., along primary beam member **110** from the first end region **112** to the second end region **114**, proximate the first end region **112**, proximate the second end region **114**, between the first and second end regions **112**, **114**, etc.). The electrical system may also electrically connect the sheet material **142** to an additional component (e.g., module, housing, satellite portions, solar array drive assembly, diode board, etc.) at a location, e.g., proximate the first end region **112**, proximate the second end region **114**, between the first and second end regions **112**, **114**.

The deployable sheet material system **100** may also include a plurality of guy wires **170** (e.g., cables, tethers, etc.) to support and stabilize the deployable apparatus **140** when the deployable sheet material system **100** is in the deployed configuration as shown in FIG. 5. The plurality of guy wires **170** may be defined by various different configurations such as, e.g., a multi-stranded tether defined by a cross-strapped pattern. In other words, each of the plurality of guy wires **170** may include (e.g., be formed up) a plurality of strands.

Generally, the plurality of guy wires **170** may extend from a location outside of the plane defined boom axes **103** and the primary beam member axis **113** to any location of the structures or apparatus described herein so as to provide support and stability to the sheet material **142** when in the extended, deployed configuration. For example, the plurality of guy wires **170** may extend to one or more of the distal sheet region **143** of the sheet material **142**, the end beam **144**, and the distal boom regions **154**, **164** from the location outside of the plane defined boom axes **103** and the primary

beam member axis **113**. As shown in this embodiment, the plurality of guy wires **170** may include a first guy wire **172** extending from at least the distal region **124** (e.g., the distal end) of the first mast **120** to the distal region **154** (e.g., the distal end) of the first boom member **150** and a second guy wire **174** extending from at least the distal region **124** (e.g., the distal end) of the first mast **120** to the distal region **164** (e.g., the distal end) of the second boom member **160**. The plurality of guy wires **170** may also include a third guy wire **176** (e.g., the distal end) extending from at least the distal region **134** (e.g., the distal end) of the second mast **130** to the distal region **154** (e.g., the distal end) of the first boom member **150** and a fourth guy wire **178** extending from at least the distal region **134** (e.g., the distal end) of the second mast **130** to the distal region **164** (e.g., the distal end) of the second boom member **160**. Additionally, although the guy wires **172**, **174**, **176**, **178** are coupled to the distal regions **154**, **164** of the first and second boom members **150**, **160**, the guy wires **172**, **174**, **176**, **178** may be coupled to anywhere along the first and second boom members **150**, **160**.

The combination of one or more of the first boom member **150**, the second boom member **160**, the first mast **120**, the second mast **130**, the end beam **144**, the primary beam member **110**, the first guy wire **172**, the second guy wire **174**, the third guy wire **176**, and the fourth guy wire **178** may be described as forming a truss structure. As a result, the internal member loads of each of those one or more elements above may be placed either substantially in compression or tension. For example, the plurality of guy wires **170** (e.g., first, second, third, fourth guy wires **172**, **174**, **176**, **178**) may be placed in tension while the one or more boom members (e.g., the first boom member **150**, the second boom member **160**) may be placed in compression to, e.g., stabilize and support the system **100**. Specifically, tension applied to the plurality of guy wires **170** may apply compression to the one or more boom members, which is in contrast to systems that do not apply any compression to the one or more boom members (e.g., the boom members are free standing in such systems without guy wires or other devices to place booms in compression). Placing the one or more boom members in compression may provide a variety of different advantages such as, e.g., providing stability, rigidity, support, etc. to the system **100** that may not be present in systems including boom members that are not in compression.

Further, in one or more embodiments, one or more of the primary beam member **110**, the first and second masts **120**, **130**, the first, second, third, and fourth guy wires **172**, **174**, **176**, **178**, the end beam **144**, and the sheet material **142** may be described as forming a winglet structure. In one or more embodiments, a plurality of winglet structures may be arranged such that the sheet material **142** of each winglet may be in a planar configuration and may form a solar array wing (e.g., two winglets may form a wing). In one or more embodiments, the system may include a plurality of winglets (e.g., aligned along an axis, distributed along a mounting structure, etc.).

The exemplary deployable sheet material system **100** may include a first guy wire housing **181** (e.g., spool) configured to store (e.g., roll up, spool) at least a portion of the first guy wire **172** when in the stowed configuration as shown in FIG. **2** and a second guy wire housing **182** (e.g., spool) configured to store (e.g., roll up, spool) at least a portion of the second guy wire **174** when in the stowed configuration as shown in FIGS. **2** and **3**. Each of the first and second guy wire housings **181**, **182** may be located on the primary beam member **110** or the first mast **120** such that the first guy wire **172** and the second guy wire **174** may extend to the first and

second boom members **150**, **160**, respectively, through the distal region **124** of the first mast **120**. For example, in one or more embodiments, the first and second guy wire housings **181**, **182** may be located at the distal region **124** of the first mast **120**. Further, for example, as shown in FIGS. **2** and **3**, the first guy wire housing **181** may be located proximate the first end region **112** of the primary beam member **110** and the second guy wire housing **182** may be located proximate the second end region **114** of the primary beam member **110**. In one or more embodiments, the system **100** may include multiple guy wire housings to position and store a corresponding guy wire of the plurality of guy wires **170**.

As shown in FIGS. **4-5**, the first guy wire **172** may extend from the first end region **112** of the primary beam member **110** to the first boom member **150** through the distal region **124** of the first mast **120** and the second guy wire **174** may extend from the second end region **114** of the primary beam member **110** to the second boom member **160** through the distal region **124** of the first mast **120**. The system **100** may include a plurality of guy wire mast pivots **171** positioned proximate the distal region **124** of the first mast **120** as shown in FIG. **9** that may be configured to guide one or more of the plurality of guy wires **170** from the first mast **120** to a corresponding boom member (e.g., the first or second boom members **150**, **160**) when the system **100** is moving between the stowed configuration and the deployed configuration. For example, the guy wire mast pivots **171** may move (e.g., pivot about an axis perpendicular to the primary beam axis **113**) relative to the first mast **120** as the first and second boom members **150**, **160** deploy (e.g., passively) with the sheet material **142**.

In one or more embodiments, the deployable sheet material system **100** may further include one or more tensioners **179** as shown in FIG. **9** to place the plurality of guy wires **170** in tension. Placing the plurality of guy wires **170** in tension may help to form the truss-like structure with distributed internal loads. In one or more embodiments, the one or more tensioners **179** may be located proximate (e.g., attached to) the first or second mast **120**, **130** through which the corresponding guy wire **170** passes. The tensioners **179** may be configured to be biased such that the tensioners **179** pull on the guy wire **170** until the guy wire **170** is taut.

In one or more embodiments, the deployable sheet material system **100** may include additional deployable apparatus **240** coupled to the primary beam member **110** opposite the deployable apparatus **140** (e.g., as shown in FIG. **5**) and may be deployable opposite the deployable apparatus **140**. The additional deployable apparatus **240** may be a mirrored structure of the deployable apparatus **140**. For example, the additional deployable apparatus may include a third boom member **250** proximate the first end region **112** of the primary beam member **110** and fourth boom member **260** proximate the second end region **114** of the primary beam member **110**. The additional deployable apparatus **240** may also include an additional sheet material **242** between the third boom member **250** and the fourth boom member **260**. The additional deployable apparatus **240** may function in the same ways as described herein regarding the deployable apparatus **140**.

In one or more embodiments, a control apparatus (e.g., one or more processors employing one or more programs or routines carrying out one or more methods or processes and implemented with one or more types of memory) may be configured to control the system and/or one or more elements thereof moving between the stowed configuration and the deployed configuration. In one or more embodiments, the control apparatus may be configured to control the



deployable apparatus actuator **149** to release the deployable apparatus **140** and control a rate of deployment such that the deployable apparatus **140** deploys (e.g., passively) from the stowed configuration (e.g., spooled state) to the deployed configuration (e.g., extended state). In one or more embodiments, the control apparatus may be configured to control the mast actuator **129** to release the first mast **120** (or second mast **130**) and control a rate of deployment such that the distal region **124** of the first mast **120** moves (e.g., passively) from proximate to the primary beam member **110** to a distance away from the primary beam member **110**.

The methods and/or logic and/or configurations described in this disclosure, including those attributed to the systems, or various constituent components, may be implemented, at least in part, in hardware, software, firmware, or any combination thereof. For example, various aspects of the techniques may be implemented within one or more processors, including one or more microprocessors, microcontrollers, DSPs, ASICs, FPGAs, or any other equivalent integrated or discrete logic circuitry, as well as any combinations of such components, or other devices. The term “processor” or “processing circuitry” may generally refer to any of the foregoing logic circuitry, alone or in combination with other logic circuitry, or any other equivalent circuitry.

Such hardware, software, and/or firmware may be implemented within the same device or within separate devices (e.g., within the system, outside of the system, or a combination of both) to support the various operations and functions described in this disclosure. In addition, any of the described components may be implemented together or separately as discrete but interoperable logic devices. Description of different features is intended to highlight different functional aspects and does not necessarily imply that such features must be realized by separate hardware or software components. Rather, functionality may be performed by separate hardware or software components, or integrated within common or separate hardware or software components.

When implemented in software, the functionality ascribed to the systems and methods described in this disclosure may be embodied as instructions and/or logic on a computer-readable medium such as RAM, ROM, NVRAM, EEPROM, FLASH memory, magnetic data storage media, optical data storage media, or the like. The instructions and/or logic may be executed by one or more processors to support one or more aspects of the functionality described in this disclosure.

An exemplary method **1000** of deploying an exemplary deployable sheet material system **100** is shown in FIG. **10**. The method may include providing **1010** a deployable sheet material system such as, e.g., the deployable sheet material system **100** described herein with reference to FIGS. **2-9**. The method **1000** may also include deploying **1020** the distal region of the first mast from proximate the primary beam member to a distance away from the primary beam member. The method **1000** may further include moving one or more masts (e.g., first mast **120**, second mast **130**) relative to a primary beam member (e.g., primary beam member **110**) to position a distal region of the one or more masts further away from the primary beam member than when in the stowed configuration and extending a plurality of boom members (e.g., first boom member **150**, second boom member **160**) and sheet material (e.g., sheet material **142**) away from the primary beam member to deploy the sheet material.

The method **1000** may also include releasing the deployable apparatus to extend away from the primary beam member and/or releasing the one or more masts to move

relative to the primary beam member. In one or more embodiments, the method **1000** may also include tensioning one or more of the plurality of guy wires after the plurality of boom members and the sheet material are extended away from the primary beam member. For example, a tensioner, or tensioner apparatus, may pull the plurality of guy wires until each of the plurality of guy wires is taut and carries a tensile internal load.

All embodiments described herein with regards to the system may be used in conjunction with embodiments described herein with regards to the methods. Additionally, all embodiments described herein with regards to the method may be used in conjunction with embodiments described herein with regards to the system.

The following provides details about a plurality of embodiments of the present disclosure. One or more of the various features described may be used in various combinations to provide such embodiments.

All patents, patent documents, and references cited herein are incorporated in their entirety as if each were incorporated separately. This disclosure has been provided with reference to illustrative embodiments and is not meant to be construed in a limiting sense. As described previously, one skilled in the art will recognize that other various illustrative applications may use the techniques as described herein to take advantage of the beneficial characteristics of the system and methods described herein. Various modifications of the illustrative embodiments, as well as additional embodiments of the disclosure, will be apparent upon reference to this description.

What is claimed:

**1.** A spacecraft system for deploying sheet material comprising:

a primary beam member extending from a first end region to a second end region;

a first mast coupled to the primary beam member;

a second mast coupled to the primary beam member opposite the first mast, wherein each of the first and second masts extends from a proximal region coupled to the primary beam member to a distal region, wherein the distal region of the first and second masts is positioned farther from the primary beam member when the system is in a deployed configuration than when the system is in a stowed configuration;

a spoolable apparatus coupled to the primary beam member, wherein the spoolable apparatus comprises:

a first boom member proximate the first end region of the primary beam member,

a second boom member proximate the second end region of the primary beam member, and

a sheet material extending from a proximal sheet region to a distal sheet region and located between the first and second boom members,

wherein the first boom member, second boom member, and the sheet material are in a spooled state when the system is in the stowed configuration, and wherein the first boom member, second boom member, and the sheet material are unspooled into an extended state when the system is in the deployed configuration; and

a plurality of guy wires comprising:

a first guy wire extending from at least the distal region of the first mast to the first boom member,

a second guy wire extending from at least the distal region of the first mast to the second boom member,

a third guy wire extending from at least the distal region of the second mast to the first boom member, and

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a fourth guy wire extending from at least the distal region of the second mast to the second boom member.

2. The system of claim 1, wherein each of the first and second boom members extends from a proximal boom region located proximate the primary beam member to a distal boom region when in the extended state, wherein the first and third guy wires extend to the distal boom region of the first boom member and the second and fourth guy wires extend to the distal boom region of the second boom member.

3. The system of claim 1, wherein the first and second boom members of the spoolable apparatus are biased to extend along extension axes to deploy the first and second boom members and the sheet material from the spooled state to the extended state.

4. The system of claim 3, wherein the spoolable apparatus further comprises a spoolable apparatus actuator to restrict movement of the first and second boom members into the extended state along the extension axes and to release the first and second boom members to extend along the extension axes to deploy the first and second boom members and the sheet material from the spooled state to the extended state.

5. The system of claim 1, wherein the first mast is biased to move relative to the primary beam member to move from the stowed configuration to the deployed configuration, wherein the spacecraft system further comprises a mast actuator to restrict movement of the first mast and to release the first mast such that the distal region of the first mast moves from proximate the primary beam member to a distance away from the primary beam member.

6. The system of claim 1, wherein the sheet material comprises one or more photovoltaic arrays.

7. The system of claim 1, further comprising one or more tensioners to tension one or more of the plurality of guy wires.

8. The system of claim 1, wherein the first mast comprises:

- a first mast portion, and
- a second mast portion, wherein each of the first and second mast portions extend from a proximal mast portion region pivotably coupled to the primary beam member to a distal mast portion region, wherein the proximal mast portion region of the first mast portion is proximate the proximal mast portion region of the second mast portion, wherein the proximal mast portion regions of the first and second mast portions are located between the distal mast portion region of the first mast portion and the distal mast portion region of the second mast portion when in the stowed configuration, wherein the distal mast portion region of the first mast portion is proximate the distal mast portion region of the second mast portion when in the deployed configuration.

9. A system for use in deploying sheet material comprising:

- a primary beam member extending from a first end region to a second end region;
- one or more masts coupled to the primary beam member, wherein each of the one or more masts extends from a proximal region pivotably coupled to the primary beam member to a distal region;
- a first boom member extending from a proximal first boom end region coupled to the first end region of the primary beam member to a distal first boom end region

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located farther away from the primary beam member than the proximal first boom end region;

- a second boom member extending from a proximal second boom end region coupled to the second end region of the primary beam member to a distal second boom end region located farther away from the primary beam member than the proximal second boom end region;
- a sheet material extending from a proximal sheet region proximate to the primary beam member to a distal sheet region located farther away from the primary beam member than the proximal sheet region, wherein the sheet material is further located between the first and second boom members; and

one or more guy wires extending from at least the distal region of the one or more masts to the first boom member and the second boom member.

10. The system of claim 9, wherein the one or more masts comprises:

- a first mast pivotably coupled to the primary beam member, and
- a second mast pivotably coupled to the primary beam member opposite the first mast.

11. The system of claim 9, wherein the one or more guy wires extend to the distal first boom end region of the first boom member and the distal second boom end region of the second boom member.

12. The system of claim 9, wherein the one or more masts are biased to move relative to the primary beam member, wherein the system further comprises one or more mast actuators to restrict the one or more masts from moving relative to the primary beam member and to release the one or more masts to move such that the distal region of the one or more masts is located farther away from the primary beam member than the proximal region of the one or more masts.

13. The system of claim 9, wherein the sheet material comprises one or more photovoltaic arrays.

14. The system of claim 9, further comprising one or more tensioners to tension the one or more of guy wires.

15. The system of claim 9, wherein each of the one or more guy wire extends from one of the first and second end regions of the primary beam member to one of the first and second boom members through the distal region of one of the one or more masts.

16. The system of claim 9, wherein each of the one or more guy wires extends from at least the distal region of the one or more masts to one of the distal first boom end region and the distal second boom end region.

17. A method of deploying sheet material from a spacecraft comprising:

- providing a deployable system comprising:
  - a primary beam member,
  - one or more masts extending from a proximal region pivotably coupled to the primary beam member to a distal region,
  - a deployable apparatus coupled to the primary beam member and configurable in a stowed configuration and a deployed configuration, wherein the deployable apparatus comprises:
    - a plurality of boom members, and
    - a sheet material extending between at least two of the plurality of boom members, wherein the plurality of boom member and the sheet material are located proximate the primary beam member when in the stowed configuration and extend from the primary beam member when in the deployed configuration, and

a plurality of guy wires extending from the distal region of one or more masts to the plurality of boom members;

moving the one or more masts relative the primary beam member to position the distal region of the one or more masts farther away from the primary beam member than when in the stowed configuration; and

extending the plurality of boom members and the sheet material away from the primary beam member to deploy the sheet material.

18. The method of claim 17, wherein the deployable apparatus is biased to extend into the deployed configuration, and wherein the method further comprises releasing the deployable apparatus to extend away from the primary beam member.

19. The method of claim 17, wherein the one or more masts are biased to move relative the primary beam member to position the distal region of the one or more masts farther away from the primary beam member than when in the stowed configuration, and wherein the method further comprises releasing the one or more masts to move relative the primary beam member to position the distal region of the one or more masts farther away from the primary beam member than when in the stowed configuration.

20. The method of claim 17, further comprising tensioning the plurality of guy wires after the plurality of boom members and the sheet material are extended away from the primary beam member.

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