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Large Retractable Appendages in Spacecraft

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This is the first comprehensive review of large spacecraft appendages that are both deployable and retractable. Its aim is to gather information on retraction-specific issues, to guide the design, development, and ground testing of retractable appendages for future spacecraft. Following a survey of existing retractable booms and masts, solar arrays, and antennas, including examples of special latching systems, an extensive investigation of the in-orbit performance of appendages that were deployed and retracted in space during the last 25 years has been carried out. Remarkably, almost all appendages that had deployed successfully could also be retracted and, despite widespread concern about total reliance on electric motors for deployment and retraction, the evidence shows that practically all electric motors have performed well.

Introduction

MANY spacecraft appendages are deployed after launch, but very few are ever repackaged in space. Automatic repackaging, or retraction, may be required for many reasons. Recent examples are the deployable solar arrays and antenna booms of the European retrievable carrier (EURECA), which were retracted in June 1993 when EURECA was retrieved by the Space Shuttle, after eleven months in space. Similarly, the solar arrays and high-gain antennas of the Hubble Space Telescope (HST), Fig. 1, were retracted in December 1993 after three years in space. New solar arrays were fitted by astronauts, and one array was brought back to Earth.

It is expected that in the future an increasing number of missions will involve the retraction of large appendages, and the main aim of this review is to gather information and then reflect on retraction-specific issues, to guide the design, development, and ground testing of retractable appendages for future spacecraft. Retraction is opposite to deployment, and any deployable structure whose deployment is inherently reversible can, in principle, be made retractable. In practice, however, this is not entirely straightforward. Furthermore, successful retraction after a long exposure to the harsh space environment requires, for example, the selection of durable materials and the correct design, manufacture, and testing of all mechanisms. Many of these points are dealt with in the literature on deployable appendages, e.g., Refs. 1 and 2, and only those issues that are specific to retraction are discussed in this paper.

This paper is divided into two parts. A survey of existing appendages that are both deployable and retractable is followed by an extensive investigation of the in-orbit performance of appendages that have been deployed and retracted in space during the last 25 years. A discussion of the performance of electric motors in retractable mechanisms, after long periods of inactivity and exposure to the space environment, concludes the paper.

Survey of Deployable-and-Retractable Appendages

There are two basic types of deployable-and-retractable appendages: one-dimensional elements (i.e., booms and masts) and two-dimensional elements (i.e., solar arrays and antenna structures). They are reviewed in that order. Examples of latching systems specially designed for deployable-and-retractable appendages are discussed at the end of the section. In most systems deployment and retraction are driven by electric motors.

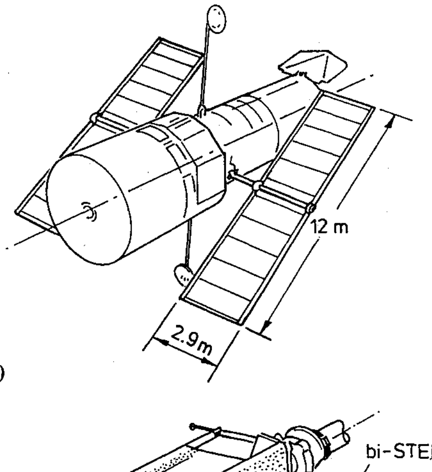
Booms and Masts

Retractable booms and masts are frequently used. Typical applications include communications, where a boom acts as a low-gain antenna; the support of payloads, e.g., high-gain antennas or magnetometers, away from the main body of a spacecraft; and gravity-gradient stabilization. Also, retractable booms and masts are used in larger systems, e.g., solar arrays, as actuators of deployment and retraction.

Articulated booms consist of one or two tubular elements, joined by motor-driven hinges. For example, HST has two 3.58-m graphite–aluminum booms, which support 1.32-m-diam high-gain antennas. The root of each boom is connected to the main body of the spacecraft through a mechanism consisting of a motor-driven hinge, including a dc stepper motor with harmonic drive, and a passive hinge containing a self-aligning spherical bearing, which compensates for any misalignments.

Tubular booms can be made in different ways. For example, an open-section tubular boom can be made from a thin strip of metal whose cross section has the shape of a circular arc. Such booms can be flattened, starting from one end, and coiled on drums for compact storage (Fig. 2a). Rimrott[3] has shown that the coiling process is entirely elastic if the strip is sufficiently thin. The limiting thickness depends on the ratio between the elastic modulus and the yield stress of the material, and on the ratio between wrapped and unwrapped diameters. Typical materials for tubular booms are CuBe and stainless steel, with thicknesses up to 0.2 mm.

Several types of deployable-and-retractable tubular booms are available. In all of them the coiling drum and most of the ploy region,



a)

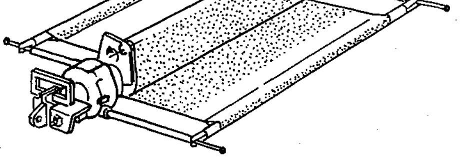


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Fig. 1 Retractable HST appendages.

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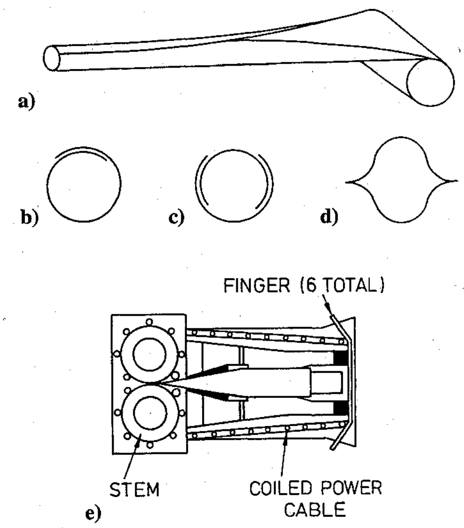

Fig. 2 a) Tubular boom, b–d) different cross sections, and e) deployment cassette of Apollo 15 and Apollo 16 bi-STEMs.

where the cross section of the tube changes from flat to a circular arc, are contained within a deployment cassette, which contains also the deployment-and-retraction motor. The most well-known examples are the storable tubular extendible member (STEM),[3] based on a single strip (Fig. 2b), and the bi-STEM,[4] consisting of two identical strips placed one inside the other during deployment (Figs. 2c and 2e). The main advantage of a bi-STEM over a STEM of similar length and stiffness is that, because each of the two strips making the bi-STEM is considerably narrower than the single strip in the STEM, the bi-STEM requires a shorter drum. More importantly, its shorter ploy region can be accommodated in a more compact deployment cassette. Bi-STEMs with noncircular cross section are also available.[5]

Another commonly used tubular boom is the interlocked, or zippered, version of the STEM, where, instead of overlapping the edges, a series of matching tabs are formed on both edges of the strip.[6] A narrow zipper roller between the shape-forming rollers inside the deployment cassette mates the tabs during deployment. The interlocked design provides much larger torsional stiffness to the boom, which can be useful for locating the angular position of a tip payload and, more importantly, reduces the possibility of thermal instability.[7]

Closed-section tubular booms, made from two strips bonded at the edges, are also available. Such booms are rolled up and deployed much in the same way as STEMs, but in the deployed configuration the two strips spring back to the unstressed, lenticular cross-sectional shape shown in Fig. 2d. Continuous manufacturing methods for closed-section booms made from CuBe or carbon-fiber-reinforced plastic (CFRP) have been recently developed,[8] and, following the use of a 7.5-m deployable-only, closed-section boom on the Ulysses spacecraft, a retractable version has been developed.[9] Tube thicknesses between 0.05 and 0.25 mm, with corresponding boom widths, when flat, between 42 and 180 mm, have been considered.

Telescopic masts consist of a series of concentric, thin-walled cylindrical tubes that can be nested inside one another in the stowed position. In the extended position there is only a small overlap between consecutive tubes, as in a radio aerial. Typical materials for telescopic masts are Al alloy and CFRP, and a typical wall thickness is 0.5 mm.

Three telescopic booms have been developed. Humphries[10] describes a sequential deployment technique where tubes are deployed by a chain drive that runs on an inner support tube extending almost the full length of the tube stack. The chain is driven by an electric motor. First, the chain picks up the innermost tube and pulls it up until its bottom end becomes latched to the upper end of the second tube. Then, the second tube is similarly deployed (together with the first tube), and so on. A three-tube, 5.5-m-long deployable-only demonstration boom has been tested, and with a modified latching system this boom could be retracted.

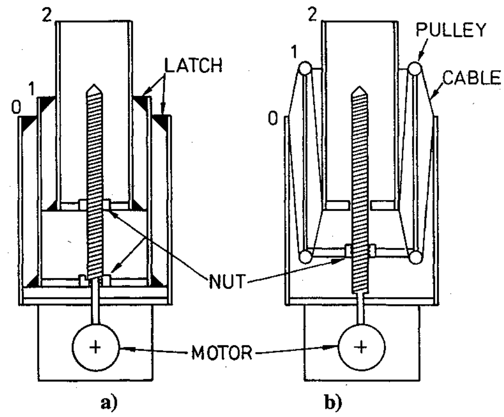

Fig. 3 a) Sequential and b) synchronous deployment of telescopic mast.

Figure 3(a) illustrates the operating principle of an alternative telescopic boom,[11] with a deployment sequence similar to that described above. This boom is driven by a spindle with a short unthreaded part at the bottom. Each tube has a threaded nut at the bottom. When deployment begins, the threaded part of the spindle becomes engaged with the nut at the bottom of the innermost tube. This nut is pushed out until, when it has reached the end of the spindle, three latches at the bottom of the first tube capture the upper end of the second tube. At this point, a further small rotation of the spindle drives the nut at the bottom of the second tube onto the threaded part of the spindle, and so on. For retraction, the spindle rotates in the opposite direction; delatching is activated each time a tube segment becomes fully nested.

Two synchronously deployed 2.4-m-long telescopic masts have been developed for the Tethered Satellite.[12] Each mast consists of seven tubes. During deployment, the outermost tube is driven out of an outer support by a spindle-and-nut arrangement, driven by an electric motor, while a system of synchronization cables extends the other six tubes by equal amounts. The principle is shown in Fig. 3b for a small number of tubes. There is no latching system: when the mast is fully deployed, the deployment motor is locked and the mast is held in position by the synchronization system. For stiffness, the tubes slide on tight-fitting Vespel pads, and a minimum overlap of 1 diameter is maintained. For retraction, the spindle rotates in the opposite direction and, as the outer tube is drawn in, all other tubes have to follow.

Coilable masts are lattice trusses with triangular cross section, specially designed for purely elastic folding. Three continuous unidirectional glass-fiber-reinforced plastic (GFRP) rods, or longerons, form the edges of a truss, which is divided into bays of equal length by GFRP triangular battens hinged to the longerons. Each bay is braced by six thin GFRP diagonal members, or by six steel cables. The diagonals are made a little shorter than their nominal length, so that the battens are permanently in a state of compression and hence prestress the bay. Typically, the length of a bay is about 0.6 times the diameter of the deployed mast. A simpler design of the battens and their connection to the longerons is known as the hingeless mast.[13] Double-laced coilable masts, where the diagonals brace two bays for extra strength, are available.[14,15]

A coilable mast is stowed by coiling the longerons, starting from one end of the mast. Thus, when the mast is partially folded, a transition zone separates the extended region at one end from the stowed region at the other end; see Fig. 4. The details of the deployment process have been analyzed by Eiden et al.[16] The retraction process can be considerably different from the deployment process, because the effects of friction and structural imperfections combine differently, and also because coilable masts store strain energy during folding, but release energy during deployment.

There are two techniques for deploying and retracting a coilable mast. In the deployment-nut technique a thin-walled tube, or canister, encloses the stowed part of the mast and the transition zone Fig. 4. Deployment and retraction are controlled by a large motor-driven nut in the upper part of the canister and concentric with it: roller lugs connected to the longerons become engaged with guide

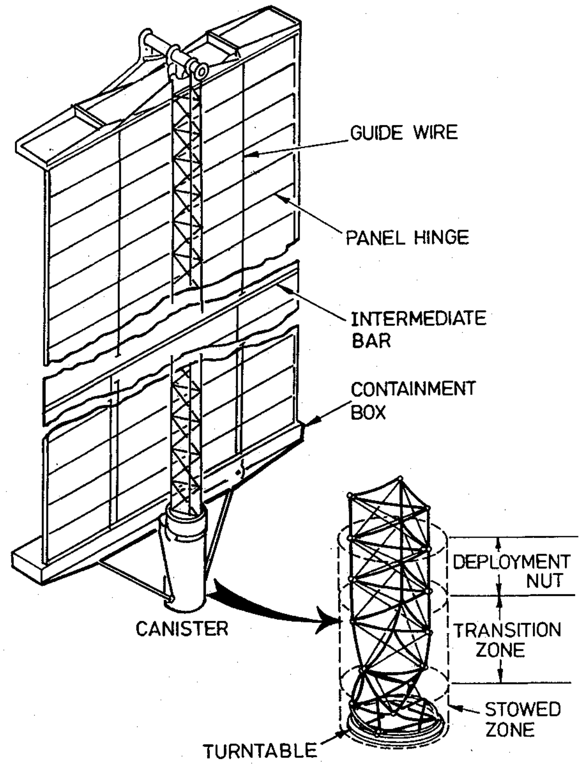

Fig. 4 Flat-fold solar array, deployed by coilable mast.

rails fixed to the canister and are pushed out or in, respectively, when the nut rotates. The bottom end of the mast is connected to a turntable, which allows free rotation of the stowed zone as the mast deploys or retracts.

The second, more compact technique for deploying a coilable mast makes use of a cable, or lanyard, running along the length of the mast. The lanyard is attached to the top end of the mast through a wire system[17] and to a motor at the bottom of the mast. During deployment the lanyard controls the deployment rate. To initiate retraction, the lanyard applies an axial force and a torque to the top plate, and once the mast has started to coil, the lanyard provides the axial force required to move the transition zone towards the storage canister. The lanyard force changes considerably during a full deployment–retraction cycle, with the largest value reached when retraction begins.

A variant of these two techniques[18] has a half-length canister, without the deploying nut, and a smart motor that can drive the turntable in a fast deployment–retraction mode or in a slow stepper mode to accurately rotate the extended mast and its payload (typically an antenna).

Nut-deployed masts tend to be much heavier and bulkier than lanyard-deployed masts. Lanyard-deployed masts are relatively weak and flexible during deployment, because the transition zone is near the tip: full stiffness cannot be achieved until the mast is fully deployed. Also, the tip of a lanyard-deployed mast rotates relative to the base during folding and deployment, which is unacceptable for some applications. The deployment-nut technique is chosen for longer masts, usually above 10 m: the longest one is 45.7 m long, for the LACE mission discussed later on. Typical diameters are in the range 0.2–0.4 m. The lanyard deployment technique is frequently used to support high-gain antennas (typical lengths are 1–2 m and diameters 0.5 m) or magnetometer booms (5–7 m and 0.2–0.3 m).

Truss structures are three-dimensional assemblies whose members contain hinges in suitable positions. Most of the deployable trusses developed so far cannot be retracted, and hence are beyond the scope of this review.

The folding articulated square truss mast (FASTmast)[19] consists of a series of cubic bays. Each bay has rigid frames at the top and bottom, hinged to four lateral members with midbay hinges. Two pairs of diagonal cables brace each side face. A compression hoop, formed by four GFRP struts connecting neighboring midbay joints, pre-tensions the diagonals and removes joint backlash. To

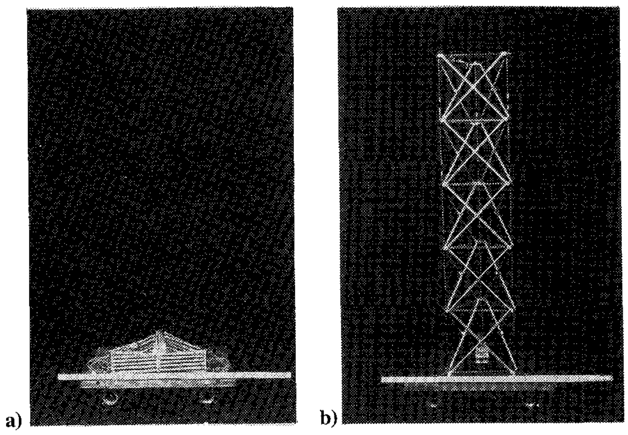

Fig. 5 Triangular pantographic mast.

fold a bay, the four midbay joints are pushed sideways in an anticlockwise sense. The bay naturally redeploys itself by releasing the strain energy in the GFRP hoop, as soon as the midbay joints are allowed to move in a clockwise direction. The FASTmast is deployed and retracted by a variant of the deployment-nut technique employed in coilable masts. A 12-m-long truss that folds into a 1.52-m-long canister (diam 0.76 m) has been used in the Tethered Satellite mission.

A 12-m deployable-and-retractable truss with 0.4-m square cross section has been developed by Zwanenburg,[20,21] primarily for rigid-panel solar arrays. This truss is based on two identical, synchronously deployed, two-dimensional trusses whose ingenious folding scheme requires no intermediate hinges in the bars. Deployment and retraction are driven respectively by the strain energy stored in the hinge springs and by winding a longitudinal cable onto a drum driven by an electric motor. When stowed, this truss has a footprint of 1.6 by 0.4 m, and it is only 0.1 m high.

Two synchronously deployed trusses have been developed by Kwan et al.[22] The first truss, shown in Fig. 5, consists of a three-dimensional pantograph with triangular cross section, formed by a series of bars hinged at the ends and in the middle. The truss is deployed by winding a special active cable—which runs on a series of small pulleys—onto a drum, connected to a dc motor. When this truss is fully deployed, a series of passive cables become taut, and the active cable imparts a state of pre-tension to these cables. The resulting structure has high stiffness and no backlash. Retraction is driven by constant-force springs at the base of the mast; the retraction rate is controlled by the dc motor. The second truss is also deployed by an active cable and stiffened by pre-tensioned passive cables after deployment, but, instead of a pantograph, it is based on two interconnected frames, which move closer to each other during deployment.

Solar Arrays

An extensive review of deployable solar arrays is available in Chapter 7 of Ref. 23. Basically, there are two different types of deployable solar arrays: a flexible blanket type, where solar cells are supported on a flexible membrane made of fiber-reinforced Kapton, and a rigid panel type, where the cells are supported on lightweight panels of aluminum honeycomb bonded to CFRP layers. Traditionally, blanket-type arrays have been used for larger systems, where total mass is critical. Recently developed rigid arrays, though, have challenged the mass advantage of blanket arrays. A few retractable implementations of both types are available and are discussed below.

Blanket arrays consist of one or two continuous blankets that are rolled on a single drum. Figure 1b shows one of the two arrays of the HST, where the drum is supported by duplex bearings on an inner tube, connected to the spacecraft through a primary deployment-and-retraction mechanism (not shown in the figure). Each blanket ends on a spreader bar connected to the tips of two bi-STEMs. Rotation of the drum is resisted by a constant-torque spring that maintains a tension of around 100 N in the two blankets, both during deployment and retraction and during operation. Note that, as the blankets are deployed by the bi-STEMs, a cushion layer is rolled up on a reel above the main drum. The electrical interface between the (rotating) drum and the (static) inner tube is through a flexible harness wound onto the tube: the harness unwinds during the first half of deployment and then rewinds onto the tube, but in the opposite sense, during the second half. This concept was used in the flexible rolled-up solar array[24] (FRUSA) in 1971 and subsequently in the HST, where, for redundancy, two dc brushed motors have been used, one in each storage cassette.[25] Deployment and retraction of the array require that only one motor be operational (maximum power is required during retraction). The size of a two-blanket array has increased from approximately 10 × 1.6 m in the FRUSA to 12 × 2.3 m in the HST.

An alternative to the rolled-up blanket is the flat-fold system shown in Fig. 4. It consists of a series of flexible panels, connected by hinges, that are folded flat into a containment box. The box cover is fixed to the tip of a nut-deployed coilable mast whose canister is fixed to the side of the containment box (a deployable truss structure can be used instead of a coilable mast). Deployment and retraction of the array, latching and unlatching of the box cover, and tensioning of the blanket after deployment are driven by the mast. In the rolled-up system it is easy to maintain a constant tension in the blanket during deployment, but the flat-fold concept results in a floppy accordionlike structure that requires lateral support from guide wires tensioned by constant-tension springs.

A mechanism that controls the deployment and retraction sequence of a flat-fold array has been proposed by Behrens.[26] During deployment, this mechanism allows only one pair of panels at a time out of the containment box: the next pair is released only after sufficient tension has built up in the panels previously released. During retraction, a series of stops on the tensioning wires initiates folding of the pair of panels currently nearest to the containment box.

The flat-fold solar array has been investigated in considerable detail because it is the selected concept for the Space Station Freedom. It appeared in embryonic form in Lindberg[27] and has continued to evolve ever since. The largest is a solar array wing[28] with forty 2.85-m-wide panels and a total length of 15.25 m. Of particular interest to this review is the 30.9-m solar-array wing used in the solar-array flight experiment (SAFE). This array consists of 84 Kapton panels of size 0.37 by 4.00 m (Fig. 4). It can be operated in a 70% extended configuration—with 60 panels deployed and tensioned between the box cover and the intermediate tension bar—or 100% extended. Small leaf springs along the panel hinge lines cause the panels to refold in the correct direction. Four constant-tension wires stiffen the panels during deployment: two guide wires extend the full length of the array and have the main function of providing out-of-plane stiffness to the array during deployment; the other two link the intermediate tension bar to the containment box, thus preventing deployment of the 24 bottom panels until the top 60 have fully deployed.[29] Two redundant brushless dc motors activate deployment and retraction of the 33.5-m-long coilable mast, which, since there are no latches, has also the function of applying to the box cover the preload required to prevent damage of the panels during launch or re-entry. For this reason, the longerons in the outboard $1\frac{1}{2}$ bays of the mast—which are not required to coil even when the mast is fully retracted—are made of aluminum to provide a stiff stress path between the containment box cover and the box itself.

Rigid-panel arrays make use of the solar panels as an integral part of the structure. The two solar-array wings of EURECA consist of five 3.4 by 1.4 m panels and a Y-shaped yoke with a hinge in the middle.[30] Each wing is synchronously deployed or retracted by two pairs of active cables, one for deployment and one for retraction on either side of the array, for redundancy. The cables are supported by free-running pulleys connected to the hinge shafts. These cables are connected at one end to the outboard panel, and at the other end to a central drive unit including a dual dc motor that activates deployment and retraction. The motion of the five panels and the yoke is synchronized by a series of cables; when the central drive unit winds the active cables in (out), the whole wing deploys (retracts). After the array has fully deployed, the current to the motor is doubled to increase the tension in the cables and preload all hinge stops. Finally, a dc brake is applied in the central drive unit, to maintain the preload. To retract, the brake is released and the motor switched on in the reverse direction. If one motor fails to start, a second motor, connected to the same output shaft through a differential, takes over.

Bobo[31] has proposed a retractable array based on the TVSAT design. A concertina of rigid panels, connected by hinges along the long edges, is integrated with two sets of rods to form a pair of three-dimensional pantographs. This system has a single degree of freedom, like the previous concepts, but here the coupling between panels is achieved by means of rods, not cables. Deployment is driven by springs along the panel–panel hinges, whereas retraction is driven by an electric motor located at the root of the array. The rate of deployment is also controlled by this motor. The use of paraffin actuators in rigid-panel solar arrays has been proposed by AEC-Able Engineering (California).

A retractable solar array whose panels are not part of the main load-carrying structure has been developed by Zwanenburg.[32] The panels are connected to the deployable truss developed by the same author and described previously.

Antennas

The large, flat retractable antenna for the SIR-B mission has been described by Presas.[33] This antenna consists of eight subarrays on a flat tubular aluminium structure divided into three leaves; it is 10.7 m long (deployed; 4.0 m if stowed) and 2.2 m wide. The center section (three subarrays) is backed by a rigid truss structure, connected by a motor-driven tilt hinge to a pallet truss fixed to the Shuttle cargo bay. For launch and landing, the upper truss is latched to the pallet truss. The forward section (two subarrays) and the aft section (three subarrays) are hinged to the center section for stowage onto the center section (forward section first) and restrained by a launch–landing latch. For deployment, the two latches are released by electric motors, then the aft section is rotated through 180 deg by dual-drive actuators, and finally the forward section is rotated through 180 deg. Each actuator consists of two dc motors driving two harmonic drives through independent shafts. Retraction and relatching are required before closing the cargo-bay door for re-entry. If both motors that drive retraction of a section of the antenna fail, they can be mechanically disconnected from the hinge by a pyrotechnic pinpuller. The section is then restowed by a spring-loaded actuator activated by a further pyrotechnic pinpuller. This is the only example identified by this survey of a purely spring-driven retraction system. Because a two-failure-tolerant retraction mechanism had been adopted, no jettison capability was provided.

The antenna is tilted by the hinge between the truss structure and the pallet truss, to take images at various incidence angles. The actuator in this hinge is identical to the actuators in the fold hinges and, to remove backlash, is mounted in parallel with a constant-torque spring.

Many existing deployable antennas are also retractable: they are listed below. The precision deployable antenna[34] and the MEA reflector[35] are symmetrical rigid-panel antennas whose deployment is spring-driven (although motor-controlled) and purely motor-driven, respectively. The active phased-array lens,[34] the radial-rib antenna,[34,36] the hoop–column antenna,[37] the wrap-rib antenna,[38] and the tension truss antenna[39] are mesh reflectors whose deployment is purely motor-driven. In the wrap-rib antenna the mesh is connected to tubular booms that unwrap from the central hub under the action of a rotating mechanism. In the tension truss antenna the mesh is deployed and tensioned by motor-driven coilable masts.

Latching Systems

A variety of launch–landing restraint latching systems have been developed to restow retractable appendages that are to be returned to Earth. Typically, latching systems in deployable appendages are single-shot devices, e.g., pyrotechnic actuators, but most latching–relatching systems are driven by electric motors. Three systems are presented here.

Warden[40] describes a relatchable launch restraint mechanism for lanyard-driven coilable masts. Automatic delatching and relatching of a center post connected to the plate at the top of the coilable mast are driven by the same electric motor that drives the lanyard reel.

Table 1 Summary of retraction in space

Mission	Date	Appendages	Comments
DODGE	1967	10 STEMs (6 were 46 m long) driven by ac motors	1 STEM never worked; the other 9 deployed and retracted many times
Apollo 15	1971	2 bi-STEMs	12 deployments and retractions planned; anomalies during 5 retractions; similar anomalies on Apollo16
FRUSA	1971	4 bi-STEMs, 2 blanket arrays	5 complete deployment and retraction cycles, plus a few partial retractions
SAFE	1984	33.5-m-long nut-deployed coilable mast, driving a flat-fold blanket array	Several deploy–retract cycles (70% or 100%); anomalies: increasing rate of deployment and retraction, sticking of panels, dynamic resonance
SIR-B	1984	3-section flat antenna with motorized hinges	Anomalies: oscillations after de-latching and failure to relatch during first deploy–retract cycle
Solar Max	1980–1989	1.5-m lanyard deployed coilable mast	Deployed in 1984; partially retracted and deployed twice in 1989
DEBUT	1990	1.2-m lanyard-deployed hingeless mast, 24-panel aerobrake (0.9-m diam)	Mast fully deployed and retracted 34 times; aerobrake deployed and retracted 52 times
Classified	1990–1991	1 interlocked STEM	Retracted from 12.8 to 10.7 m, extended at regular intervals; motor or mechanism failure when 11.6 m long
EURECA	1992–1993	2 rigid panel arrays, 2 S-band antennas on 2.2-m-long articulated booms.	Arrays successfully deployed and retracted; incomplete retraction of booms
LACE	1990 to date	Three 45.7-m nut-deployed coilable masts	Hundreds of deployments and retractions; dynamic identification tests 1991–1992

During the final stages of retraction, a spring-loaded mechanism inside the reel decouples the motor from the reel, while continuing to hold the lanyard. Once relatching is complete, with the wedge securely held by the detente, the motor could actually be removed without releasing the mast. This latching system has been used on the Explorer Platform.

The stack of five panels and yoke forming each solar-array wing in EURECA is restrained by a system of six latches driven by a central stowage unit, which includes a redundant motor-driven winch, through a system of synchronization cables. Each latch consists of two hooks driven by a crank-and-wheel arrangement, whose large travel would permit latchup of slightly deformed panels.

The launch–landing restraint mechanism for the second mission of the shuttle-borne imaging radar (SIR-B) consists of a double-failure-tolerant primary system and a secondary system. The primary latching system is a motor-driven claw (there are two motors, for redundancy), and in case of double motor failure, a single-shot, spring-driven secondary latch released by pyrotechnic actuators can take over. However, it appears that this secondary latching system would provide no redundancy if excessive antenna distortion prevented the correct latchup of the primary claw, because the claws of the secondary system operate in precisely the same way.

Retraction in Space: the Evidence

The number of missions that have involved the retraction of an appendage is small in comparison with the number of missions involving deployment. However, quite a number of retractions have been performed, almost all successfully, over a period of 25 years. Practically all retractions performed so far have involved a tubular boom or a coilable mast. This section reviews the performance of these appendages, together with any available evidence on their development and ground testing. Table 1 summarizes the material presented in this section.

The earliest application of deployable and retractable tubular booms was in gravity-gradient stabilization during the 1960s. The orbital stability of different spacecraft configurations was investigated by altering the length of the booms, and many boom retractions were performed during these experiments. Also, some gravity-gradient-stabilized satellites have exhibited unexpectedly large libration angles, often leading to spacecraft inversion (the spacecraft ended up pointing away from Earth): this behavior is not yet fully understood.[41] A way of reinverting an inverted spacecraft is to rotate it slowly by partially retracting a boom and then reextending it to (hopefully) recapture the spacecraft in the Earth-pointing mode. Nowadays this maneuver is done more reliably by momentum wheels. There is an extensive literature on the subject of spacecraft inversion.[42]

Department of defense gravity experiment (DODGE). Mobley[43] reports on experiments performed on this satellite, launched in July 1967 with the aim of investigating gravity stabilization in nearly geosynchronous orbits. This satellite had ten tubular booms of the STEM type, made from 50.8-mm-wide BeCu strip. When fully deployed, all tubes had 12.7-mm diam and some overlap. Six booms had a maximum length of 46 m; the others were somewhat shorter. The booms had small tip masses of 1 to 4 kg. For boom deployment and retraction, ac motors were chosen to avoid the brush wear problems of dc motors. Also, in view of the many extension–retraction cycles to be performed, dry-lubricated bearings were used. Soon after injection into orbit, all ten booms were unlocked and extended a short distance: nine booms worked properly, but one stalled after a short extension. This boom never worked afterwards, and hence one of the two planned spacecraft configurations could not be achieved. A long series of experiments were performed during the period July–December 1967 involving many partial deployment and retraction cycles and also a few complete retractions. All deployments and retractions were entirely successful from a mechanisms viewpoint. The only anomaly was that on one occasion, due to overheating of an electrical component, a deploy signal for four booms—correctly sent and received—was executed as deployment of two booms and retraction of the other two.

More recently, boom retraction experiments have been carried out by the Naval Research Laboratory, Washington. Melvin and Rodriguez[44] have attempted to regain control of a spacecraft whose motion had been practically chaotic for a long period. In February 1990, a CuBe boom with interlocked tabs was retracted from 12.8 to 10.7 m. During subsequent months, it was deployed, a small amount at a time, searching for a stable spacecraft configuration. In the autumn of 1991, the boom failed to respond, at a length of 11.6 m, before any successful results had been obtained. From the evidence available, it appears that the cause of the failure is motor or mechanism failure.

Apollo 15 and Apollo 16. Two retractable bi-STEMs were used on the Apollo 15 service module, and then again on Apollo 16, for the support of payloads that had to be retracted before thruster firing. Each boom consisted of two 140-mm-wide, 0.3-mm-thick tempered steel tapes, which formed a 51-mm tube about 8 m long. The payload and the service module were electrically linked by a 19.2-m-long helical power cable, with circular cross section, made up of 20 conductors and a coiled spring wire. The power cable had an unstressed length of 2.6 m. In the stowed configuration the cable was tightly coiled around the deployment cassette of the bi-STEM, inside an outer mechanism housing; see Fig. 2e. During deployment the bi-STEM would pull the power cable out of its housing, and during retraction the bi-STEM would apply an axial compressive force on the cable, thus pushing it into the annulus between the mechanism housing and the deployment cassette. Six guiding fingers connected to the experiment mounting flange, at the tip of the boom, directed the cable towards the annulus. During the Apollo 15 flight twelve full retractions of the two booms were planned, but on five occasions the boom supporting the mass spectrometer did not retract fully. However, it retracted fully after being extended by about 1 m and then retracted again. Telemetry data from the spacecraft showed that the motor current had remained nominal (3–4 A) for quite some time, before it increased suddenly to stall level (9 A). From this evidence, it was decided that retraction must have been nearly complete, and hence it was decided that there was no need to jettison the booms. At a later stage, the pilot of the service module was able to confirm that the boom was almost fully retracted, during routine extravehicular activity. A postflight investigation[45] concluded that the anomaly was due to improper stacking of the cable resulting from a faulty design of the cable housing. Similar booms had already been made for Apollo 16, and, since there was insufficient time to implement and flight-qualify any extensive modifications to the cable winding system, proximity switches were fitted to indicate that a boom was within 30 cm of full retraction: it had been shown that 30-cm-long booms would not be damaged by thruster firing. Small changes to the guiding fingers were also made, but proved to be inadequate, since the anomaly recurred on both booms of Apollo 16. However, in all cases the proximity switches showed that the two booms were within 30 cm of full retraction.

Skylab. Two 9.1-m bi-STEM booms with twin-lobed cross section have been used on Skylab over a period of nine months[5] to transfer film cassettes from the airlock module to the telescope mount. High startup torques during development testing at low temperature of these booms led to larger tolerances in the deployment mechanism and gears. Also, difficulties were encountered in the selection of a suitable brush material for the dc motors. The steady-state current was limited to 12 A, but the motor electronics were designed to allow current spikes up to 25 A for a maximum duration of 150 ms. In space the two booms performed many faultless deploy–retract cycles. Manual operation of these booms would have been possible and a spare boom was also available, but they were never needed.

In addition to the application of tubular booms for gravity-gradient stabilization and for the support of payloads, retractable tubular booms have been used in solar-array systems. Such applications will be reviewed in the section on solar arrays.

Coilable Masts

Solar-Maximum Mission (Solar Max)

The high-gain antenna system[17] (HGAS) of Solar Max was mounted on a six-bay, 1.5-m-long, lanyard-deployed coilable mast with a deployed diameter of 0.47 m. During launch into low Earth orbit, in February 1980, both the mast and the antenna drive mechanism were accommodated in a canister contained within the spacecraft envelope; only the antenna dish went beyond this envelope. The plan was to deploy the HGAS as soon as the Tracking Data Relay Satellite became operational, but because of the failure of the attitude control system on Solar Max, deployment took place 3 years after launch, after the successful Solar Max repair mission. In 1989, prior to Solar Max entering the Earth's atmosphere, a series of end-of-life engineering evaluation tests were carried out,[46] including two partial (80–100-mm) retraction–deployment tests. These tests demonstrated that the deployment and retraction mechanisms were still operational after 5.5 and 9.5 years, respectively, of inactivity in space. The mast could not be retracted fully, because, as a result of a previous gimbal-motor failure, the antenna drive mechanism could no longer re-enter the canister.

Solar Max was the first spacecraft designed for in-orbit servicing by the Shuttle, and a series of issues related to the retraction of a high-precision, large deployable structure were addressed for the first time during its development. A possible cause of failure was, of course, wear of the lanyard, but it was found on a development model that at least 150 deploy–retract cycles could be completed without failures. Differential wear between ball and cup supports of the diagonal members, which occurs because one set of diagonals goes slack during folding while the other set doesn't, was measured and found to be small. Low-vapor-pressure lubricants were used in the dc motor, exposed to hard vacuum. Also, different brush compounds were investigated, to control wear.

Deployable Boom and Umbrella Test (DEBUT)

A hingeless mast was tested on this small spacecraft[47] in February 1990. Thirty-four full deployments and retractions of the 1.2-m-long, lanyard-deployed mast were carried out over a period of 10 days (Fig. 6). The mast had a diameter of 150 mm and was driven by a brushed dc motor powered by lithium batteries. The tests were in both eclipse and sun conditions, with boom temperatures in the range 24–32°C. There is good correlation between deployment or retraction duration and battery voltage; hence it appears that there was no degradation in the properties of the mast, or indeed in the properties of the lubricants. A deployable and retractable aerodynamic brake with a diameter of 0.9 m, i.e., a kind of umbrella consisting of 24 CFRP panels, was located on top of the mast. The aerodynamic brake was itself deployed and retracted 52 times by a dc motor located under the hub of the aerobrake.

Low-Power Atmospheric Compensation Experiment (LACE)

This spacecraft was launched in February 1990 and is still operational. It is stabilized by means of a 45.7-m-long, nut-deployed coilable gravity-gradient mast with a diameter of 0.25 m. This mast carries a 91-kg mass and magnetic damper at the tip. The spacecraft has two more coilable masts, the retroreflector mast and the balance mast, of identical characteristics to the gravity-gradient mast but with smaller tip masses, along and opposite to the velocity vector, respectively. Deployment and retraction of the three masts are driven by two brushless motors, for redundancy. Over 300 partial retraction–deployment cycles of the retroreflector and balance masts have been carried out during a period of about 2 years. Although detailed data on these cycles has yet to be released by the Naval Research Laboratory, it appears that no major failure has occurred in the two masts, despite the large number of cycles performed. During one particular set of experiments, in January 1991, Fisher and Schultz[48] used an Earth-based laser system to examine spacecraft vibration induced by constant-rate retraction of the retroreflector

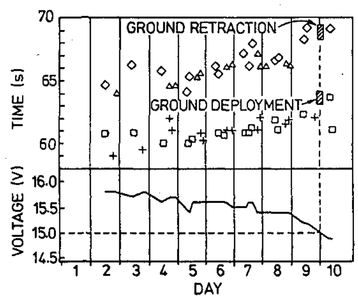

Fig. 6 Deployment and retraction of DEBUT hingeless mast, from Ref. 47. Day: □ deployment, △ retraction. Night: + deployment, ◇ retraction.

mast from 24.4 to 4.6 m, while the two other masts remained fully extended.

Solar Arrays

Both blanket and rigid-panel solar arrays have been retracted in space. The first retraction validated a new technology, in 1971. More recently, solar arrays have been retracted in the course of two high-profile missions. Blanket arrays will be discussed first.

FRUSA

The first retractable solar array was flown on STP 71-2 in October 1971. It had been instrumented with accelerometers, strain gauges, and temperature sensors, which provided a wealth of data. An extensive series of deployment and retraction tests were carried out during the first four months after launch.[49] The array was fully deployed and retracted ten times: five times on Dec. 22–23, 1971, and then five times on Jan. 4–5, 1972. Some of these cycles occurred in eclipse conditions with a main-drum temperature of −40°C. Partial retractions to 1/3 and 1/6 of maximum length were also carried out. The key aim of these tests was to detect any signs of degradation in the solar cells, of which there were none, but they also demonstrated the faultless performance of the deployment and retraction mechanism in the space environment. Olson[50] reports on the ground testing of the FRUSA prior to launch. In addition to standard tests, a life test of 314 extension–retraction cycles was carried out on a bi-STEM, to demonstrate that the flight model could undergo 35 cycles (25 during standard ground testing and 10 in orbit). Also, extensive development tests were carried out on the drum system, to measure the effects of uniform low temperatures and of thermal gradients, and on the cable harness, to estimate stiffening at low temperatures.

HST

The two solar arrays of the HST were deployed in April 1990 and replaced during the first servicing mission in December 1993 (STS-61).[51] One array was successfully retracted and returned to Earth. The second array had formed a severe bend in one of the booms and could not be retracted fully. It appeared that one of the booms on the buckled array had stopped retracting, and hence the array was jettisoned. During design of these arrays full motor redundancy was aimed for; however, it later turned out that retraction under worst-case conditions would have required that both motors on a drum be driven together. Full redundancy has been provided in the replacement set of arrays.

SAFE

The flat-fold flexible blanket array used in SAFE was deployed from the Shuttle cargo bay in September 1984. Key aspects of this experiment were to demonstrate multiple deployment and retraction capabilites, to verify operation under maximum temperature gradients, and to verify the application of preload prior to re-entry. A dynamics experiment was conducted in parallel with SAFE, with the objective of refining the analytical model of the array.

The experiment lasted three days. It included a sequence of partial (70%) and full deployments and retractions; dynamic experiments were also performed. From the large number of experimental data available in the final report on the experiment,[29,52] the following three sets of results are of interest.

1) *Comparison of motor currents.* Motor currents in space were approximately the same as on Earth with peaks of 7.3 and 11.9 A, respectively, during nut unlocking and locking (the motor stall current was 25 A). However, all pre- and postflight ground tests were conducted at 28 V, whereas in space the mean bus voltage was 30.6 V; hence extension and retraction were somewhat faster in space. The mean full deployment times were 808 s preflight, 754 s flight, and 812 s postflight. The mean full retraction times were 790 s preflight, 722 s in-flight, 789 s postflight. A kind of wearing-in effect led to steadily increasing extension and retraction rates throughout the flight. But, since the pre- and postflight deployment and retraction times were approximately the same, this effect cannot be attributed to any sort of degradation. During acceptance of the flight model, full deployment and retraction tests were carried out, both before and after the acoustic and thermal-vacuum tests. Shortly before launch, following 7 months in storage, a poststorage deployment–retraction test was carried out.[53]

2) *Sticking of panels.* During the first extension from fully stowed to 70% deployed, sticking between adjacent panels of the solar array caused a nonuniform unfolding motion of the blanket. A similar effect was also observed in the bottom 30% of panels during the first full extension of the array. This effect had been observed already during preflight testing and was attributed to traces of adhesive remaining on the blanket.

3) *Dynamic resonances.* Large-displacement oscillatory motion of the mast and blanket were observed when the mast was about 4 m (retraction only), 18 m (both deployment and retraction), and 29 m (both deployment and retraction) long. In all cases, a local accordionlike mode developed in the blanket, and the amplitude of the excitation was such that adjacent panels came into contact on a few occasions. An explanation of this effect invoking the coupling between blanket dynamics and the periodic disturbance generated by deployment or retraction of a coilable mast has been proposed.[29,54]

EURECA

EURECA's solar arrays were deployed in August 1992 (STS-46) and retracted in June 1993 (STS-57), prior to EURECA's retrieval by the Shuttle. Deployment was successfully performed in sunlight, even though eclipse conditions would have been more favorable, on account of timeline constraints. Off-calibration of a potentiometer was the only anomaly observed at that time. The timing of the full sequence was as follows: unlatch 5 min 7 s, wait 19 s, deploy 4 min 40 s, wait 19 s, tension 48 s. Retraction was performed in eclipse conditions. Failure of a potentiometer delayed relatching. The timing of the retraction sequence was: retract 4 min 59 s, wait 7 min 4 s, relatch 4 min 54 s. A fuller account of the deployment and retraction sequences is available in Racca et al.[55] The times taken for retraction and relatching are approximately equal to the corresponding deployment operations, which indicates that no mechanism degradation had occurred.

Antennas

The SIR-B antenna was operated from the Shuttle cargo bay in October 1984, and because it had to be stowed prior to firing orbit-adjusting thrusters, it had to be fully deployed and retracted three times. There were two mechanical anomalies in this antenna,[56] in addition to other anomalies unrelated to mechanisms, during the first deployment and stowage cycle. When the tilt latch was released, because of incorrect preloading of the tilt hinge springs, the stack of three antenna sections suddenly separated from the truss structure, causing strong vibration of both the antenna and the Shuttle. Later on, when the antenna was first restowed, the outer leaf failed to latch completely, in spite of repeated attempts. Finally, relatching was achieved by pushing on the top section of the antenna with the Shuttle remote manipulator arm. The antenna was not redeployed for the following 24 h while several contingency plans were examined, but eventually it was redeployed and both hinge motors were powered during the final stages of restowage, to increase the latchup speed. This attempt was successful, and the same procedure was followed during the third deploy–retract cycle. Postflight inspection of the antenna revealed that the outer and inner leaf cup and cones were misaligned.

Discussion

It is remarkable that, among the retractable appendages surveyed in this paper, practically all those that had successfully deployed could also be retracted successfully. It is clear therefore that established procedures for the design and testing of deployable space mechanisms[1] should be carefully followed.

Spacecraft engineers have often expressed concern about the reliability of appendages that rely on electric motors for deployment and retraction. The evidence from the present study is that, possibly because of the extra care taken in their development and testing, practically all electric motors have performed well. In addition to the evidence already presented in the previous section, it is noted that several electric motors were used on the long-duration exposure facility (LDEF) in space from April 1984 to January 1990. The two stepper motors that were used to open and close the French boxes were found to be in very satisfactory conditions when inspected by the manufacturer.[57] Also, of the five dc motors driving the environment exposure control canisters, only one has shown higher than expected current draw during postflight testing, and it appears that the cause is a damaged screw drive.[58] From this evidence, it can be concluded that dc, brushless, and stepper motors are, in principle, all acceptable in retractable appendages. Including driving electronics, dc motors are invariably the lightest, simplest, and cheapest, and brushless ac motors are the most expensive. More detailed guidance on the choice of electric motors is given below.

Dc motors can fail to start or restart for the following reasons:

1) Detachment of brushes or disconnection of the winding, due to launch vibrations. To minimize this risk, dual-wound motors with redundant brushes are commonly used.

2) Filming, i.e., formation of an insulating layer between brushes and commutator. This type of failure is most unlikely after a motor has been run at high current levels.

3) Cold welding between brushes and commutator. This is rather unlikely.[59]

4) Failure of the (relatively simple) driving electronics.

Also, most brush compounds suitable for operation in vacuo cannot be operated in presence of oxygen or moisture. Hence purging of the motor with nitrogen or argon is required for tests in air.

Stepper and brushless motors are generally considered more reliable than brushed motors. However, they can fail to start or restart for the following reasons:

1) Failure of electrical contact.

2) Failure of the (relatively complex) driving electronics.

If stepper motors are used, it is necessary to independently monitor the progress of deployment or retraction because stepper motors are operated by current pulses of nominal magnitude. The torque margin is unknown unless it falls below 1, in which case the motor fails to operate.

Final Remark

The remarkably good performance of retractable appendages in the missions surveyed in this paper does not result, unfortunately, from a complete understanding of their behavior in the space environment. Generally speaking, it results from a rather conservative design philosophy and the use of large margins to cover for unexpected behavior. This situation is unsatisfactory, and there is a clear need to obtain more information on the real behavior, in space, of these structures. Well-planned, in-orbit experimentation has always provided a wealth of useful information, and hence it should continue. In addition, direct monitoring of the performance of deployable–retractable appendages should become a standard requirement for as many missions as possible.

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