Historical Survey Lecture

Two Decades of Spacecraft Attitude Control*

Robert E. Roberson
University of California, San Diego, Calif.

Introduction

THIS paper does not fit into the usual pigeonholes of technical works, so it is necessary to start by telling the reader what it is and what it is not. It is a very personal perspective on spacecraft attitude control since the subject was first formalized in 1957, given by one who has followed it from the beginning. Special emphasis is on the period of concept formation, mainly prior to 1965, and on topics that fall within my own areas of special interests. The paper is obviously not an exhaustive literature survey of attitude control; the archive literature alone, with several thousand items, is simply too vast. Nor has there been any attempt to make the coverage complete, in the usual scholarly sense, even within its restricted scope. Although I have tried to maintain a balanced viewpoint, the reader must recognize that problems are always possible when history is recounted by an active participant.

At the end of two decades of space flight it is appropriate to take a retrospective look at some of the major functional ingredients of spacecraft.† Attitude control is one of these. In the classical literature of astronautics it was scarcely recognized as an area worth studying. In 1977 I heard it said that in extreme cases the attitude control subsystem can represent up to 30% of the cost of the spacecraft. This much change in the subject's perceived importance is reason enough to review its evolution over the past two decades. If its role could be so underestimated then, what might have changed in our viewpoint toward the structure of the discipline itself and the methods available to perform the attitude control function?

We would hardly expect attitude control to have suddenly emerged as a new discipline exactly 20 years ago, at the time space flight began. On the basis of the published literature, it is not unreasonable to pick 1952 as its nominal birth year. A history of the subject prior to 1952 already has been given[1], in which it was pointed out that the first systematic study of spacecraft attitude control in its own right began that year. (This study was documented only in unpublished form[2], i.e., as a company report whose original classification was "Secret".) Some forerunners existed (described in Ref. 1), extending from the technology of spin-stabilized projectiles in the 16th century, through the gyroscopic stabilization proposals in early speculative studies of space flight done in the late 1920's, to several secret studies of spacecraft sponsored by U.S. government agencies (under the euphemism "High Altitude Test Vehicles") in the second half of the 1940's. But as regards the specific subject of attitude control, published work was sparse, neither comprehensive nor intensive, and invariably formed an incidental part of broader system studies. Not until the mid 1950's did a trickle of publications begin in which spacecraft attitude control was the explicit central theme.

Gravitational torque on an artificial satellite was the motivation of one work[3] in 1956, although its wording had to be very carefully couched to avoid hinting at such a vehicle. In 1957 another[4] addressed the effect of the Earth's magnetic field on satellite spin. Finally, in 1957 a third[5] described for the first time in the open literature the general problem of actively controlling an artificial satellite so that one of its axes remains pointed downward toward the Earth. In the USSR that same year, Beletskii made two contributions[6,7] to problems of "classical type" (see later) having implications to the uncontrolled behavior of artificial satellites. Thus the open, archive publication of works on artificial satellites began at almost exactly the same time as the first space flight (in October, 1957), giving us a double motivation for choosing 1957 as the initial point of the two-decade period with which we are dealing.

The purpose of this paper is to give an overview of the attitude control discipline as we see it at the end of 1977, and to put this into perspective with the 1957 viewpoint. Certain subsequent developments could be foreseen fairly well at that time, and these are reviewed. Perhaps more interesting is to identify those unforseen developments which were essentially new to the period. Finally, a few words are ventured about the future.

The real substance of the two decades lies, of course, in the attitude control systems themselves, those that actually have been put into space. A review of those and their observed performance would be very appropriate at this time, but this

R.E. Roberson graduated from the University of Chicago (B.S. Physics), George Washington University (M.S. Mathematics), and Washington University (St. Louis) (Ph.D. Mechanics), the latter in 1951. He was Chief of Astronautical Sciences at the Autonetics Division of North American Aviation, was Vice-President of Systems Corporation of America, and has been a private consultant since 1960. He served as a Professor of Aerospace Engineering at the University of California, Los Angeles, and since 1967 has been a Professor of Engineering Sciences at the University of California, San Diego. At present he is also Chairman of the Department of Applied Mechanics and Engineering Sciences. Most of his current research pertains to dynamic simulation and applications of general multibody systems.

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*Editor's Note: This paper was invited for the AIAA 16th Aerospace Sciences Meeting as a historical survey. It is published here primarily for its historical interest to our readers. It is not meant to be a comprehensive survey of the field. It represents solely the author's own experience and opinions.

†For the purpose of this paper, "spacecraft" means any extra-atmospheric vehicle in orbit or on an escape trajectory. Purely for the author's convenience, its scope is further limited to unmanned craft.

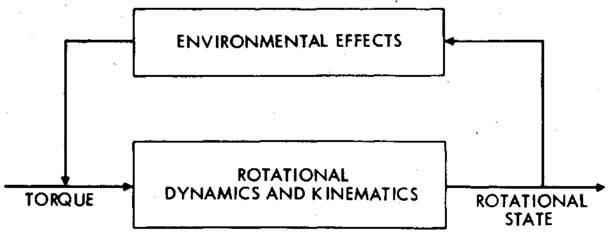

Fig. 1 Rotation without active control.

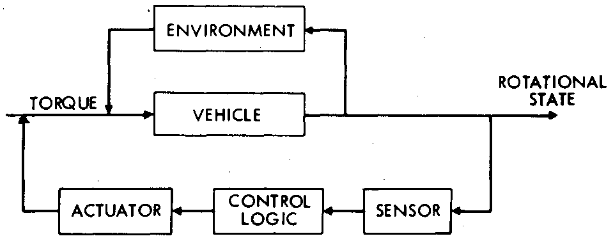

Fig. 2 Actively controlled rotation.

is not our chosen direction. Our retrospect is on how such systems fit conceptually into the complete picture and how events led to them. Thus the focus is more on what is revealed by twenty years of the written word than on the evolution of hardware, although the latter is not totally ignored. I believe that most readers will be more familiar with recent physical systems and less so with a view of the field "through the wide end of the telescope."

To make our scope explicit it is useful to distinguish several kinds of works:

1) publications on kinematics and dynamics of rotating bodies and systems of bodies: rigid, gyrostatic and flexible;

2) those problems of classical type (whenever written): natural motion, equilibria and stability of bodies under prescribed force systems, in the spirit of 19th century investigations unrelated to artificial satellites;

3) those specifically on attitude control, including the addition of dissipation and the various aspects of active closed-loop control;

4) those with kinship to spacecraft attitude control, but with some significant differences, such as control aspects of missiles and rockets as well as gyroscopy in its general forms;

5) "unpublished" documentation consisting of company reports, internal memoranda and the like (but not major NASA publications, which are widely available in archive collections).

Major attention is devoted to item 3, with some remarks on 1 and 2 as appropriate. Items 4 and 5 are ignored.

Perspective

To give a basis for discussion, Fig. 1 is a schematic for the rotational behavior of active control. A torque acts on the vehicle and, through its dynamical and kinematical equations, produces a rotational state—an orientation and angular velocity. But some of the torque-producing environmental effects depend on the rotational state itself, so an inherent implicit feedback loop exists. It might be stabilizing or destabilizing relative to a specified attitude reference, depending on the particulars of the vehicle configuration.

Figure 2 shows the addition of a second feedback loop for the active control of rotational state. It comprises sensors, some kind of control logic implemented by circuitry or a computer, and actuators to apply the control torque. (The sensors are shown as if they measured the rotational state directly, but this is a detail; they might equally well measure deviations from a desired state.)

Clearly three elements offer themselves for manipulation to obtain or augment attitude stabilization or control: the vehicle itself, the passive environmental feedback, and the active control feedback loop. Thus it is convenient to divide control methods into three broad classes.

1) Gyroscopic Stabilization—This often is characterized as spin-stabilization, but includes cases of non-spinning vehicles with internal angular momemtum. The idea is to reduce the sensitivity of a vehicle axis to the natural drift-producing effect of applied torque by giving the body more angular momentum.

2) Field Stabilization—Here one augments those ambient field torques that tend to stabilize the vehicle in a desired orientation or to damp its oscillations, and suppresses those that tend to be destabilizing. This is done by proper vehicle design: geometry, magnetic properties, number and interconnection of sub-bodies, etc.

3) Servo Stabilization—This is the active closed-loop control of rotational state. The vehicle may be rigid or flexible, with or without internal angular momentum, and its normal state may be one of spin or of three-axis alignment with a specified reference frame.

Each of these basic classes has its own story of development. But before pursuing these, let us continue with the establishment of our perspective by returning briefly to items 1-3 mentioned in the introduction in connection with scope, and expand them so as to slice the field in another direction.

Rotational Kinematics and Dynamics

The problems of the rotating rigid body and gyroscope are classical. Those of multi-body systems, however, have arisen mainly in response to the needs of spacecraft attitude control; more particularly, to needs for digital simulation of attitude behavior. A complete discussion of spacecraft dynamical modeling, with emphasis on the development of multibody formalisms, is given elsewhere.[8] It is shown there that three areas have motivated the evolution of multibody formalisms: (primarily) attitude control, biomechanics, and mechanisms. Aside from a few forerunners in the 19th century, specialized works on the subject began to appear in 1958 and continued through the first two decades of the 20th century. However, formalisms for very generally interconnected systems of bodies date from 1965 and 1966, when two works appeared[9,10] on this subject, each taking a somewhat different approach. Most subsequent published work (surveyed in Ref. 8) has used these as a foundation.

Problems of Classical Type

There are two major problems in this category. One involves spinning rigid bodies or gyroscopes, torque-free or under the action of gravitational torque. The latter case is related to the natural phenomenon of the precession of the equinoxes. The other problem originates in the libration of the moon and includes the equilibrium and stability of a rigid body with respect to an orbiting frame. Both problems go back to the 18th century, having been treated by Euler (by Wangerin and Volterra in the 19th century in the case of the gyrostat) and Lagrange respectively, and a body of 19th century literature exists on each. Nevertheless, they have been pursued further in the past 20 years because in their classical setting they dealt with restricted parameter ranges—nearly symmetric, nearly spherical precessing Earth and librating Moon. Artificial satellites come in a wider range of shapes. Furthermore, the initial state of motion can vary drastically from that of natural bodies.

One more recent variation should be put into the same category, namely the librating gyrostat. This problem belongs to mid 20th century, motivated by artificial satellites having gyrostatic properties. Yet the spirit of this new problem is that of classical dynamics, and I believe that it should not be included among the problems of attitude control.

Particularly in this last case it may seem hairsplitting to separate the problems of classical type from those of attitude control, but there are good reasons to make the distinction.

To keep a correct perspective we must recognize that the former do not, strictly speaking, apply to artificial satellites at all, even when they have been motivated by such systems. They may give a rough insight into expected behavior by predicting what it would be under idealized conditions, but they lack that essential ingredient of engineered systems: dissipation.

It may be invidious to single out a few references from the substantial literature on this subject, but it should be noted that a 1956 work[11] by Klemperer and Baker is the first to discuss the libration problem for artificial satellites, although it is confined to planar librations of a dumbbell on a circular orbit. (It also is the first to suggest an internal pendulum as an indication of the gravitational vertical.) The general libration problem in the context of artificial satellites, including librational dynamics of an asymmetric body of an elliptic orbit and a complete stability investigation, was first taken up by Beletskii[6,7,12,13] 1957, 1958, and 1959. The newer area of stability of gyrostats with respect to an orbiting frame became an active area of investigation in the mid to late 1960's. The unwitting forerunner[14] of this concerned an orbiting rotor, which is just the special gyrostat whose body has no inertia of its own.

Attitude Control

We now come to the heart of our subject. The three basic classes of attitude control methods already have been listed. Under the control rubric we also include the formulation of the attitude control requirements and the analysis of the torques acting on the craft.

Most functional requirements fit within three general categories: 1) One axis is to be kept in an inertial or quasi-inertial direction, permitting rotation about this axis. Examples of real spacecraft form almost an "embarassment of riches," so we may as well return all the way to Explorer 1 as a specific illustration (even though in that case it became the wrong body axis after dissipation had been at work a while.) The earlier communication satellites were of this type. 2) Three axes are to be kept in an inertial or quasi-inertial direction, a case exemplified by most vehicles devoted to astronomical-type observation. 3) Three axes are to be kept aligned with a rotating frame of reference. Most typically, one axis is geocentrically aligned, while another is normal to the orbit plane. Several variations are possible, especially within the third type. Within one mission the requirement may change, as when a vehicle is spun to establish direction for orbit injection thrust and is later despun to be oriented inertially or geocentrically. Additional requirements may exist for subsidiary parts of the vehicle, such as Sun-pointing for gimballed solar panels. One example in this case is SATCOM (1975 118A).

In retrospect, I have the feeling that some of the earlier works, especially my own, gave too much attention to the fine points of attitude reference frames. For example, for Earth-pointing systems it was a still-open question whether one should be concerned with the geocentric, gravitation, geographic or sensor-established verticals. In dealing with real vehicles on real orbits, any one of the choices results in attitude excitation from one source or another. A second question is how the orbit plane should be defined. It is not clear that these questions ever were cleared up definitively as the discipline involved. What seems likely, as one scans the literature, is that was an implicit decision to visualize the requirements in the simplest terms, ignore the distracting alternatives, and accept the control implications of so doing. Experience taught that the questions were not worth worrying about.

Quantitative requirements range from loose attitude limits of several degrees to attitude stability over a limited time interval of better than 10^{-4} degrees. Although the diversity of mission types has grown over the past 20 years, the anticipated requirements have not really changed very much. Initially, accuracies of the order of 1 deg were considered typical for three-axis stabilization. There was a relaxation to several (or even tens of) degrees to admit gravitationally stabilized systems. There was drastic tightening to accommodate the needs of astronomical experiments. Yet, for the most part the range cited here was quoted as early as 1958. Even the extreme requirements of astronomy were being discussed by 1960.

Much of what has been said thus far is of 20- to 25-year vintage. Identification of requirements formulation, disturbance (torque) analysis, and the elements of an active closed loop as the basic questions of attitude control is explicit in Ref. 2. (The torque sources, sensor and actuator types that it examines are detailed later.) That work was unpublished, of course, but Ref. 5 makes the same points. Spin was taken for granted as a stabilization mechanism (as in Ref. 4), representing at least a part of our first category of methods. In the same category, gyrostatic characteristics were recognized as a useful supplement to active three-axis control, the specific word "gyrostat" not being used until much later.As for the second category, gravitational stabilization was explicitly recommended as a supplementary method, although it was concluded that as a sole, independent method its "adequacy [is] not demonstrated." Thus we find that the general structure of the discipline was well-recognized at the outset. The major subsequent changes were the development of a much better appreciation of the relative importance of its parts, the suggestion of new possibilities within the recognized classes, and, of course, the creation of suitable hardware to implement the principles.

Torque

As we all recognize, the torque on a spacecraft is important because it determines what stabilization techniques are feasible, underlies the attitude performance, and sizes the control system. Peak torques imply actuator torque capacity, while torque impulse over time implies total propellant or energy needs. I think that all the torque sources were recognized early[25]: gravitational, magnetic, aerodynamic, pressure from incident and emitted radiation, the reaction of internal moving parts, the effect of the angular motion of the reference frame, and a few others. Which of these is most important, of course, depends on the craft and its mission, but inertial reaction, gravitational, magnetic, and incident radiation were felt to be especially prominent. Several others were considered briefly and then dropped as probably insignificant and certainly hard to estimate.

One difficulty in the early days was that torque predictions had to be made before any real spacecraft had ever been constructed and flown. There was a premium on being able to make the calculation purely in terms of the geometric and material properties of the vehicle, together with a knowledge of its intended orbit. Nowadays, while applying the same formulae, one usually can draw on experience to estimate critical vehicle parameters, based on familiarity with previous craft of roughly the same type.

One torque initially missed was that of magnetic hysteresis. Initially, magnetic torque was regarded as produced by eddy currents and the vehicle's permanent magnetic moment. Magnetic polarization was soon added,[5] but hysteresis did not crop up for several years.[15] Accidental expulsion of gas was overlooked as a hazardous torque source until satellite 1963-38B overturned from this cause and could not be recaptured in the correct orientation. (Satellite 1963-49B also tried to overturn, but was reoriented by an electromagnet foresightedly included to guard against this very eventuality.)

Improvements in torque calculation followed the steady increase of knowledge about the ambient fields. Better magnetic field models have been constructed. The Earth's gravitational field has become better known too, but this seems less important. Only in certain extreme cases does one need the oblateness term, and to the best of my knowledge the higher harmonics never have been more than curiosities as regards motion about the center of mass. More sophisticated ways were devised to estimate radiation pressure torque taking account of the shadowing of the vehicle by its parts.

The way these torques are put to use in stabilizing the vehicle is more interesting than the simple existence of the torque models. This subject is deferred to later sections.

Gyroscopic Stabilization

Spin-stabilization of rigid bodies is a classical method about which not much need be said. It was well on the scene in the mid 1950's in connection with the proposed Vanguard. But we see here a prime example of the gulf between problems of "classical type" and problems of attitude stabilization and control. The lack of dissipation in the former, together with the known stability results for the torquefree rigid body, set a trap into which Explorer 1 fell precipitously. It goes without saying that the stability question in the presence of dissipation was quickly taken up, and the need for body oblateness became a watchword. Once bitten, twice shy, for when a new idea permitted prolate bodies to be spun stably about their long axes the community was reluctant to receive it.

Gyrostats were not entirely new on the scene. Reference 5 and a patent[16] filed in 1956 suggested turning a rigid body into a gyrostat in the interests of stability and enhanced roll-yaw coupling. In this case, however, the body of the gyrostat was not spinning.It seems an obvious step to turn this around and regard the body as spinning while the former rotor is almost fixed in space, but this shift in viewpoint did not seem to materialize until perhaps 1964—I am not certain who first had the happy inspiration. Combined with the discovery by Landon (1962, published 1964[17]) that spinning dissipative gyrostats can have very different and advantageous stability properties compared with spinning "rigid" bodies having dissipation, one has the so-called "dual-spin" satellite that has been so popular for synchronous communication satellites over the past decade. OSO 1 (1962 ζ1) was the first spinning gyrostat in space, although it did not need to rely for stability on its gyrostatic properties. TACSAT 1 (1969 13A) was the first gyrostat depending on the special property that stable spin can occur about the axis of smallest moment of inertia. The period 1964-1970 saw substantial theoretical (and some experimental) work on the stability criterion in terms of the relative amount of energy dissipation in the spinning and despun parts. (See especially Refs. 18 and 19. For further comments on the history, see Ref. 20.) All in all, these developments were certainly among the more important of our two-decade period.

Some of the pioneers of astronautics wrote of stabilization by gyroscopes, but the reader cannot be sure exactly what they meant. In any case, though , the method was proposed in 1946 as part of the "High Altitude Test Vehicle" studies mentioned previously. I discussed it briefly in Ref. 2, but, more familiar with precision navigational gyros, guessed wrongly that the control torque would be insufficient and failed to anticipate the subsequent development of control moment gyros. A gyrostabilization system is subject to saturation, in the sense that when the gyro has turned completely around its output axis it can compensate no further torque impulse in the same direction. It can be used, however, if a supplementary torque source is available for desaturation, which means that it can be used as a part of either a field-stabilization or servo-stabilization method.

What one might regard as the classical control problem for spin-stabilized bodies, gyrostatic or otherwise, are 1) the control of spin speed and 2) the introduction of dampers to cause any nutation angle to decrease.Specific works in these areas are numerous, and I simply observe that they were appearing by 1960. However, an unanticipated line of investigation developed from the discovery[21] that certain spinning bodies with internal moving parts can take on states of spin other than about a principal axis of inertia. These have become known as trap states.

Field-Stabilization

All the torque sources mentioned previously are candidates for control torques. Some are attractive supplements to closed-loop feedback control. Others imply vehicle equilibrium states that are operationally useful, so they individually have a potential for providing stabilization. Aside from the equilibrium and stability characteristics themselves, the most important feature of field-stabilization is the way dissipation is introduced into the system. In some cases this might be done by an active control system. At the same time, a servo-stabilization system may rely on ambient field torque as a supplement, as when they are used to desaturate internal angular momentum storage. Such combinations form a grey area where a method can be assigned to one class of stabilization or the other only by a sometimes-subjective decision as to which is the "primary" means.

Gravitational stabilization and the need for a librational damping mechanism was already in the cast of characters on opening night, so to speak. Discussed in Refs.2,5,11,22 as well as a number of other early works, and the subject of one patent,[23] all that was lacking was a practical engineering design for the damping mechanism.

Some of the most attractive of these involve booms dissipatively hinged to the craft, the first of which was proposed in 1962.[24] Many other configurations were devised in the next few years. One embodied a mass attached to the end of a boom by a lossy spring, and this was the first to fly (on 1961 $\alpha\eta$2, whose boom failed to deploy, and on 1963 22A, which was a complete success). A form of gyrostabilization in which gyroscopes provide damping to a gravitationally oriented satellite was described as early as 1963, but its roots were in work done at MIT in the late 1950's. Methods were devised[25] to assure capture in the proper orientation. The thermoelastic excitation of booms, a totally unexpected phenomenon, was first observed in 1963 22A and led to considerable design effort to reduce the effect.

One of the important new ideas of that period was that by skewing the hinge line of an internal moving part one can introduce intermode coupling that permits an internal device with one degree-of-freedom to damp all three modes of rotational motion.[26]

Together with the elastic vibration of components of spinning satellites, I believe that the elastic behavior of the long booms of gravitationally stabilized satellites played the major role in awakening interest in flexible satellites during the mid 1960's.

Aerodynamic stabilization of a gyrostat has been used in the USSR, but this seems to be an isolated case. Most satellites are above the altitude where this is feasible. At the other extreme of altitude, solar radiation pressure can become the major torque and made the basis for a stabilizing technique. However, the details of these two cases are not pursued here.

Servo-Stabilization

A few months ago I attended a conference in the Netherlands, sponsored by the European Space Agency, whose eight sessions spanned all aspects of attitude control. As I listened I had a strong sense of déjá vu. Although the tone was more confident, the hardware more sophisticated and its performance numbers more advanced, I almost felt that I had been carried 20 years back in time and that I was again hearing lectures on the new field of attitude control. I do not mean to disparage in any way the excellent works reported there, but just to emphasize that the changes over the two decades have not been in the principles but in the hardware development and the feeling of assurance that comes from the components having done their job in space.

Active closed-loop control can be used, of course, as a part of the operation of spin or field-stabilized vehicles. Acquisition, reorientation, even damping, can be applied actively. Such applications employ the same kinds of sensors and actuators that are mentioned below, but our main concern is three-axis attitude control.

The basic categories of sensing methods are listed in Ref. 5 as inertial, sightings in Earth or celestial bodies, measurements on ambient fields, and observations from the Earth. Almost nothing of the fourth type has developed.As regards the fields, both an internal pendulum and differential accelerometers have been proposed to measure the gravitational fields, the latter in a series of papers starting in 1959. Events passed these by: it was judged better to let the vehicle itself do the sensing, in effect, by assuming a gravitationally stable attitude. Magnetometers to measure the magnetic field, however, have had and do have practical application.

Inertial means include the gyrocompass for yaw measurement and a gyro vertical monitored by other means, typically optical. The former has been a part of the Nimbus instrumentation in the mid 1960's, for example.

Finally, the optical class is represented mainly by the horizon scanner, sun sensors and star sensors. The former, of which several conceptual versions exist, was first mentioned in the open literature by Stuhlinger in 1956. It was used in space in the Discoverer satellites of early 1959. Horizon scanners have since become a mainstay of the instrumentation of three-axis stabilization systems. Sun sensors are also in frequent use. Star sighting is exemplified by the Canopus tracker used on some craft away from the neighborhood of the Earth.

Actuator classes are even simpler: reaction with inertial space or interaction with the ambient fields. The former comprises control moment gyros, reaction wheels, jet mass expulsion, and the control vehicle mass geometry or gyrostatic character. All have been used in practice, some alone and some in combination with other methods. It was recognized at the outset that momentum storage devices could saturate and would require the application of unloading torques. The first proposal for the latter was mass expulsion, but by 1958 or 1959 both gravitational and magnetic field interactions had been proposed. Note that reaction wheels as a sole device is a classical method dating back at least to 1930.

The field interaction torques are the same as we already have discussed, but now they are being used actively rather than passively for stabilization. Active magnetic methods were passed over as too complicated in 1957, but by 1961 were being proposed both as a desaturation tool[28] and as a sole source for active control.[29]

A listing of sensor-actuator combinations used in actual spacecraft is beyond the scope of this work. It is a subject deserving its own treatment, because the combinations can get to be quite elaborate when all modes of operation are considered. It should be mentioned in passing, however, that the application of modern methods of control optimization began about 1963.[30]

Unexpected Talents

Let us imagine ourselves at the opening of a new theatrical production 20 years ago. The stage is already crowded with characters. While many of them are solid flesh and blood, arrayed in bright and attractive costumes, others are mere wraiths, while a few more are still backstage. We can see some of them dimly, but they are shadowy and lack substance. They give us tantalizing glimpses of what they might become, but we are unable to foresee the sparkling roles they ultimately will play as the drama unfolds. Here are four of the characters that revealed themselves only with the passage of time.

First, the digital computer. Not for five or more years could we begin to talk with confidence about acceptably small, reliable, on-board digital computers. Not for ten could we face truly large-scale digital simulation of satellite rotation. The lack of on-board computation capacity made us cautious about the degree of complication we could accept in our control logic.

Second, the gyrostat. This is a perfect example of something that stood before us in 1957 whose real importance to our drama was completely overlooked.

Third, the natural environment. To be sure, it was clearly understood that gravitational stability could play a useful supporting role, but I think that most of us did not see it as star material. The magnetic field was considered to be too erratic an actor to settle down into the serious sustaining parts in which we now find it. Our gaze did not go low enough in altitude to discover aerodynamic stabilization waiting there, a character that thus far has been invited only onto the Russian stage.

Fourth, the big, floppy, flexible satellite. The flexible satellite, with its implications to control system design, wandered onto the boards after the play was half over. Its role is an important one today and shows promise of becoming more so as spacecraft increasingly take the form of large structures.

I'm sure each of us has his own nomination for the characters whose talents were least visible on opening night. These are mine.

What of the Future?

In a work of 1960 I said that "the systems area in attitude control is a rich mine still to be worked." Now I feel I must say that attitude control, at least in many aspects, is about exhausted as a field of research. Much of the field is rapidly becoming an area of development or of conventional engineering practice. Certainly some areas of active research will continue for a time, such as the attitude control of flexible satellites, control under extreme pointing requirements, and certain others. But the days of easy accomplishment are gone. I do not mean by "exhaustion" that there is nothing left to learn; only that each increment of knowledge is bought at an increasingly high cost, to the point where decisions are made that certain increments simply aren't worth it.

Component development will continue. The design of new attitude control systems will not necessarily be trivial, but the procedures for doing so will be, for the most part, well known. The problems of theory and analysis that are left are relatively intractable. Work presumably will continue at a somewhat reduced level on dynamic simulation, on academically appealing problems of classical type, and on fine points involving specific control systems and vehicle configurations. Some methodologies that have blossomed in the light of attitude control will be brought to bear in different technological areas; indeed, multibody dynamic simulation already has been generalized to apply to land vehicles.

As an unconventional discipline that combines dynamics, control, and the environment as few others do, the research area of attitude control, notwithstanding a continuing trickle of new work, will have run much of its course in its first quarter-century.

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