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UTILIZATION OF SMART STRUCTURES IN ENHANCED SATELLITES

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ABSTRACT

At Defence Research Establishment Ottawa, there is an interest in the research and development of large flexible space structures for use as phased arrays in space-based radar. These large space structures perform precision operations that require control of both rigid-body and elastic deformations. Smart structure technologies, based on a network of sensors and actuators, will increase the performance versatility and the structural stability of these space structures. Smart structure technology is particularly important in the environment of space due to the absence of gravitational damping forces. With the advent of lightweight, high-strength composite materials, much attention has been given to the use of these materials in the structural elements of space structures. This paper presents the results of a feasibility study based on the use of smart structures in Enhanced Satellites.

INTRODUCTION

Antenna satellites in space are increasingly being used for defence and civil applications such as navigation, communication, identification and jamming, electronic warfare, remote sensing, mapping, earth observation, weather monitoring, etc. These satellites use large parabolic reflectors and/or phased-array antennas. Defence Research Establishment Ottawa (DREO) has an interest in the development of affordable, large and flexible antenna structures for use in space-based radar. One such application would involve a phased-array antenna with four to 22-meter aperture.

Structures and systems for space applications are usually flexible, deployable, lightweight, unattended, and/or remotely operated, which makes them expensive and their precision operation and maintenance very difficult. These structures are constantly exposed to the harsh environment of space, which subjects them to low gravity, vacuum, thermal cycling, large temperature gradients, radiation damage, impact from space debris, etc. These conditions can cause undesired shape deformation and uncontrolled vibrations, oscillations, twists, and nodding in the structure, which can adversely affect the performance of space systems (e.g., pointing accuracy of antennas). Also, exposure to space environment can cause degradation in material properties, which can shorten the useful life of the structure.

The need for large antennas exists in satellite communications, space observation and resource sensing. Several studies have been conducted to define requirements for future antennas, and a summary of such applications is presented schematically in Fig.1. The antennas are required to be lightweight and deployable to meet the restrictions of the launcher capability. They must also have sufficient accuracy and aperture area to accomplish their missions. Trusses are candidates for large space structures, and when used as backup structures for antenna reflectors, maintaining accurate surface shape is important. For space-borne applications, thermal stresses and lack of rigidity of deployable designs restrict their usefulness.

The disturbances that affect the shape of large space structures may be divided into two types. One type is transient, which leaves the structure unchanged once damped out. Such disturbances usually call for active or passive control that enhances the damping of the structure. The second type of disturbance is typified by fixed deformations such as manufacturing errors or those that are slowly varying and may be considered quasi-steady. These latter disturbances can be offset by slowly applied, long acting corrections. Most research to date has concentrated on the first type of disturbance and the use of damping actuators. There has been less research on countering quasi-steady disturbances. Most of the work on active control of such disturbances is related to the active control of optical systems such as mirrors, and most of the actuators employed are force actuators. These are sometimes characterized as displacement actuators, because they are stiff enough to enforce a given displacement at a point.

EFFECT OF SPACE ENVIRONMENT ON SATELLITES

The space environment is particularly harsh, and its effects on materials are often dominant criteria in the design of space structures (Larson and Wertz, 1995). The adverse effects of the space environment on materials and systems have been identified, and the means to overcome them have been the subject of much research. The environment consists of the following elements:

- thermal cycling (> 175,000 cycles over life) and temperature extremes (-75^{o}C to $+135^{o}$C, depending on surface properties)

- very high acceleration and vibration during launch, followed by long term low gravity on orbit
- vacuum (10^{-4} to 10^{-6} torr)
- AO (atomic oxygen) bombardment (10^{14}-10^{15} atoms/cm^2/s at □ 5eV)
- UV (ultraviolet) radiation (average 126 W/m^2 between 10 and 400 nm)
- charged particle radiation (electrons, protons, atomic nuclei: total dose approximately 107 to 108 rads)
- micrometeoroids and space debris (sub-millimeter to centimeter range, flux inversely proportional to particle size, velocities to 15 km/s)

Of the above environmental effects, the most important one from the operational point of view for large antennas is the thermal cycling.

A typical orbiting space antenna can undergo one thermal cycle every 90 minutes. In the projected 30-year lifetime of the structure, this yields approximately 175,000 thermal cycles. The thermal cycling experienced by a space antenna is shown schematically in Fig. 2 (Larson and Wertz, 1995).

The depth of the cycle, which is defined as the maximum difference between the high and low temperatures, varies with different materials and, in particular, the surface optical properties, such as solar absorbency and thermal emissivity. The potential for material distortion and damage, particularly in composites, increases with the depth of the thermal cycle. Fibre-matrix composites usually contain residual stresses owing to slight differences in the coefficient of thermal expansion of fibre and matrix. Thermal cycling will amplify the residual stresses, which can lead to reduced stiffness and residual strains. These, in the case of antennas, should be corrected to maintain optimum performance levels.

Careful selection of surface finish can minimize temperature extremes, but the system can still see large temperature extremes between facing the sun and being under the Earth's shadow. The depth of thermal cycle can be minimized using materials with low solar absorption and a low thermal emissivity. This is achieved using coatings such as aluminum, silica, or alumina. However, the cycle is still too large for accurate shape control of the antenna by passive means.

Large space-based satellites possess many characteristics that make dynamic control a particularly challenging problem. These include the sheer dynamic complexity of deformable space structures that leads to difficulty in modelling and the potential for dynamic variations. Larger satellites, particularly those that are erected or deployed on orbit, will face even greater challenges in achieving the required precision with purely passive structures. The high level of performance that is required of precision space structures has motivated research on a new approach to structural design called active or smart structures.

NEED FOR SMART STRUCTURES

DREO has an interest in the development of affordable, large and flexible space structures that require control of both rigid-body and elastic deformations. Smart structure technologies, based on a network of sensors and actuators, are currently being investigated with the view of increasing the performance, versatility, and the structural stability of these space structures.

One such smart structure technology uses piezoelectric-based sensors and actuators. In addition to correcting for thermal deformation, such smart structures can be used to suppress vibrations induced by differential thermal expansion and to control the pointing accuracy of the satellite. Such applications must simultaneously realize high-strain and low-hysteresis properties.

High-gain space-borne communication antennas must accurately maintain their gains to provide the required link margins. Lightweight space-based antennas are particularly vulnerable to erection-induced and thermal deformations. The impact of these errors becomes increasingly more severe as the operating frequency increases. Thus correction techniques for shape control of antennas will become more and more important in future systems. Such alignment techniques and systems can also be applied to large ground-based antennas. The control/structure interaction problems have been in existence since the start of the space systems deployment, with impact ranging from moderate to very serious. Table 1 summarizes the control/structure problems with various satellites.

The objective of active structure technology is to produce lightweight structures with superior stability and precision, through the use of feedback control of actuation and sensing devices embedded within the structure itself. Active structures find application in situations in which system-level performance is compromised by the inherent limits of passive design. Such an adaptive system can be defined as a structural system whose geometric and inherent structural characteristics can be changed beneficially to meet mission requirements, either through remote commands or automatically in response to external stimuli. Large satellite structures with low weight requirements will be very flexible and therefore will need some type of active control system to suppress vibration and to maintain shape specifications. The effectiveness of such control is strongly dependent on sensor and actuator sensor locations.

The drawback of the active approach is the added complexity of the associated sensor, actuator, and electronics components, together with the issue of reliability. Only when the advantages clearly outweigh the costs does it make sense to use active structures technology.

One example of such an adaptive structure is the Hubble Space Telescope (HST) (R. Mitchell, 1986). The two large deployable solar array panels attached in a cantilever-beam fashion to opposite sides of the HST main body have introduced a new dimension to the problem of controlling the HST's pointing direction. In particular, the uneven thermal expansions of the solar array's collapsible structure members caused by cyclic solar heating effects and by mechanical friction effects that resist thermal expansion cause persistent flapping motions of the solar array. The Hubble telescope uses graphite/epoxy metering trusses of unprecedented dimensional stability. The Hubble Space Telescope primary mirror cell is equipped with 24 figure actuators so that small, localized figure errors can be corrected on orbit. In addition, the secondary mirror support structure can be repositioned in six axes to allow periodic correction of metering truss misalignments.

Several factors limit the performance of passive structural systems. The first of these involves the dimensional stability of structures. The best precision structures are still susceptible to dimensional changes due to thermal expansion, thermal cycling, and long term creep in the materials and joints. Deployable structures, in addition, must have moving joints: another source of dimensional error. The large space structures are subjected to a variety of dynamic perturbations produced by the crew, the docking of other spacecraft, transient thermal states during the orbit, and micrometeoroids.

Use of smart structure technologies, based on a network of sensors and actuators and suitable control systems, offers the potential for precision shape control and correction in deformation of space structures. Smart structure technologies can also provide active suppression of local vibrations and undesired oscillations in space systems. They can also be used to control both rigid body and elastic deformations in space structures. Smart structures can allow space structures and systems, such as phased-array antenna satellites, to maintain their long-term, stable, reliable, and precision operation in space. Smart structure technologies can also offer real-time structural health monitoring and predict or detect failure in these space structures. Thus smart structures are very promising for utilization in space structures and systems such as enhanced antenna satellites. High-gain antennas are required to support high data rates with low transmitter power. The basic antenna types used for this application, summarized in Table 2, are the reflector, lens, and phased array. A phased-array antenna may generate one or more beams simultaneously, forming these beams by varying the phase or amplitude of each radiating element of the array. This technique is used extensively for microwave radiometry. Such a phased array may also use an adaptive array to automatically point a null toward a jamming signal source to reduce the jamming-to-signal ratio. To support high data rates with low satellite power, the antenna beam width should be narrow (Larson and Wertz, 1995).

The use of phased arrays offers an alternative means of varying the beam angle of the signal. Typically these arrays consist of a number of small elements of width comparable to or smaller than the wavelength. Communications satellites at EHF (extremely high frequency) provide the ability to communicate to and from remote locations and with high data rates and large bandwidth. At high frequencies, microwave power is limited and antenna directionality becomes very important. Phased-array antennas offer attractive solutions to both these demands because of their ability to spatially combine microwave power from an array of low-power amplifiers and because of their ability to electronically steer the beam very quickly.

ACTIVE INTEGRATED ANTENNAS

The recent advances in smart structure technologies make it possible to obtain extremely thin and flexible phased-array antennas. The concept grew from the need to improve structural efficiency and antenna performance to support the requirements for communication, navigation, identification, and electronic warfare functions (M. A. Hopkins et al., 1996). It is even possible to adjust the antennas to the shape of the mechanical supporting structure. This emerging new kind of phased-array antennas is called smart skin antennas or active integrated antennas. Such technology allows for a high degree of integration in the feed network and signal control circuitry. The grid pattern of the antenna is determined mainly by the radiation pattern and the frequency. There is no fundamental difference in the basic building blocks between the traditional phased-array and smart skin antennas. The composite skins may have imbedded apertures or be electrically transparent with smart or adaptive antenna structures behind. Each approach offers advantages. Imbedded apertures combine the highest electromagnetic performance potential with lowest weight. An adaptive antenna system could offer configuration alteration potential for future systems, eliminating the need to retrofit. As smart antenna structures are developed that can serve multiple functions, address numerous frequencies, and provide improved performance, the number and size of apertures on aircraft will be significantly reduced.

Active integrated antennas provide a new paradigm in the smart antenna concept (Y. Qian et al., 1996). The active integrated antenna can be used as a single element or in an array form. From the functional point of view, it can be used for transmission, reception, and transponder applications. In an array form, a number of functions can be incorporated. In addition to an obvious application for quasi-optical power combining, several innovative concepts for beam steering, beam switching, and beam shaping have been investigated. A phased-array antenna consists of the radiating aperture, the feed network, and the signal control devices.

An active integrated antenna array can also function as a phased array by controlling the phase relationship among the array elements. The most significant characteristic of this type of active phased array is the possibility of eliminating the need for phase shifters, which have been indispensable in conventional phased arrays, since the mutual coupling among the array elements can be used for inter-injection locking to establish the required phase relations. The injection locking can also be realized by an external reference signal. These efforts make it possible to design very compact, inexpensive phased arrays for many radar and communication systems.

CONCLUSIONS

Undesired shape deformation, vibrations, and structural failure are major problem areas that adversely effect the performance and control of precision satellite systems. Smart structures, which can sense changes in their environment and actively and adaptively respond to these changes in a positive manner, can be used for actively controlling the shape and vibrations in a system. Smart structures can also be very useful in early detection of faults in a complex structure and more accurately predicting its life expectancy.

The need for active shape control has been identified in numerous space communications applications. One of the promising applications of active shape control is in high-gain large parabolic communication antennas. Communication antennas, whether space borne or terrestrial, often make use of large surfaces for receiving radio-frequency signals. The maximum dimensions, at which large microwave and millimeter wave reflectors produce acceptable gain and radiation patterns, depend on the precision of the contour (and hence sharp focus) as manufactured and retained over long-term use. The focus or pointing accuracy of these antennas generally degrades over time due to the shape deformation as a result of long-term environmental stresses. These stresses are caused by gravitational pull, thermal cycling, structural loading, and other forces. Active shape control can be used to retain and regain the original precision shape of the reflector.

Other applications that would benefit from maintaining and/or improving pointing accuracy of a reflector by the use of active shape control concept are weapon systems for defence, fibre optic and laser systems, etc. Large, lightweight, flexible and deployable space structures can also benefit tremendously from active shape-control techniques (E. H. Anderson et al., 1990).

The need for active vibration sensing and damping is also well established in many space, aerospace, and communications applications. It is well recognized that vibrations cause fatigue and premature failure in materials. If vibrations can be eliminated, the life expectancy of materials and structures can be tremendously improved.

The last category of applications that can benefit from smart structure approach is active health monitoring in aerospace structures (C. Boller et al., 1992). Structural panels embedded with a series of sensors and actuators can be used for this purpose. These panels can actively monitor the structural integrity and detect faults at early stages, thereby providing precise information on structural failure and life expectancy. This will be very useful for the aerospace sector where, in the absence of active health monitoring, satellite systems are prematurely taken out of service. If the health of these structures is known more accurately, considerable cost savings could be realized by extending the useful life of these satellite systems.

Use of smart structure technology offers promising solutions to the problem areas described above. The smart structures themselves are not a standard product. They are customized for each application. However, the basic sub-systems of smart structures are similar for most applications. The major difference is in the control circuitry and strategies. Most of the smart structures require either high-displacement high-load-bearing sensor/actuator packages for truss members and vibration damping mounts, or flexible panels with strategically located and embedded sensors/actuators. Both configurations require customized active control systems.

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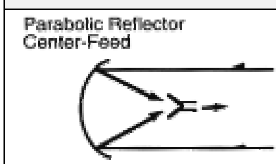
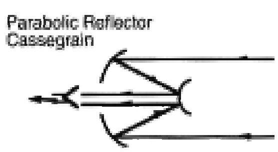
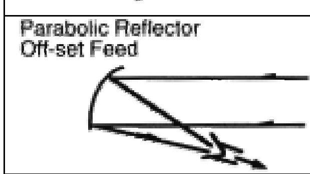
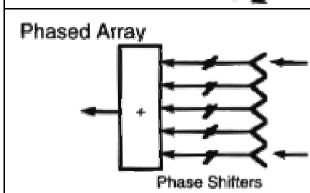
Table 1: Control/Structure Problems with Various Satellites				
Year	**Satellite**	**Control Technique**	**Problem**	**Probable Explanation(s)**
1962	Alouette 1	Spin stabilized	Rapid spin decay	Solar torque on thermally deformed vehicle
1963	1963-22a	Gravity stabilized	Vibrations excessive, but within specification	Boom bending due to solar heating
1966	OGO III	Reaction Wheel	Excessive oscillations in attitude	Control system interaction with flexible booms
1966	OGO IV	Gravity Stabilized	1- to 2-deg oscillation	Solar radiation induces boom bending
1973	Mariner 10	Attitude thrusters	Unstable roll, depleted fuel	Thrusters and gyros noncollocated with flexible panels between them
1982	LANDSAT	Spin stabilized	0.1-deg oscillation	Thermal bending induced by entering and leaving umbra
1984	LEASAT	Spin stabilized	Orbit transfer instability	Unexpected liquid slosh modes
1989	Galileo	Spin stabilized	Schedule impacted, system identification added	Structural frequencies close to control bandwidth, model uncertain
1989	Magellan	Attitude thrusters	Design cost and schedule impact, redesign control law	Design of solar panels ignored attitude control system during solid rocket motor burning

Table 2: Antenna Configurations Used in Satellite Systems	
	• Aperture blockage raises sidelobe level. • Simple, lightweight structure. • Feed-mounted equipment exposed to environment. • Long transmission line from feed reduces efficiency.
	• Aperture blockage raises sidelobe level. • Lightweight structure. • Short, low-loss transmission line. • Feed-mounted equipment accessible behind reflector. • Shaped subreflector increases efficiency (increases gain by ~1.5 dB).
	• Same as Center-fed Parabolic Reflector except low aperture blockage reduces sidelobe level and increases efficiency. • Convenient for satellite mounting with feed embedded inside satellite.
	• High aperture efficiency. • Multiple independently steerable beams. • High reliability (distributed active components). • High cost, weight. • Higher losses in feed distribution system. • High EIRP obtained from many small transmitters (space combining).

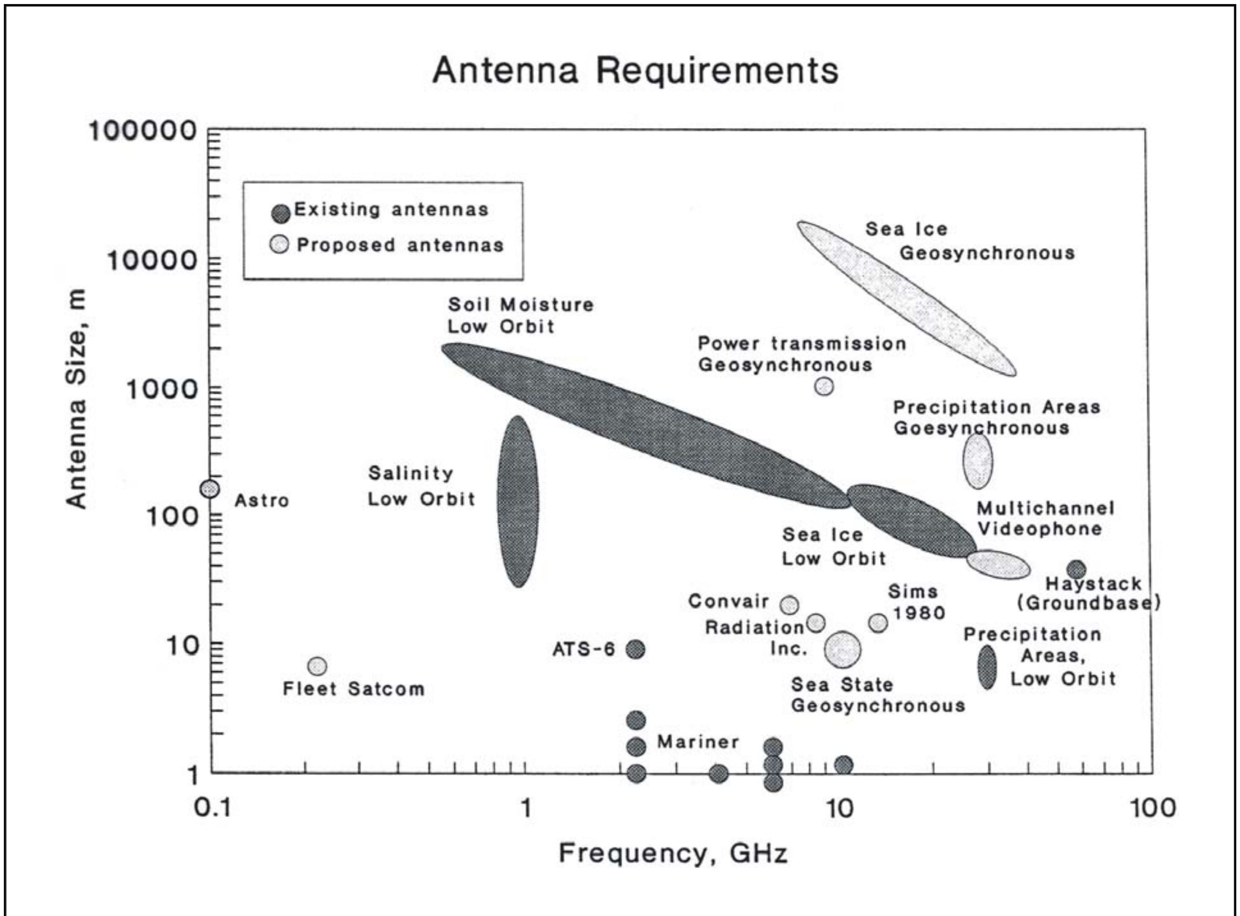


Figure 1: Antenna Requirements

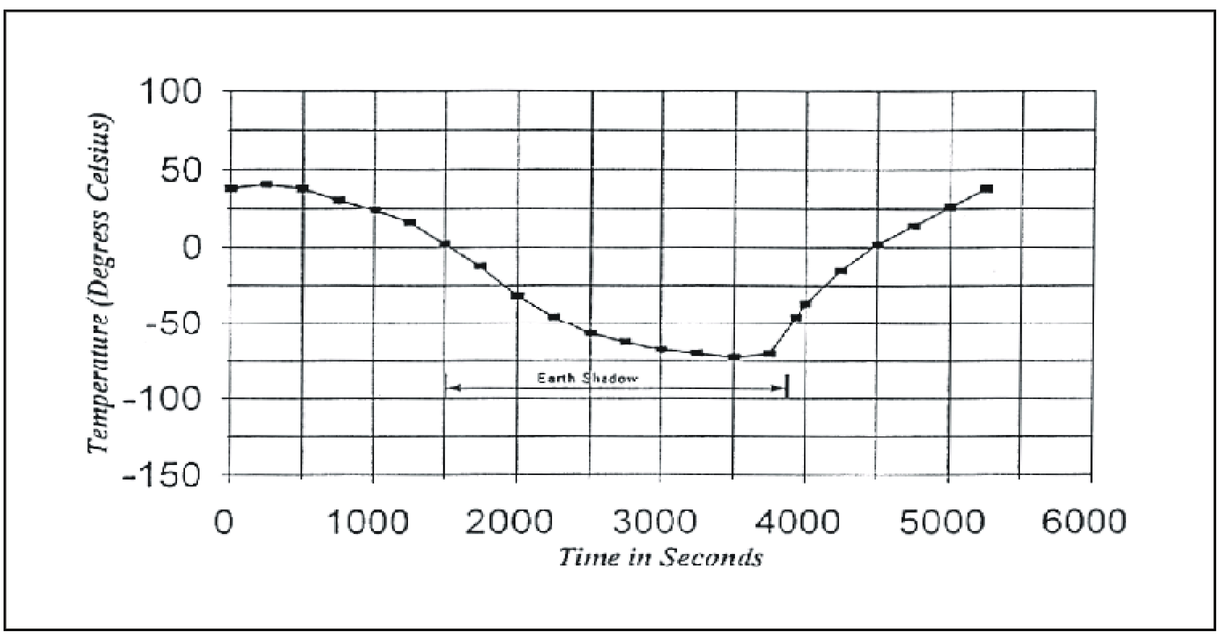


Figure 2: Thermal Cycling Experienced by a Space Telescope