THE DESIGN AND DEVELOPMENT OF A MULTI ELEMENT TELESCOPIC BOOM (KNOWN AS THE SULA BOOM)

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ABSTRACT

The Sula Boom is a compact low cost Boom designed by SULA Systems, built by ESR Technology and qualified by SSTL for use on the their Cibola Flight Experiment Satellite (CFE Sat), which was launched in March 2007. The boom concept was originally conceived and proto-typed by the main author in 1980 and was presented at the 15th Aerospace Mechanism Symposium held in 1981.
The paper will outline the original design concept and then shows how this concept was rapidly re-engineered and qualified (within twenty months) to take into account the SSTL requirements, and in particular the need for a highly cost effective solution (compatible with SSTL's philosophy of affordable access to space). In particular it illustrates how the design was refined using components, materials and processes which were not available when the original concept was first conceived.

1 BACKGROUND

The original telescopic Boom was designed in the late seventies and was designed to deploy large fold out/roll out solar arrays. In its original form it the boom was a single shot device using compressed cold gas system to deploy. After many problems related to deployment control, the author established an alternative mechanical deployment system which could be integrated directly into the existing gas deployed boom and this was bread-boarded to demonstrate proof of concept.
The boom structural elements consisted of thin walled commercial aluminium alloy tubes which were nested within each other. The use of CFRP at that time was considered far too costly and excessively risky. Each tube was nominally 2 m long and was fitted with a front collar fitting which was clamped around flares on the outboard end of each tube. The collar fittings accommodated adjustable bearing pads, and a pair of spring plunger latches which lock the inner tube into its fully deployed state. The system of radial guidance pads used the inherent tube wall flexibility to preload the tube joints and thereby eliminate mechanical backlash. A system of ramping fingers (used to prime the plunger latches) and latch rebates (to accept latch engagement) were used to ensure that the tubes deployed in a sequential manner; the smallest tube deploying first.
The device has a mode of operation similar to that of a conveyor belt. In simple terms, an endless flexible element supported by a column mounted within the tube stack makes contact with a projecting lug on one side of the innermost tube. The tube is driven through its stroke until fully latched and then the next tube is pulled into contact with the drive element. The process is then repeated for each tube and results in a continuous and sequential deployment of any number of tubes, so enabling a wide range of boom lengths to be deployed.
The concept is shown schematically in Figure 1-1.

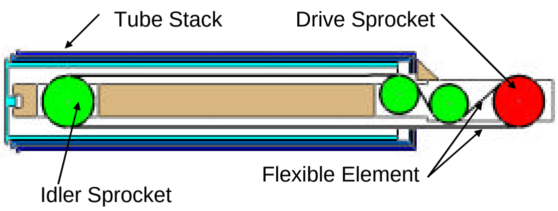

Figure 1-1: Deployment mechanism concept

The flexible element was driven by an electric motor which can also provide retraction of the mast when its direction of motion is reversed.
As the actuation forces were high (>500N) and the bending radius very small (to suit smallest tube i.e. 40mm), a miniature pitch chain drive was used as the flexible element. At this time there were no vacuum compatible plastic belts or posi-drive metal belts. There was also no obvious way of transferring the high drive force into these other types of flexible elements, whereas the chain could accommodate customised chain links to act as loading points.
In order to accommodate thermal expansion, assembly tolerances and elastic deflections when loaded the drive system needed to incorporate a tensioning device and this was designed to allow powered retraction.

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2 REQUIREMENTS

In May 2004 SULA Systems were approached by SSTL regarding the design and development of a boom for the CFE Sat mission. The SSTL specification presented a significant challenge and offered a unique opportunity for the author to introduce many of the potential boom design refinements that he had identified over the many years since the original design conception. The main technical requirements are summarised below:

- Compact stowage (within a cylindrical envelope 450mm long 150mm diameter).
- Deployed length >3.6m to be achieved within 5 minutes.
- Deployed frequency (with 3kg payload) >1Hz
- Stowed frequency >150 Hz
- Deployed alignment at payload to be maintained within +/- 3°
- Deploy and support a 10mm diameter payload harness.
- Minimise mass (target <4.5kg)
- Minimise deployment power
- Provide indication of deployed length to precision of +/- 10mm.

A pair of qualified fight standard booms was required within two years of kick-off. And it was vital to minimise recurring costs. A similar effort was needed to minimise system level costs e.g. by ensuring simple ground testing and minimising electrical interface requirements. To aid this approach it was agreed early in the programme that redundancy of the drive actuators was not needed and retraction is only needed for the purpose of ground testing.

3 DESIGN -DEVELOPMENT APPROACH

Based on the above requirements the original boom concept was re-engineered to provide a technically compliant boom design that minimised recurring costs and development risks. The most important design drivers were; the need to minimise stowed volume, accommodate the payload and S/C interfaces and minimise recurring costs. A number of specific design areas were identified where design/material modifications were essential and these are identified below:

1. Tube Materials – to achieve the on orbit alignment stability the boom material CTE needed be close to zero. Therefore it was necessary to establish a means of producing low cost carbon fibre tubes which could have integral flanges and machined features.
2. A more compact and simpler latching device was needed which could be manufactured in large quantities at lower cost.
3. The tube joints needed to be re-engineered to save space and eliminate friction sensitivity to tolerances and thermal effects thereby reducing the required deployment force and actuator size.
4. The more compact and lower cost drive system was needed and it was necessary to re-visit the original trade-off regarding the choice of flexible drive element. The original design used a miniature chain system and this has major lubrication issues and is relatively bulky. It was originally adopted due to the lack of access to metal band technology. However this technology is now very mature and commercially attractive (mainly due to the use of metal belts in the automotive and food processing industries). Also as powered retraction is not required the tensioning system was to be simplified to save space and cost.
5. The design and development of new customised interface hardware is also necessary including accommodation of the payload harness in stowed condition and also provision of controlled and reliable harness deployment during boom deployment. For launch. a customised payload hold down was also needed.

4 BOOM DESIGN

4.1 General

The original deployment mechanism concept using an endless flexible belt was retained but the detailed implementation drastically modified.
The principal boom elements are

- Telescopic tube system including inter-tube guidance.
- A dedicated inter-tube latching system to retain the tubes in the stowed condition and to provide latching of the tube elements once deployed.
- Boom interfaces including interfaces with the payload, the spacecraft and the payload harness.
- Deployment drive system for providing boom deployment.
- Launch restraint system for retaining the boom and the payload in the stowed configuration.

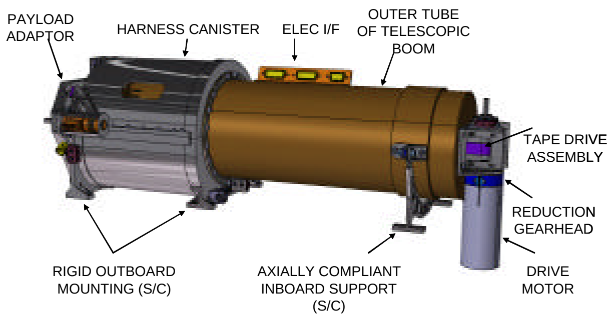

Figure 4.1: General configuration

These various boom elements are described in detail in the following sections and the general configuration is shown in Fig 4.1

4.2 Telescopic Tube and Latch System

The boom system comprises of a stack of 13 thin walled hollow section circular tubes (12 of which deploy). The tubes are stacked within each other with the smallest tube having an external diameter of 46mm and the outer (static) tube a diameter of 120mm. The design provides a very compact configuration that allows a high extension ratio to be achieved. The tubes are made from carbon fibre (CFRP T-300) which are laid up on a precision mandrel and externally ground to size. This achieved good mechanical tolerances and smooth sliding surfaces. The tubes deploy through varying strokes in order to provide an overlap joint length equal to one tube diameter. This provides a higher degree of overlap for the larger diameter tubes at the root of the boom and this provides a structurally/mass efficient solution.

In the stowed configuration the tubes are nested with a 3mm forward extension at each tube interface. This stacked arrangement enables a bonded CFRP front fitting to be accommodated at the front end of each tube which allows harness restraint elements to be included which used to provide distributed support to the harness during and after deployment. At the other end of each tube is a bonded in end plate and this is used to stiffen the tube locally and act as a drive interface with the deployment mechanism.

The tubes are radially supported within each other by a system of contacting pressure pads. There are 4 internally projecting pads uniformly distributed at the front end of the tube, and a similar number of externally projecting pads at the rear end of each tube. To eliminate inter-tube backlash and provide a stable and controlled preload at the tube joints a system of sprung loaded kinematic mounts beneath some of the contact pads. These pads are elastically supported on the tube surfaces. This elasticity is provided by the introduction of a simple set of axial slots on either side of the pad, which allow the supporting tube surface underneath to act as a simple cantilever spring (see Fig 4.2). Therefore at each radial section where there are support pads, two of these pads are rigidly secured to the tube surface, and diametrically opposite the other two pads are elastically supported on this cantilever flex system. The pad material is Delrin AF as this has good heritage in vacuum and also ensures consistent friction levels and low wear both in air and in vacuum. All of the pads are identical and are a simple snap design which avoids the use of additional fixing elements or adhesives (i.e. cost effective). The tube pressure pads have a relatively narrow width which minimises the total running area on the outer surfaces on the tube and allows for the application of thermal finishes/thermal tape to this outer surface

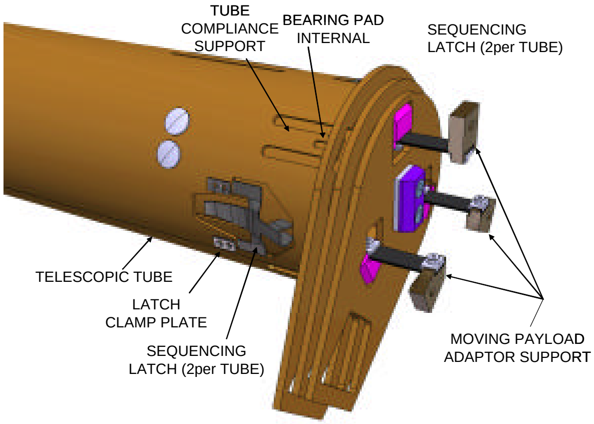

Figure 4.2: Tube outboard end showing cantilever springs supporting contact pads

To maintain the required payload alignment the tube set also need to be constrained in a torsional sense. This torsional constraint is achieved by a simple axial key strip (made from CFRP sheet and bonded on the outside walls of the tubes) that runs along the axial length of each tube. This interfaces directly with a pair of Delrin pins which are mounted on the adjacent outer tube and protrude through its inner surface of the next outer tube. In the stowed configuration the entire tube stack is restrained by the hold-down system which only holds one of the tubes. This tube being the inner most tube onto which the payload is attached. The relative position of the remaining stack in the stowed configuration is controlled by a simple latch. This latch locks each adjacent tube to each other until the tube is ready to be deployed. Deployment of the tube is started with the motion of the inner most tube which is released by the launch latch. The drive system must drive this inner most tube until it reaches its end stop, at which point the next tube needs to be released, and so on. This sequential tube deployment is an absolute necessity for the deployment system as this system deploys each tube at a time.

It is essential that while the inner most tube is being deployed the remaining tube elements are secured in their stowed configuration and only when the inner most tube has reached its end of travel, is the next tube released. This level of control is provided by a sequencing latch system mounted on each of the moving tubes. There are two sequencing latches on each tube to provide some level of redundancy and these are located in diametrically opposite locations. The radial locations of these latches like the tube bearing pads are circumferentially staggered, in order to maximise useful volume within the tube gaps. The sequencing latches are located at the front of each tube, between the contact pressure pads so that when deployed they are located

approximately in the middle of the overlap zone. As there are many latches it was important to establish a single common latch design that was reliable, simple and easy to manufacture and integrate, in order to minimise boom costs.
The latching sequence is shown in Fig 4.3 and it shows 3 tube elements; an inner most element, an outer most element and an intermediate element. The illustration shows the latch mounted on the intermediate element as this is the required location to provide a sequential release of the intermediate tube when the inner-most tube reaches the end of deployment.

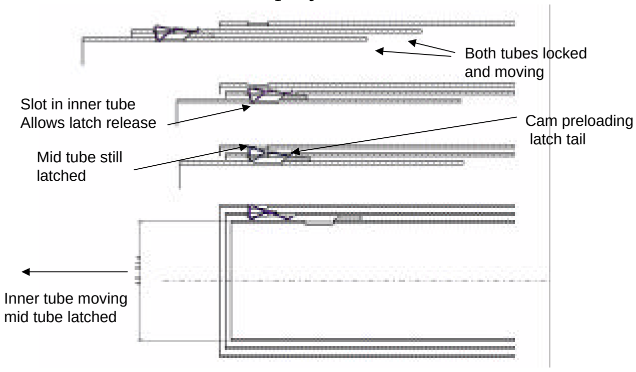

Figure 4.3: Latching sequence

The lower figure shows the first stage of operation whereby the intermediate tube onto which the latch is structurally attached, is restrained from deploying (moving towards the left) by the fact that the outer most limit of the latch is engaged in a slot in an outer tube. The latch therefore locks the intermediate tube in the stowed configuration while the inner tube is still free to slide.
The next view up shows the latch in a pre-stressed condition whereby a cam-surface mounted on the moving tube has engaged with the elastic tail of the latch. The latter is now elastically strained such that the latch element at the tail is biased outwards. As the latch is designed to rotate about its centre point, this means that the inner section is biased towards inward motion. At this point the intermediate tube is still latched in the stowed configuration due to the fact that the latch is still engaged with the outer element thus preventing relative axial motion. The inner tube is also still free to move.
At the next position one can see that the inner tube has now moved to the limit of its deployment and the latch inner surface has penetrated into a slot in the inner tube. This releases the rotational constraint on the latch and allows the strain energy within the latch system to be released by virtue of the latching surface moving in an inward direction. This latch radial motion means that the latching surface that was engaged with the static tube has now been released, thereby releasing the intermediate tube and allowing it to slide towards the left (i.e. to deploy). At the same time it should be noted that the latch remains in a semi-strained position with its tail still on the top of the cam surface but with its inner contacting surface now still engaged in the slot in the inner most tube. This function essentially has locked the inner tube to the intermediate tube. This whole latching sequence is repeated at each tube joint.
The latch element is shown in Fig 4.2 and is manufactured from a single piece of thin titanium sheet. The latches unshaped detail profile is cut using spark erosion and by stacking the blanks, many latches are cut in a single machining operation. The shape of the latch is hot formed using a jig and these processes make it a very low cost item to produce (especially when compared to the original spring plunger design). This was an important design driver as so many of them are needed for the each complete boom assembly. The spring element is shaped to provide the required latching surfaces as well as those sections that need to flex during operation. While the latch appears to be a very simple design it is a very sophisticated solution to the boom latching issue. The complete latch element itself is attached in a cantilevered fashion to the intermediate tube on two pads and this configuration helps to energise the latch engagement. An integrated latch is shown in fig 6-1 in section 6.

4.3 Boom Interfaces

The two CFE-Sat booms are mounted either side of a singe square spacecraft panel. They are oriented along opposite diagonal to maximised the available stowed axial envelope and thereby minimise the number of tube elements. As the panel is made from aluminium alloy and also has significant dynamic out of plane deflections (during launch) the boom design must accommodate differential thermal strain and avoid attracting excessive loads interface or internal loads during launch. However the boom also needs to provide a stiff interface for the payload and this is effectively overhung from the smallest telescopic tube. In addition, a rather bulky payload harness needed to be supported during launch and allowed to be deployed in a controlled manner to avoid entanglement with itself or the boom.
The solution (shown in Fig 4.4) was a separate harness canister, fabricated from aluminium and rigidly attached to the S/C panel at four locations. In the launch configuration a payload adapter (carrying the payload) was preloaded into contact at three V- block interface points mounted around the canister aperture. This provided a rigid interface with kinematically defined interface forces which to ensure reliable separation at deployment. The payload harness is coiled in a tight helix within the canister and around the outer diameter of the outboard section of the boom which is also supported radially and axially by the canister. The connection is engineered to avoid the transmission of in plane moments

At the other end of the boom assembly only a radial support is provided and this was achieved by introducing flex features in the support bracket itself. This enables the whole boom assembly to expand and contract along its axis without introducing statically indeterminate loads between the boom itself and the spacecraft structure.

To accommodate panting of the panel during launch without introducing high forces at the payload-boom interface the payload adaptor must be attached to the booms smallest tube in a manner that accommodates relative out of plane (i.e. the plane of the mounting panel) movement but still provides a stable interface for on orbit operation. This was achieved by introducing a set of three leaf spring assemblies (shown in Fig 4-2) between the payload adaptor and the booms smallest tube (1^{st} to deploy).

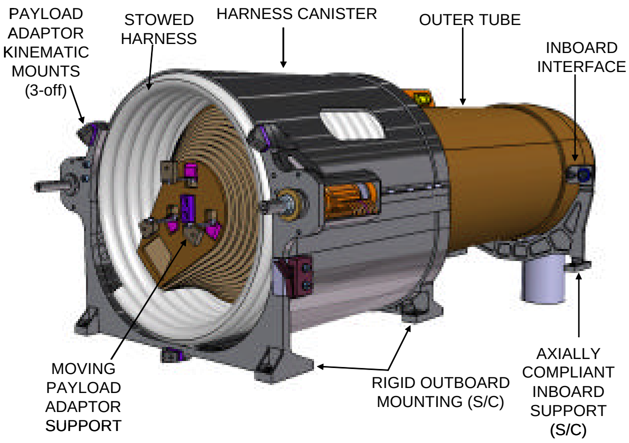

Figure 4.4: Boom assembly showing stowed harness and support system

As the boom elements sequentially deploy, the outward most harness loop will be deployed with the boom such that it forms a relatively tight helix about the tube diameters. The relative shape of the helix is controlled during deployment by small tubes which are attached to the front end fitting of each tube section by a semi-rigid strap

During launch the kinematic mounts of the payload adaptor and static flange are preloaded by the application of tensile preload force. This is achieved by two hold down devices located at diametrically opposite sides of the canister. The hold devices use shape memory alloy actuation and have an integrated damper to minimise release shocks.

The electrical interface comprised a D.C drive interface with a current monitoring capability. It also provided suitable interfaces for a number of micro switches that provided; confirmation of payload release, confirmation of full deployment and revolution counts at the drive sprocket. The latter was used in combination with drive current to determine the booms axial position at any time during deployment, to the required precision.

4.4 Deployment Drive System

The key components and design features of the baseline deployment system are shown in Figure 4.5 and described in the following sections.

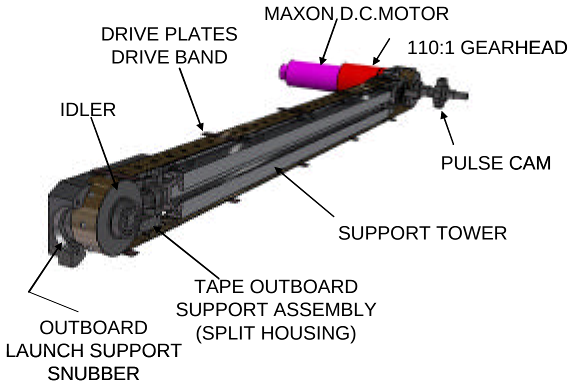

Figure 4.5: Deployment mechanism

4.4.1 Tape Drive System

The drive system comprises a metal band or tape drive system. The tape has tube interface features (drive plates) that are used to provide a simple conveyer action which sequentially extends each deployable tube from its stowed position. The advantages of this system compared to other flexible drives include is that it offers high strength to weight ratio and requires no lubrication. It is also commercially available and can include customised features that are electron beam welded to the belt to provide the necessary load transfer capability.

The chosen belt is an endless stainless steel drive belt made from 301 high yield stainless steel. The belt has circular perforations along its length which mate with hemi-spherical features on the drive pulleys. This system provides a positive tracking control and also provides positive drive synchronisation, i.e. traction. Traction is also enhanced by interface friction between the band and the pulleys.

Attached to the drive belt are a number of thin drive plates which are mounted at uniform intervals (spaced to suit deployment synchronisation). The plates are attached by a narrow electron beam weld line that is transverse to the tape direction and central to the plate. This allows the tape to pass around the small pulleys without inducing high stresses at the weld line.

At the outboard limit of the tape drive conveyer is the top idler pulley which is supported by the support tower. This tower reacts the tape tension from both sides of the tape in a compressive manner (i.e. loaded as a strut). It is machined from a standard lightweight aluminium extrusion, which has sufficient cross-sectional second moment of area to provide high stability against buckling. On two opposite sides (local to the drive tape) the tower is clad with PTFE rubbing strip, this snubbers the lateral motion during launch, and ensures correct engagement between the drive tape and driven tube, even when the boom is deployed in a lateral gravity field. The top idler pulley is made from stainless steel and incorporates imbedded ball bearings that provide the hemispherical tape guidance features. As the radial reacted force is highest at this location the idler pulley is supported by a pair of deep groove ball bearings which are mounted in a split housing. This housing has an external profile which enables it to be radially supported by the smallest tube when in the stowed configuration. All of the bearings associated with the tape drive system are fitted with PGM-HT self lubricating cages provides a simple low cost vacuum compatible lubrication system.

At the base of the tape loop is a diverter sprocket which ensures that just one tube is driven at a time and the drive sprocket which is directly driven by the deployment motor. The drive pulley is supported primarily by its own radial deep-groove bearing which is identical to that used for the top idler. Additional radial support is provided by the drive actuators own bearing system (mounted within the gear-head) which has been suitably sized for this load case. Fig 4.6 shows the tape drive assembly.

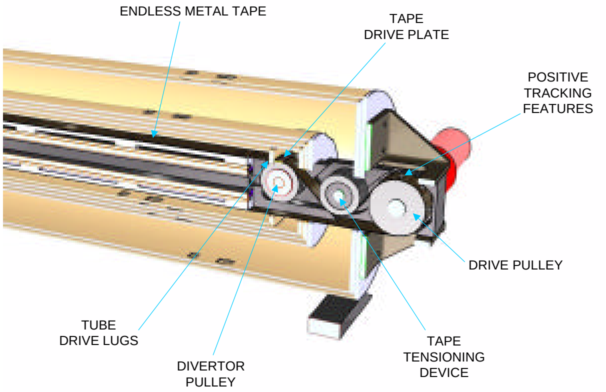

Figure 4.6: Tape drive assembly

The lower sprockets are all supported in a split lower housing and this housing is designed to ensure that the tape and its drive lugs are always fully encased. This eliminates the possibility of the tape jumping from the sprockets either during launch or deployment. It also provides a very compact configuration that fits within the lower nested tube stack prior to deployment. This feature means that the stroke of all of the tubes can be maximised for a given axial envelope, which leads to a most efficient boom configuration.

4.4.2 Tape Tensioning Device

The drive tape itself has a relatively thin section which means that the tape has some significant axial elasticity. During operation there is a high tension side of the tape and this tension is generated by the forces resisting deployment. Correspondingly there is a low tension side of the tape, which is the trailing section after the tape-tube drive interface. Given the elasticity of the tape it is possible that there could be some risk of reduced tape stability in this low tension side. In addition it should be noted that the CTE of the steel tape is significantly less than the CTE for the aluminium alloy support structure which means that at varying boom temperatures there will be significant differences in the residual tape tension and a risk that the tape could become slack.

Therefore to provide a more constant tension a dedicated tape tensioning device is introduced within the tape loop. For highest efficiency the device is located in the tape zone that has lowest tension, which is just inboard of the lower idler sprocket. This tape tensioning sprocket also provides the necessary tape guidance between the diverter and the drive sprocket, in order to avoid premature engagement of the tape guide interface with any of the stowed tubes. In this respect the tape tensioning device provides a dual function.

The tension is applied by biasing the tensioning sprocket in an inward direction by means of a pair of simple beam springs which have their stiffness tuned to provide minimal tension fluctuations throughout operation and under all environmental conditions. The stiffness also helps to more precisely define the pretension introduced into the tape loop during assembly. This pretension effectively biases the tensioning sprocket thereby minimising risk of large displacements when subjected to launch accelerations. The tensioning system is compactly housed in the lower housing and also is provided with a snubber system to limit the extremes of travel at the tensioning sprocket. This feature is implemented to eliminate risk of tape disengagement during launch.

4.4.3 Drive Motor/Gearbox

In order to provide the required deployment actuation force in a most compact mass and power efficient manner the drive sprocket is driven by a motor and gear-reduction combination. The unit is provided by a Maxon motor fitted with a size 32 gear-head which has a maximum torque capability of 4.5Nm. This is a commercial unit which is cleaned and re-lubricated by ESTL for space applications. The motor is brushed with the brushes made from precious metal for vacuum compatibility.

It provides a stable and suitably slow deployment speed and provides very good torque margins. At the same time it has a stall torque that is consistent with the load capabilities of the other drive system components so that it provides a safe stall condition. This means that deployment control can be restricted to a simple timeout/telemetry control. To minimise the impact of stray magnetic field on the S/C a customised magnetic shield was provided around the motor body.

5 BREAD-BOARD

Given the extensive design modification from the original concept coupled with the rather compressed schedule an early breadboard was considered essential. To demonstrate the majority of the most critical features a three element CFRP boom (two moving tubes) with a representative deployment mechanism was manufactured and was available for testing within five months of the project kick off.

The drive mechanism was first tested in a separate rig that comprised a set of force balances and a sliding collar (fitted around the tape support tower) that enabled the drive system to operate under different axial loads over a short displacement. This simple rig (shown in Fig 6-.2) allowed early verification of a number of very critical performance issues which include; belt function (including weld load capacity), efficiency of drive traction, tape tension control and motorisation margin. The latter also enabled the drive force to be calibrated against drive current which was later used to measure actual insitu drive forces. These checks were repeated for the Q.M and F.M

In parallel the tubes and latches were manufactured which verified the associated material/processes and costing estimates. The deployment force and latching function of the assemble tube stack was demonstrated by simple pull tests. After this the drive system was inserted into the assembly and overall functionality and motorisation margins demonstrated.

The unit was tested in a vertical orientation and was used to lift dead weights. In this orientation it was also possible to check alignment using a pair of precision inclinometers and perform some simple checks to estimate achieved joint stiffness.

Naturally enough there were many detailed problems found and these were mostly associated with latch geometry and detailed parts dimensioning and tolerancing in particular between the main and redundant latches as these were discovered the hardware was reworked or updated to verify each of the design modifications and therefore the BBM evolved along with the design and this greatly reduced the risks associated with the Q.M. The design of the motor magnetic shield was also refined using the bread-boarded drive unit. Finally the BBM was used to enable a number of payload harness control systems to be investigated which would not have been possible by pure modelling or analysis.

6 Q.M AND F.M MANUFACTURE

The QM and FM booms were manufactured and functionally tested at ESTL.

The CFRP tubes were delivered with pre-assembled CFRP end-fittings and pre-machined slots for latches and bearing pads. The titanium latches and Delrin bearing pads were fitted to each tube segment (Fig. 6.1) before assembly of the whole tube stack.

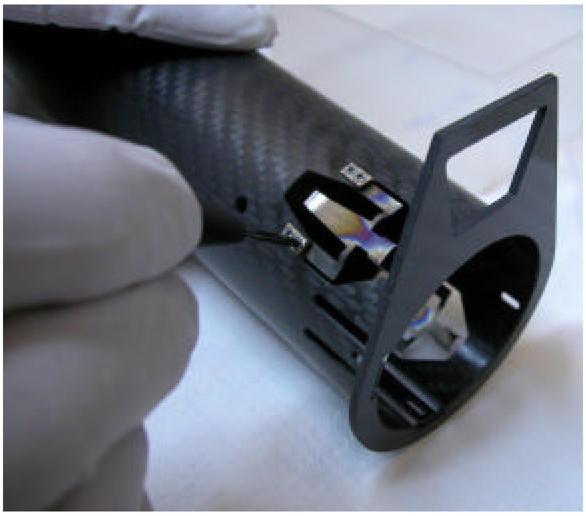

Figure 6.1 Fitting of Latches to Tube

As part of the tube-stack assembly a burnished MoS_2 lubricated track was provided on the tube surfaces and thermal tape was added to the outer surfaces. Special tooling was developed to enable insitu dressing of the latches and pads to achieve the required fits

The deployment motor gear-head was refurbished for space use and one from the batch life tested in air and vacuum in order to demonstrate the required lifetime and operation over the required -30 to +70°C temperature range.

The drive unit was assembled and tested prior to integration with the tube stack. The drive band tension was adjusted and measured in-situ.

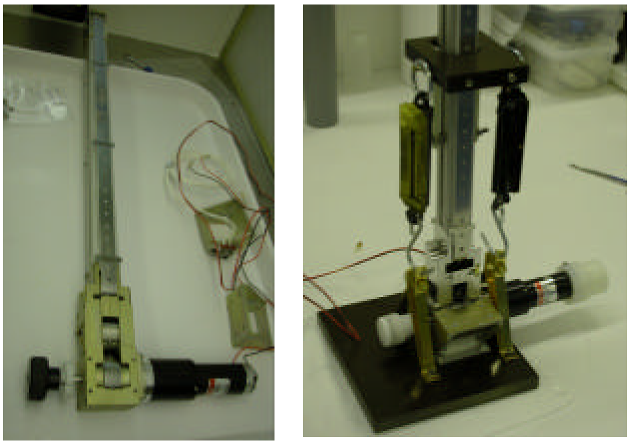

Figure 6.2 Drive Unit under manufacture & test

The completed and pre-tested drive unit was assembled into the tube-stack and the entire boom was then tested in air with axis vertical. An antigravity rig was developed using cable/pulley system driven by an identical Maxon motor which was calibrated to provide a controlled anti-gravity offload force in order to permit demonstration of the boom deployment motor current margins.

During deployment testing, motor current, boom displacement and end-of deployment payload position and orientation were monitored. The boom stiffness was also checked. To enable the full deployment to be achieved a "top-hat" extension was installed in the ESTL clean-room ceiling. The above tests were repeated on the flight units to ensure build repeatability.

7 BOOM QUALIFICATION

Extensive qualification testing was conducted on the boom with dedicated spacecraft level boom bay vibration tests and functional testing in vacuum and ambient to the temperature extremes.

Due to the deployed length of the boom (over 4m including the fixed tube) there is not a thermal vacuum facility in the UK where vertical full boom deployments could be conducted. Adding to the complexity is that to stow the boom the latches need to be manually disengaged and each segment re-stowed into each other thus a chamber would have to be large enough to work in as well

To overcome this problem the only ambient thermal chamber available with enough head room for a fully deployed boom including MGSE was the MIRA facility used normally to test vehicles to extreme environmental conditions. Due to the atmospheric testing condensation on the boom became a problem during heating back to ambient from cold conditions. This was overcome by personnel entering the chamber while at the cold extreme to cover the boom which was then purged in dry Nitrogen during the heating to prevent condensation on the boom.

Figure 7.1 shows a typical motor current trace from a deployment where the latching events (indicated by an 'L') can be clearly seen with a slight spike before a dwell in current where the drive train in free running to pick up the next tube segment.

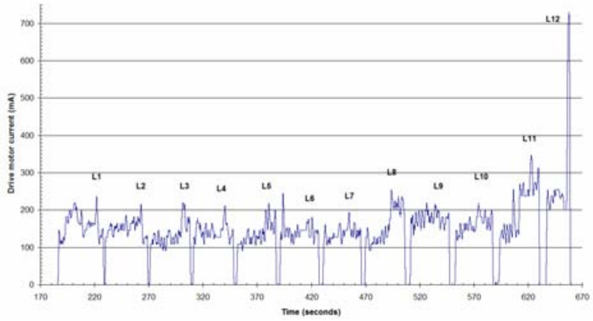

Figure 7.1 Typical drive current profile

Figure 7.2 Picture of deployed boom

Figure 7.2 shows an example of a deployed boom with MGSE at ESTL

8 CONCLUSION

The two Sula booms were successfully deployed at 02:42hrs on 16h March 2007. This event has given the main author immense satisfaction, especially given the 27 year wait between design concept conception and final on orbit demonstration.

The boom design achieved its engineering requirement in a very cost effective manner, thanks mainly to the continuous use of the BBM to explore the subtleties of the design and verify virtually all of the design modifications introduced throughout the boom development programme. It is hoped that the boom will be considered as a commercially attractive candidate for other future space applications.

9 ACKNOWLEDGEMENTS

The Authors would like to thank the staff of SSTL and ESTL who provided support to this programme and special thanks goes out to Adrian Porter without whom this project would not have happened.

10 REFERENCES

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