RICHARD W. LONGMAN (*), **Mathematical challenges in the control of future very large space vehicles**

On 1, February 1979 the unusual event occured that a well known novelist, James A. Michener, gave testimony before the Subcommittee on Science, Technology, and Space of the United States Senate. After the United States successfully landed men on the moon, the public seemed to think that the complete goal of the space effort had been accomplished. The NASA budget declined dramatically, and space activities retreated to a somewhat routine role hardly noticed by the general public. James Michener, as one who has studied the rise and fall of nations, was arguing before the committee favoring a significant space effort for the welfare of the country both materially and psychologically.

He likens this space age to the time of Columbus, Vasco da Gama, and Sebastion Cabot. The countries at that time « ... had to decide whether they wanted to participate in the exploration of the world, and if so to what degree of commitment. Those like Portugal and Spain, who made early and fast decisions, gained empires of fantastic richness ». Besides the economic advantages, the more lasting effect of participation was on the spirit of the times, « that wonderful enlarging of the human consciousness when it realized that the old definitions no longer applied, when'it knew that the world consisted of a great deal more than Europe ».

Michener goes on to say that « Each era of history progresses to a point at which it is eligible to wrestle with the great problem of that period. For the ancient Greeks it was the organization of society; for the Romans it was the organization of empire: for the Medievalists the spelling out their relationship to God; for the men of the Fifteenth and Sixteenth Centuries the mastery of the oceans; and for us it is the determination of how mankind can live in harmony on this finite globe while establishing relationships to infinite space ». « ... I believe without question that if a nation misses the great movements of its time it misses the foundations on which it can build for the future ».

These statements make a convincing appeal for a substantial funding of our space research and development, including studies of the feasibility and desirability of projects such as the Solar Power Satellite. There are those who seek much more drastic action, and let us for the moment indulge ourselves in contemplating the possibilities. While teaching undergraduates at Princepton University in 1969, Gerard O'Neill became interested in the problem of space colonization. Some years later, after generating a preliminary design for a space colony, and after preliminary studies of many pratical considerations, he concluded that a national commitment of money and time comparable to that of the Apollo program, could produce a space colony of 10,000 people [**10**]$_1$. The colony was to be placed at a stable Earth-

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Moon libration point (a point 60 deg. behind or ahead of the Moon in its orbit, where the gravitational forces of the Earth and the Moon balance centrifugal effects to form a steady orbit). The original design was in the shape of a very large cylinder spinning about its long axis to form artificial gravity; changes of night and day were accomplished with windows and shades. Pictures showed the inside of the cylinder as being very Earth-like, except for its concave curvature, and included both trees and lakes. As the colony grew, other cylinders would be added in a cluster, with transportation from one cylinder to another accomplished by spinning off of one and being captured on another. Some cylinders would be devoted to agriculture, and a nearly self sufficient community would be developed. The actual design for the space colony has evolved over the years [**10**]$_2$, but whatever the design O'Neill envisions such colonies growing, in fact growing exponentially once they pass a certain critical level. In a recent article he states that: « About 200 tons of equipment, half on the lunar surface and half in high orbit, could replicate most of its components form lunar materials, thus creating an exponential growth of industry in space » [**11**]. The energy required to bring material from the moon is less than 4% of the energy required to bring the same mass from Earth, and the Apollo landings have shown that nearly all the materials most necessary for living, working, and building in space are available on the moon [**1**]. Water is the most serious potential difficulty, but it is almost surely available from some Earth-approaching asteroids (the energy needed to bring asteroids to a space colony is minimized by the use of gravity assist from the Moon to accomplish capture into an earth orbit, but long transit times would be needed). The transportation of material would be accomplished by use of mass-drivers which combine the ideas of a linear electric motor and magnetic flight control. A small prototype of such a machine has been built that can push a 1-lb « bucket » to 85mph in 0.1 sec with an acceleration of 35g [**10**]$_3$. The same method is proposed for use as an upper-stage engine for the space shuttle. The energy required to produce useful materials from lunar soil or asteroid material would be much greater than that needed to produce the same material form ores an Earth, both because the concentrations are lower and because the chemical forms are more difficult to use. The typical energy penalty may be as much as a factor of ten, but solar energy is plentiful in space so that the energy requirements are probably not an important constraint [**1**].

By now these concepts for a space colony have been studied in some detail, with several NASA Ames sponsored summer workshops, and various conferences. Work has even progressed so far that the RAND Corporation has published a paper entitled « The Economics of Strikes and Revolts during Early Space Colonization ». The author, economist Mark Hopkins, reasons that space colonists will develop a strong sense of community, a growing sense of apartness from earth, and a feeling of exploitation by the « owners ». The situation will be made to order for union formation, strikes and even political action looking toward independence from the home planet.

Union busting will be difficult because there will be relatively few people available with the necessary skills to replace strikers. On the other hand, the management will own the air the workers breath.

The idea of a space colony captures the imagination of many people, but is far too extreme for others. The emphasis in all of the above thinking was on space colonization for the sake of space colonization. The many papers now available give lots of details on how it might be accomplished, but for the grand form discussed above, they fail to answer the question why - why would anyone want to invest the resources, time, and effort to create a space colony?

Let us return to more fundamental matters to determine what the uses are for spaceflight, and who or what organizations can profit from such use. Consider what things can be done uniquely, or better, or cheaper, or with less pollution in space than on Earth. There are three essential differences between the space environment and that on Earth: weightlessness vacuum, and solar heat, the last of which can be used to supply energy for manufacturing processes that take advantage of the weightlessness and/or vacuum properties of space. Edward Stearns, Executive Vice President of the American Astronautical Society, describes four categories of space industry:

(I) Information gathering and processing including Earth resources search and assessment from space, communications, navigation, weather surveillance, and international surveillance. To this we can add astronomy, solar studies, and other scientific purposes.

(II) Processing in space including growth of very large crystals in space, manufacturing of high quality optical glass, and of certain pharmaceuticals, and production of high quality ball bearings, etc. In the long term there would be processing of extraterrestrial materials.

(III) Harvesting space resources such as solar energy, lunar materials and asteroid materials.

(IV) Human activities including tourism, construction, factory operations, scientific research, spacecraft maintenance, space colonies, and international government!

The items of the first category are all being exploited at the present time and will be to a far greater extent in the future. Especially for the remaining items, there are serious institutional questions which must be considered - somehow it must be decided who it is that will create satellites to do the above tasks. In some cases such as astronomical or scientific investigations it is clear that it could only be accomplished by the government. But particularly for space manufacturing, it seems reasonable that private enterprise should eventually dominate the scene. As long as space flight was in the category of high risk exploration with scientific objectives, it was natural that governments would manage the operations, but with the space shuttle, NASA has taken a big step toward being a trucking or transportation organization for use by private enterprise, among others. As the investments required continue to decrease and the risks continue to decrease, private enterprise can take a dominant role.

Many people believe that the pursuit of industrial and commercial goals in space must be left to the private sector of the economy. It is this idea which made the United Nations Moon treaty so controversial in the U.S. Also it is this idea relative to communications satellites that caused the U.S. government to form Comsat Corporation, which has thrived along with the entire field of satellite communications. Now five major U.S. corporations are actively pursuing this market. A similar plan to convert the Earth resources sensing operations to industry has been proposed. Navigation is another area which might be converted to private industry. Mr. Stearns points out that the private sector demands a rewarding return on investment with a promise of early payback, and organizations such as Comsat Corporation help the government generate favorable conditions. It will also be necessary to decide how to handle proprietary matters in group space operations.

For those interested in maintaining a free enterprise system, it is clear that organizational decisions made now can be very important. Space operations will eventually grow to be a very large aspect of the national economy, and without careful and intelligent decisions along the way, this whole sector of the economy may be closed to free enterprise and be government controlled.

Now let us consider some of the project or operations oriented proposals for future large space structures. Reference [**5**] proposes a shuttle-serviced permanent manned low Earth orbit space station, or space operations center, for the purpose of construction, assembly, and servicing of space systems and spacecraft. The emphasis is on tending free-flying satellites with periodic servicing, on orbit construction, check-out and transfer to operational orbit of large complex spacecraft. The idea is that no one space station can serve all the diverse purposes required of satellites (in terms of pointing direction, orbital parameters, attitude accuracy, etc.), but economies can be made by recovery and servicing of satellites instead of building new ones. Reference [**12**] proposes an orbital international science city, a cooperative effort of many countries to pursue research and technology studies. Both of these proposals would create a working force permanently in space although not exactly a large space colony.

The use of large space structures could make possible many operations of interest to astrophysicists. A group of Soviet astrophysicists have proposed a design for a large radiotelescope assembled of 200 meter units to form a 1 to 10 kilometer antenna [**8**]. When placed in a heliocentric orbit some distance from the earth it could produce vastly improved resolution to study quasars, pulsars, and active gigantic nuclei with interferometry on a much larger base line than between radiotelescopes on opposite sides of the Earth. This would allow study of far more distant objects and also of planets revolving about other stars. This latter prospect is also of importance for the detection of extraterrestrial civilizations. Another proposal is for detecting gravity waves using a 10km spacecraft with a lazer rangefinder.

Receiving gravity waves could open an entirely new astronomical window, and exhibit aspects of physics not yet observed [**4**]. Vastly improved optical telescopes are envisioned which would consist of a 100 meter diameter annular ring of individual 1-2 meter mirrors. Adaptive optics would be used to correct misalignments, and it is felt that an improvement in angular resolution of two orders of magnitude over the Space Telescope Satellite can be obtained [**4**]. Some other proposals in the same reference discuss methods of altering the weather patterns locally using large directed mirrors in space.

Large communication satellites will be developed which will revolutionize several aspects of our everyday lives. Bekey describes a satellite with dimensions of 432 feet by as much as 543 feet, which would allow the use of wrist radiotelephones the size of theusual wrist watch (costing less than $ 10.00) to supply direct user to user links to 10% of the 1990 U.S. population [**3**]. Such telephones use very small antennas on the ground with a large antenna in space, rather than the present system of telephones connected to large antennas on the ground and a rather small antenna on the satellite. Such a system is of particular importance to emergency operations of all sorts, from emergency calls for ambulance or police, to coordinating the fight or reporting forest fires in remote areas.

The same type of satellite could be used for transmitting electronic mail. The most common concepts concentrate on rapid communication between government offices, or between government and large business offices, but such satellites will eventually repalce the written letter for nearly all purposes (except perhaps love letters?) to eliminate large transportation costs. Of course, if the government operates the satellites, a serious question of protecting the privacy of individuals will have to be addressed. A third use for such satellites is the transmission of educational TV (proposed for 65,000 schools in reference [**3**]). Here again the centralization of the system could give dangerous power to the central government if not handled properly. More complicated systems using radio telephones have been described for navigation purposes that would give a person's position without any other aid, or which could sound emergency alarms to warn off collision dangers, or warn ships of danger hazards such as reefs [**4**].

The predictions above are well on their way to realizations. Ground station equipment in getting smaller and cheaper — send and receive equipment that used to cost $ 1 million is now available for $ 100,000, and the antenna dimensions are down by a factor of two, to 10-15 ft. IBM, Aetna Life & Casualty, and Comsat General have formed a joint venture called Satellite Business Systems to supply high speed voice and data service to businesses, and it will soon launch its first satellite. Sidney Topol of Scientific-Alanta Inc. says that by the end of the decade « every major commercial building either will have an earth station or will be sharing one with the building next door for computer, voice, electronic mail, telex and teleconferencing services » [**17**].

Besides communications there are many other uses for large antennas in space. For example, they can monitor soil moisture, or make salinity measurements, or they could be used to detect sea ice from synchronous orbit for ship safety [**7**].

The application of large space structures which has received the most attention in the press as well as Congressional interest, and research funding, is the Solar Power Satellite (SPS) [**13**], [**6**]$_2$, [**4**]. In space there is no weather, no clouds, essentially no night (if far enough from the earth), and no absorption or scattering so that the amount of solar energy available in orbit per square meter is about ten times the amount available on Earth in the southern United States. A satellite designed to produce energy from solar radiation and beam it to Earth in the form of microwaves or a laser was first proposed by P.E. Glaser in 1968 [**6**]$_1$. Since then many studies have been made, and various concepts and configurations considered. In [**14**] is the American Institute of Aeronautics and Astronautics position paper on the SPS. Solar power is inexhaustible and cannot be monopolized by any small group of countries. The SPS satellite concept is one of the few solar options which offer baseload capability, eliminating the need for some form of energy storage at night. The most questionable aspect of the SPS idea is the safety considerations associated with the microwave (or laser) beam. One concept uses a power beam from the ground as a phase control reference, causing the microwave beam to loose coherence in the event of loss of pointing control.

The most striking aspect of the solar power satellite is its size - one design is roughly a 14 kilometer by 5 kilometer array of solar cells on a several hundred meter thick truss structure. While this array is maintained perpendicular to the sun's rays, a one kilometer microwave antenna must be pointed toward the Earth. To give some idea of the size of the satellite being considered, it is about the same size as the island of Manhattan, and the long dimension is on the order of 50 times as large as the Empire State Building is tall. Obviously the construction of such structures in space is a challenging problem (the entire Oct. 1978 issue of *Astronautics and Aeronautics* is devoted to it), and the development of automated construction methods will push the forfront of the robotics field [**15**]. Perhaps Norbert Weiner's predictions of robotics, cybernetics and society will finally take form.

So far we have spent considerable time discussing what types of large space structures will be built by the society of tomorrow, why they will be built, and to some extent how their presence can affect the organization of society. The subject of this conference concerns mathematics in the intellectual life and society of tomorrow, and we must therefore address the question what types of mathematics will be used, and what mathematical frontiers will have to be extended, in order to build and operate future very large spacecraft?

Some of the important properties of large spacecraft can be listed as follows.

(1) Because all of the mass in such structures has to be brought from

the Earth (or eventually the Moon or asteroids), they will use as little mass as possible to accomplish the goal. Hence, the structures will be very flexible.

(2) Because many of the structures serve as antennae, there will often be requirements for extreme accuracy in pointing the structure, and also extreme accuracy requirements for maintaining the shape to avoid distortions of the signal and antenna pattern.

(3) The structures are in fact distributed parameter systems whose full mathematical description would be in the form of partial differential equations. In theory they are infinite dimensional systems, and in practice they are of very high dimension.

(4) The extreme flexibility implies that there will be many low frequency resonance modes of the system, which often occur in closely-spaced groups.

(5) The natural damping of these vibration mode shapes is very small, usually assumed to be on the order of one half percent of critical.

(6) It is very unlikely that any of the large structures discussed could be built and tested on the ground to be sure that they function properly. Imagine trying to build something fifty times the size of the Empire State Building! In fact these structures could not support their own weight on the surface of the Earth. Under such conditions the accuracy of the mathematical modelling and computer simulations of the structural dynamics becomes critical.

(7) These large structures will have to be constructed in space, and in some cases transferred from an initial orbit to the desired orbit after construction. Whatever techniques are used to control the vibrations must also function throughout the construction process while the structure is constantly changing.

Because of these characteristics the shape and pointing of a large space structure will have to be controlled by a feedback control system. Sensors will be distributed throughout the structure to make measurements of the amount of vibration (and/or the pointing error) at various points in the structure. The information will most likely have to be processed by an on-board digital computer to decipher the information and determine what type of control action to perform to damp the vibration and also reduce the pointing error. These corrective actions must be performed by actuators at various locations throughout the spacecraft. The types of sensors and actuators to use is very much an open question. Some possibilities for sensors include accelerometers, gyros, a full inertial platform, and techniques like radar ranging and Doppler measurements of the relative positions and velocities of points on the satellite relative to the radar source. Some candidates for actuators include cold gas thrusters, ion thrusters control moment gyros to supply torque, reaction wheels, cables connecting various points of the structure using a cable tension controller, and the analogous tension control of some of the structural members of the truss.

The design of such controllers is an extremely interdisciplinary subject involving structural mechanics and dynamics, mathematical modelling questions, representation of distributed parameter systems by finite order models, design of stable control laws, optimization of the control laws or control parameters, large scale computer computations to obtain and test the control strategies, and estimation theory used by the control strategy to process the sensor data. Usually the problems to be solved are such that all of these areas are so interrelated that solutions in each area depend very much on solutions in many other areas as well. It is a challenging research area, where there are many questions and very few answers [2], [9]. No one yet has a candidate control technique which they claim will really solve the problem of control of future large flexible spacecraft.

Parenthetically it should be mentioned that there is a ground based equivalent to this problem. It is anticipated that tall buildings in the future will be designed with automatic control systems, perhaps like the cable tension control described above, in order to allow the building to combat wind loading (and perhaps even Earth quakes) with less building material [16]. Already there are tall buildings such as the Citicorp Center in New York which have tuned vibration dampers to damp the first mode of vibration - in the case of the Citicorp building the damper is a 440-ton block of concrete mounted on the 63rd floor. Suspension bridges are also candidates for active control. The potential danger of high winds on suspension bridges was dramatized by the filmed wild oscillations and collapse of the Tacoma Narrows bridge in a 67 kilometer per hour wind. Active control may in the future offer a solution to such problems that avoids expensive and massive designs.

Returning to the problem of the control of large space structures, the first consideration is how to model the behavior of these structures. One might start with a distributed parameter model and develope a finite number of modes. More likely one would start with a finite element approach and obtain from the beginning a lumped parameter model. Another alternative which might apply to the effect of each actuator on the structure is a wave propagation model. However the system is modelled, it will have a large dimension. Meirovitch states that it is not unusual for a large space structure to require several thousand degrees of freedom for proper modelling [9]. Furthermore, in computing natural frequencies of oscillation of such a structure, as a general rule only the lower-half of the frequencies will be good estimates of the actual frequencies. These high order models are addressed to the problem of obtaining a reasonably accurate model for purposes of evaluating how candidate control systems would behave when implemented in orbit. On the other hand, modern control systems in operation usually require use of a system model as well, and since the differential equations have to be integrated by the on-board computer in real time, the model must be of a reasonably low order. The discrepancy in model dimensions is a fundamental difficulty which must somehow be solved.

Because of the multivariable nature of the equations, the control system designer is forced into using techniques from so-called modern control theory, a theory which developed starting in the late 1950's. One option is the use of direct output feedback together with pole placement techniques. This means that the commands to the actuators are calculated simply by taking properly selected linear combinations of the sensor measurements. The linear combinations would be chosen so that the eingenvalues of the feedback system differential equation are sufficiently stable. The second main option is to use linear-quadratic-Gaussian optimal control theory. The theory is based on the calculus of variations generalized to handle control problems. The resulting control laws require estimates of the complete structural state of the system, based on the data, using an observer (a Luenberger observer or a Kalman filter to produce the expected value of the state based on the data). Because of the dimension problems with the latter option, the poorly understood field of reduced order controller design is considered.

Modern control theory advanced very quickly during the 1960's, and in some respects started to stagnate in the 1970's. To date rather few applications have been made to design practical control systems, and this is basically because the field is not yet really mature. In some sense, various practical considerations are still not properly dealt with, and the large space structures control problem is forcing people to try to extend the theory in ways that will close the gap, at least for these applications. The theory applies to the control of multivariable systems. A corresponding theory of the control of distributed parameter systems is in a much more primative state of development, and it will be a long time yet before that field is well enough understood to be of practical importance.

The challenges to the control field posed by the large space structures problem include at least the following eight areas:

(1) The dimension problem is the ultimate in reduced order controller design, since the original system is infinite dimensional. The order reduction problem can be viewed as some type of projection from one space to a lower dimension space. The presence of system modes of oscillation that are neglected in the controller can destabilize a control system by causing control spillover (excitation of the residual modes by the control) and observation spillover (corruption of the measurements by the residual modes being misinterpreted in the controller). Some of the candidates for handling the spillover problem include: the classical frequency separation between poles as in classical control approaches (not likely to be possible), notch filtering to eliminate the undesired frequencies from the measurements (and perhaps the controls), annihilation or suppression of spillover for certain modes by restricting the control vector to lie in or near a specific subspace, location of actuators and sensors at nodes of the appropriate modes, recapturing some of the lost dynamics of the residuals by using model error compensa-

tion, using a reduced order controller designed based on the full order system, or use of local velocity feedback at colocated actuators and sensor which introduces artifical damping. Which method or combination of methods to use is a totally open question.

(2) The control system must be robust, i.e. the stability and accuracy must be relatively insensitive not only to the residual modes, but to errors in the estimates of mode frequencies and shapes for modelles modes. The stability margin for the structural dynamics is very poor.

(3) How should the locations of the actuators and sensors be chosen, and what types of sensors and actuators should be used? In theory, for some spacecraft it is possible to use only one actuator and one sensor for shape control purposes, but this would put heavy reliance on the accuracy of the controller system model. For direct output feedback many more sensors would be required, but the on-board computations become simple. The actuators might be placed to make the system as controllable as possible, or placed as a compromise between the controllability of the modes considered and the disturbance of the residual modes. The actuators might be placed at nodes of certain residual modes to eliminate spillover of those modes, or they might be placed in an effort to decouple the system.

(4) The systems must be designed for realiability in some sense. Perhaps methods need to be developed for failure detection followed by reconfiguration of the controller once a failed actuator is found. Perhaps a heierarchical control method should be used to decentralize the control decisions so the controller would not be so vulnerable to computer malfunction. Decentralized control might dictate the actuator and sensor positions to use in order to succeed at decoupling the parts of the controller.

(5) The way in which the use of digital control equipment and the resulting sampling of the data affects the system performance must be understood. It tends to aggravate the spillover problem.

(6) Adaptive or learning controllers may have to be developed in order to stabilize the system during construction when the system dynamics are constantly changing. An alternative is to stop construction periodically, and perform some tests for purposes of system identification on the ground, followed by control system adjustment. Adaptive control theory tries to do the system identification simultaneously with control using a minimum of test signal inputs, but the theory of adaptive control so far is unable to guarantee convergence in the presence of residual modes.

(7) Robots must be developed to expedite the structure construction operations in orbit.

(8) Feedforward control designs should be employed to handle predictable or measurable types of disturbances and eliminate their effects directly. Candidates for this type of control are thermal distortion from the sun,

solar radiation pressure torques, and gravity gradient bending of the spacecraft.

It is clear that future very large flexible spacecraft will have a fundamental influence on the economics as well as the structure of future societies, including profound effects on methods of communication and navigation, on monitoring and perhaps controlling weather, on locating Earth resources, and hopefully they will help to solve our energy problems. The control problems inherent in building and using large space structures are challengine the mathematical theory and forcing advances on many fronts. It will be interesting to see how these challenges are finally met when the first large space structures are built.

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