# CHAPTER 3
# REPORT OF THE ELECTROMECHANICAL SUBSYSTEMS PANEL

## INTRODUCTION

The Electromechanical Subsystems Panel began the deliberations with summary presentations of papers previously submitted by some of the panel members. Presentations were made as follows:

1) Philip A. Studer, "Plus and Minus 90°". - This was a summary of flight anomalies of the past 20 years in space (covering 350 spacecraft from 52 different programs) in addition to a review of malfunction reports as guides to future development needs.

2) Walter R. McIntosh, "Star Tracker Sensors for Space Applications". This paper discussed the need for a solid state CCD or CID device customized for star tracker application to circumvent corona problems with the present high voltage image dissectors.

3) Derek Binge, "Mechanisms for the Deployment of Space Structures". - This paper identified troublesome areas in devices such as latches, dampers, position sensors, and others which are used for deployment and retraction.

4) Peter E. Jacobson, "Rotating Electrical Circuit Interface Failures - Slip Ring/Brush Sets Compared to an Advanced Roll-Ring Configuration". This paper identified a new arcing failure mechanism associated with minute debris particles and indicated that the development of roll-ring technology has advanced to a point of being a viable alternative to the slip ring/brush.

5) George Zaremba, "New Stepper Motor Drive Technology Circumvents a Different Servo Controller Problem". This paper described a new pointing subsystem development with biaxial capability to stably point an instrument to within 5 arc sec total error.

6) Capt. Howard J. Mitchell, "Lazarus Sleeps No More". This paper described the unique analysis and control techniques used to recover the first Defense Meteorological Satellite Program (DMSP) Block 5D satellite which had tumbled out of control shortly after launch.

7) Tom Flatley, "Counterspun Compliant Flywheel Nutation Damper". - This paper described a unique nutation damper invented by S. Tonkin of England which may provide a simple, reliable approach for short-term nutation control, such as in sounding rocket flights and for Solid Spinning Upper Stage (SSUS).

The paper by Mr. Flatley on the Tonkin nutation damper was presented to this panel for information only, since the subject matter was assigned to the Attitude Control and Determination Panel.

On the second day of the Workshop, the Panel discussed past and present deficiencies and new requirements to identify the drivers for what new developments are needed. In the area of deficiencies, lack of torque margin, lack of adequate dampers and insufficient accuracy were identified. In the area of new requirements, the following were among those identified:

1) Longer life, in general (for free flyers)
2) Operation over wider temperature ranges (Shuttle environment)
3) Operation in cryogenic temperatures
4) Operation after extended periods of inactivity in space (Shuttle retrieval)

These deficiencies and requirements were then viewed in terms of general classes of new developments which are needed, such as non-contacting mechanisms, dampers, hinge joints, forced lubrication devices, etc. As a result of this discussion, the following list of items evolved:

1) Magnetic bearings (need system application development)
2) Lubrication for long life
3) Improved signal transfer devices
4) Improved power transfer devices
5) Improved servo sensing devices
6) Deployment/retraction devices
7) Cryogenic devices
8) Ordnance substitute (EED's leak)
9) Data storage (replace tape recorders)

After some discussion, agreement was reached on which new developments the Panel would submit recommendations for, and which would be mentioned as items of merit for further consideration (but for which no recommendation would be offered). Writing assignments were then made as follows:

| | |
|---|---|
| Magnetic Bearings | Chester J. Pentlicki |
| Lubrication | Derek Binge<br>George Zaremba |

| | |
|---|---|
| Signal and Power Transfer Devices | Peter E. Jacobson |
| Servo Sensing Devices | Ron Baker<br>George Zaremba<br>Walter R. McIntosh<br>Philip A. Studer |
| Deployment and Retraction Devices | Howard J. Mitchell |
| Cryogenic Devices | Philip A. Studer<br>Richard M. Boykin |
| Digital Servo Electronics | Philip A. Studer |

Assignments on other items of merit:

| | |
|---|---|
| Data Storage | Bob Wilding |
| Ordnance Substitute | Philip A. Studer |

These assignments were completed, the writeups reviewed by the Panel, and a summary presentation was prepared. The completed writing assignments, as submitted for review by the Panel membership, are included below, and constitute part of this report.

## TECHNOLOGY DEVELOPMENT PROBLEM AREAS

### Magnetic Bearings

#### Background

Future spacecraft systems are expected to have requirements for extended lifetimes and more precise pointing requirements for spacecraft as well as instrument packages. In addition, the thermal environment is expected to become more severe, reaching cryogenic temperature levels for some applications. These considerations impact on the electromechanical actuators foreseen for these future missions. Momentum wheels and gimbal systems are examples of such actuators.

The current practice is to use ballbearing suspension in the devices. The ballbearing systems have many limitations. The stiction and running torque force compromises in terms of torque margin and servoloop design. In some cases indirect drive, with its associated gearing, is chosen over the simpler direct drive to ensure adequate torque margin and accuracy. The devices are very sensitive to temperature due to lubricant characteristics as well as the tight fits required.

A method of maintaining satisfactory lubricant supply for the extended missions (10 years) has not yet been achieved. Modeling of the lubrication system lags far behind application with consequential risks. Bearing performance is frequently, especially for higher speed devices, difficult to predict. Bearing cage instability has occurred with distressing frequency. The actuators considered here are often critical to the spacecraft success and not capable of redundant pairing. Solar array and despun antenna drives are examples. In other cases redundancy is possible, as with momentum wheels, but with weight and cost penalties. Life testing is difficult, expensive, and the results are often not timely.

Magnetic bearing systems have none of these limitations. The contactless suspension system has negligible stiction, low dynamic torque, no wearout mechanism, tolerance of extreme temperatures, and for many cases can be made sufficiently reliable to eliminate the need for redundant devices. Because of this, they have been under development for several years both in the United States and in Europe. Most of the effort has focused on incorporating magnetic bearings in momentum wheels. Several successful engineering models have been constructed, and at least one design has been flight qualified. None has yet flown. The magnetic bearing technology that has been developed has not been applied to the broader areas of devices that could profit from non-contact suspension. The progress in magnetic bearings has faltered.

## Recommendations

The application of magnetic bearing technology has faltered because of institutional inertia and the perceived risk of something new. To hurdle this barrier the following steps should be taken.

1) Flight demonstration of a magnetic bearing in orbit. Whereas development of magnetic bearing momentum wheels are far along they appear to be the best candidate for a near-term demonstration. Such a demonstration is critical to achieving acceptance of this technology by program managers. The technology is available and must be moved from the laboratory to the field.

2) Apply magnetic bearing technology to solar array drives, scanning mirror suspensions, and instrument package platforms.

3) Investigate the use of magnetic suspension at cryogenic temperatures.

4) Develop magnetically suspended nutation damper.

## Lubrication for Long Life

### Background

Oil lubricated ball bearings are key elements in satellite rotary systems. Reaction wheels, scanning devices, and despin mechanical assemblies are examples where long life and uniform torque performance are dependent on rolling element bearings.

Maintenance of a thin, clean, and uniform lubricant film at and near the bearing EHD ball-to-race contact zones and the ball to retainer picket interfaces is essential to performance. Lubricant for this purpose can be provided by passive means during the design life as long as on-orbit conditions do not vary from the design predictions.

For long life requirements and a premature lubricant depletion from the bearing cavity, a commandable oiler to replenish the lubricant, when necessary, becomes increasingly desirable.

The basic design constraint in active oiling is to deliver all of the lubricant in a small metered charge uniformly to the ball pockets and to the contact zones of both the inner and outer races. These regions are not easily accessed. Preferably, the lubrication should be done slowly by a device which is compatible with unmodified bearings and does not introduce contamination or torque transients. The knowledge of the frequency of oiling is also an important constraint which must be determined from periodic monitoring of the shaft torque, bearing temperature, lubricant film thickness, and the payload stability criteria, if appropriate.

Review of literature indicates several design ideas for the oil applicator system. None of these, however, appears to be sufficiently developed for space usage. The indicated need and the present design status are the basic motivating factors in the recommendation of serious development of a commandable oil applicator. The scope of the developmental program should not only include the implementation of an active oiler mechanism for space flight applications, but also should consider lubricant transfer modeling of passive lubrication schemes which should retain their present status of basic replenishment sources.

### Drivers

The key drivers for this technology are:

1) Continued use for conventional bearings in medium to high speed rotational mechanisms.

2) Extended operational life in excess of 8 years.

3) Operation or reoperation following extended storage or inactivity in space-retrieval.

4) Extreme thermal environments

- Shuttle
- Cryogenic systems coolers.

Major Areas of Application

1) Lubrication for momentum wheels, reaction wheels, scanners.

2) Lubrication systems for actuators (motors, gears, bearings) for one-shot limited duty cycle devices activated after long time storage in the space environment.

3) Tribology considerations for devices operated at cryogenic temperatures.

Rationale

The rationale for technology development includes:

1) Difficulty in assuring more than 8 years life with existing one-shot lubrication techniques.

2) No assurance that power will be available to heat actuators at end of life in orbit.

3) Self-lubricating materials must be resistant to cold flow type problems.

4) Tribology considerations for operations of mechanisms at cryogenic temperatures. Heaters are not usable on devices.

Recommendation

The recommendations of the panel include:

1) Forced feed lubrication systems for conventional bearings.

2) Develop techniques to assure a metered replenishment of oil to the bearing surfaces.

3) Develop technology and/or sensors to determine need for relubrication.

4) Develop sensors or techniques to detect reduction in oil film on bearing surfaces.

5) Lubricants or materials for use in bearings and gears compatible with the extended storage in space prior to reactivation or retrieval.

6) Materials for long life storage

- Changes in physical properties
- Outgassing considerations
- Long-term storage under stress (cold flow).

7) Develop technology for mechanisms, actuators operating at cryogenic temperatures.

8) Obtain an understanding of sliding or rolling contact at cryogenic temperatures.

## Signal and Power Transfer Devices

### Background

As spacecraft systems become more active, higher torque margins between the driver and the various load sources are required. Tighter positional accuracy also places a stronger emphasis on reduced load torques. These existing deficiencies place new demands upon electrical transfer devices. As magnetic bearings become recognized suspension elements in future spacecraft, their inherently low and noise free torque characteristics and longer life can best be utilized if improved electrical transfer devices are developed. Increased ball bearing life will also result from improved lubrication technology and will require compatible electrical transfer improvements for these systems. New and wider operating temperature requirements also place new demands on electrical transfer devices.

### Specifics

Signal transfer devices must not only be improved to correct these deficiencies listed but must also be capable of transferring greater data rates. Many new technologies now exist which should be explored in greater depth in this regard. Non-contacting signal coupling may be optical, RF, magnetic or capacitive. The optical and magnetic coupling have become, or will soon be, space qualified. The signals, which are converted to AC to be compatible with the interface are processed on either side of the interface as required. Rolling contacts provide an alternate means of signal transfer.

It is recommended that a development program be conducted consisting of an initial compilation of existing technology followed by actual brassboard testing of prime candidates. This second brassboard phase would include environmental and life testing. In the initial phase the inherent advantages and disadvantages of both contacting and non-contacting signal transfer devices would be compiled and specific risk, performance and environmental factors established. It is probable that the variety of both existing and future applications may identify more than one candidate for brassboard development and test in the second phase.

Power transfer devices must also be improved to correct the deficiencies of torque margin, positional accuracy and life and to accommodate the new temperature requirements as stated in the "Background" discussion. These improved devices must consider both magnetic suspensions and ball bearing configurations. Although it is true that new technologies exist for power transfer, some of the candidates listed for signal transfer are either not applicable or are not as mature. Magnetic power transfer coupling for instance by means of rotary transformers requires new technology development for future power requirements. Until power lasers become sufficiently mature optical power coupling is not a candidate. Although it is improbable that capacitive and RF coupling can be utilized for power transfer even at higher frequencies, they should be considered as candidates in the initial phase. In the contacting category, rolling contacts, because of other unique advantages, are another power transfer candidate.

It is recommended that a two-phase development program be conducted identical to that recommended for the improved signal transfer device. This program differs, however, from the standpoint of technology requirements since it is much less mature at this time. This technology study should not only consider power transfer candidates on the basis of risk, performance and environmental factors but power efficiency as well since a low efficiency results in undesirable thermal and power characteristics.

## Servo Sensing Devices

### Background

As future missions are defined, the need for more stable and more accurate servo performance requirements emerge. Past experience in the servo control area has identified the fact that a feedback servo control loop can never perform any better than its feedback sensor. In addition servo design has been compromised by and servo performance has been restricted by the presence of undesirable frictional and "spring" load torques. With the development of magnetic bearings and the application of flexural pivots, the need for sensors consistent with non-contacting technologies is amplified. The application of microprocessors to servo control loops results in the need for sensors directly compatible with microprocessor interfaces.

The recommendation is to apply funds to support the evaluation and improvement of existing sensors and development of new sensors with finer accuracy, non-contacting mechanical designs, direct microprocessor compatibility, and improved temperature range and life. Some examples follow:

### Zero Ripple Torque Motor

Torque ripple is characteristic of motors, which poses some difficulties in meeting high performance servo requirements. There have been several approaches which can potentially eliminate this problem: (1) Magnetic field shaping which requires special motor design; (2) Control sensing techniques which require sensing instantaneous flux distribution (or generated voltage) and current. These approaches should be evaluated and the most universal and cost-effective solution developed and qualified.

### Shaft Encoding Devices

Implementation of high accuracy pointing systems (1 to 2 arc-sec) requires displacement transducing devices capable of encoding a fraction of one arc-sec.

At the present time, there are optical encoders which can fulfill such a function. However, their geometric size, weight and excessive power consumption make them unsuitable for applications where low power and weight are the dominant constraints.

Since the basic contributor to the encoder errors is its ball bearing suspension and since it is not possible to further enhance the performance of the ball bearings, magnetically suspended encoder elements are suggested.

The developmental scope of such a device should emphasize:

- Small size and light weight
- Low power consumption
- Active correlation of the transduced signal with the measured bearing errors.

Scanned Encoder

An incremental optical shaft encoder, if equipped with an array of light source/detectors instead of a discrete readout station, would be useful at all speeds including zero and have an increased resolution by a factor of 8 to 10. A monolithic array of detectors is necessary to obtain the positional accuracy necessary to subdivide the least bit of resolution of the optical disc. Electronically scanning the detector array at a rate outside the physical rotation rate of interest would make all rate measurements relative to the (crystal controlled) scan frequency. Thus a high information rate needed for direct compatibility with digital (microprocessor) control would be obtained.

Servo Sensing Devices

The development drivers for image sensors include:

- Improved reliability
- High accuracy
- Longer life
- Multi-mission usage

One of the major problems with present star trackers is a common high voltage failure (HEAO-2 being the latest). The high voltage is necessary to operate the sensor used in the tracker, that is, the image dissector tube (IDT). Star trackers using the IDT have achieved noise-limited performance and meet most accuracy requirements of present systems. The fact that these IDT trackers have achieved noise-limited performance in effect means that star accuracy cannot be improved with an IDT. (The IDT is approximately 15 years old).

During the past several years, solid state sensor (SSS) arrays have been in the process of being developed. These arrays operate with low voltage which would eliminate the failure mode of the IDT. Analytical studies have been made that have found a number of other distinct advantages that the SSS has over the IDT:

- Higher quantum efficiency
- Magnetic field immunity
- Broader spectral response
- Greater linearity
- Digital output

However, with all the potential advantages of the SSS they are not directly applicable to star trackers. This is due primarily to the fact that the major development work on the SSS has been directed toward TV cameras. Although many of the requirements for the SSS are the same there is a major difference, that is, the method used to obtain the output. For the TV mode, elements are raster scanned with the video shifted out sequentially. For star trackers a raster scan is required until a star is detected; at this point a random access readout is desirable so that the video of the star image can be shifted out at a low rate; that is, only the elements with the star image are shifted out.

Recommendation

The recommendation made by the panel includes the need to customize a solid-state sensor with random access of data suitable for star tracker applications.

## Deployment and Retraction Mechanism

The development drivers for developing technology for deployment and retraction mechanism include:

1) Past history of problems.

2) Increased usage of deployables considering launch cost and size of structures.

3) Retractability required for Shuttle.

The major areas or needs include:

1) Deployment mechanism for non-retractable devices.

2) Deployment mechanism for retractable devices.

The primary recommendation made by the panel is to develop a Standard Deployment Mechanism. This will involve the design, fabrication and testing of a Representative Deployment Mechanism considering the following variable component philosophy:

1) Variable Rate Required
   a) Damper
   b) Motors

2) Variable Torque
   a) Springs
   b) Motor

3) Type of Deployment
   a) Permanent
      i) Restraint and release mechanism
      ii) Latching mechanism
   b) Retractable
      i) Beginning and end of travel restraint
      ii) Beginning and end of travel release

4) Hinge Selectability
   a) Bearing size
   b) Shaft size

5) Lubrication Selectability
   a) Permanently deployed
   b) Retractable - long life required

6) Continuous positioning sensing

7) Other Considerations
   a) Thermal environment
   b) Launch loads
   c) Redundancy
   d) Testability of the deployable

Additional rationale for the development is that:

1) Currently no design standards exist

2) Variable design allows for tailoring to the particular application

3) Current problems can usually be traced to the deployment mechanism, not the deployable

## Cryogenic Devices and Materials

### Deficiency

In order to obtain increases in accuracy and sensitivity the trend in detectors is toward operation at cryogenic temperatures. This imposes new and specialized demands on materials and devices used in this environment. Problem areas include thermal expansion and contraction causing high stresses and failure, embrittlements causing failure due to thermal shock and/or fatigue, severely limiting lifetime, and binding or leakage due to material shrinkage or hardening. The lack of knowledge as to the characteristics and behavior of material at cryogenic temperatures is a major problem to the design.

The basis for the Panel's recommendations does not include any flight deficiencies since little prior flight experience exists. The requirements stem from the need for active devices, primarily scientific instruments and scanning devices, in a new environment which precludes conventional lubrication and where thermal dissipation must be kept to extremely low values (refrigeration requires 1000 W/W of dissipation).

### Development Required

Methods to characterize properties of materials at cryogenic temperatures are needed. The identification or development of materials that will retain those properties at the low temperatures are needed. These materials include adhesives, lubricants, and flexible materials for seals and dynamic isolation. Devices that are needed would include actuators and control devices.

New development is required in suspension systems which require no lubrication such as flexures or magnetics. Suspension of moving elements by these means further requires caging devices to survive the launch environment. Passage of signals and power to moving devices while preserving low thermal conductivity will require non-contacting or intermittent contacts. The materials themselves need special selection due to thermal coefficient of expansion, brittleness, and conductivity requirements. For the electromagnetic devices which can take advantage of the low and zero resistance state, however, switching and control of currents is a unique problem area. The design of electromagnetic devices to make practical use of the superconducting state is still in its infancy.

### Recommendation

It is recommended first that from the standpoint of materials that a test program be started to identify and characterize the properties of existing materials at cryogenic temperatures. This would provide the necessary data for the designers and would identify where deficiencies exist. A materials development program, leading to materials to satisfy the needs, could then be structured.

Basic work needs to be done on the design and control of actuators and suspension techniques at superconducting temperatures.

## Cryogenic Coolers

### Development Drivers

The need for lower temperatures and greater thermal load capacity than that which can be provided by small passive coolers is already being felt as larger (array) detectors become available and the need to cool the optics as well as the detectors themselves becomes apparent. Alternative approaches such as solid cryogens have obvious life limitations.

The prospects of very small low power computers of huge capacity operating at cryogenic temperatures are being evaluated.

### Major Areas

Mechanical coolers exist which have the requisite thermodynamic performance but which are not capable of long term unattended operation and which impose dynamic disturbances which adversely affect the instrument application and the spacecraft. In small sizes these are reciprocating devices and need to be designed to eliminate rotary to linear conversion and sliding contact seals and bearings, and to incorporate dynamic balancing. Multiple state or combined cycle machines (e.g., mechanical and magnetic) need to be developed to extend the range of temperatures down to liquid helium.

### Recommendation

It is recognized that programs are already in progress to develop the necessary technology in this area. The continuation of these developments should be supported.

## Digital Servo Electronics

### Deficiency

Rather than a deficiency of prior flight history, the new capability offered by digital control was amply demonstrated by the saving of the first DMSP Block 5D spacecraft by in-flight reprogramming of the entire control system. The applicability of these techniques to achieve significantly better performance in electromechanical systems was exemplified by an arc-sec stepping scanner. Reprogrammability in the Shuttle era to permit parameter changes to accommodate mission-to-mission and instrument complement changes between flights without hardware changes is crucial. While abundant attention has been paid to microprocessors and related software, the power level interface with electromagnetic actuators has seen little attention.

### Development Required

The development required includes:

1) Monolithic construction and packaging of 2-phase and 3-phase power switching modules employing the latest power-FET technology and fast recovery diodes.

2) Monolithic integrated circuit decoding devices for motor commutation and stepper motor sequencing.

3) Programmable digital servo compensation circuits with feedback sensor compatibility.

Recommendation

The recommendation made by the Panel includes:

1) Evaluate currently used discrete and analog circuitry presently used for these repetitive functions.

2) Develop programmable circuits in monolithic form which provide all the essential motor control functions and qualify them as preferred parts.

3) Document and disseminate specifications and user guidelines for these devices.

Rationale

Numerous flight programs have not used current state-of-the-art technology for short term or non-mission critical applications because of cost or availability - many otherwise competent suppliers of electromechanical devices do not have electronic expertise or resources to provide these devices in any form. Flight programs for instruments and major spacecraft components expend considerable resources developing functionally identical circuitry yet, because of the low quantities in each application are often not providing the proven reliability, size, power, and performance advantages afforded by large- or medium-scale integration. The present switch to microprocessor-based systems makes this an opportune time to meet the Shuttle era's need for reprogrammability and conserve resources on many individual instrument and spacecraft programs.

The following areas were also discussed by the Panel and determined to be worthy of consideration for future technology development. However, the preceding areas are considered significantly more important than the ones that follow.

## Ordnance Substitute

Deficiency

Laboratory testing has shown that pyrotechnic actuators and release mechanisms are prone to leak, especially after firing, which builds extreme internal pressures. This situation has not appreciably improved over the years and the resultant contamination is of great concern in radiometric and other sensing systems.

## Development Needed

A high force lightweight electrically triggerable actuator is needed. It should be reusable to permit test verification. A candidate device is available commercially with some flight history as a magnetometer "flipper". The commercial device requires an electrical heater and special insulation for this purpose, since it is used as an automobile thermostat. Minimal development would be required to evaluate and qualify it as a release element. With some further development it potentially could provide the controlled rate deployment which is sought to eliminate leak prone viscous dampers on antenna, array, and boom deployment.

## Recommendation

The recommendations include:

1) Evaluate "wax pellet" actuators for release and one-shot actuation requirements.
2) Develop rate controlled deployment and retraction actuators based on the same design concept.

## Rationale

A low-cost device may be a safer, testable, and reusable alternative avoiding some of the perennial problems of explosive devices. Relatively small development might suit the same concept to other more sophisticated requirements.

# Tape Transports for Data Storage

## Development Drivers

The development drivers include:

1) Past flight experience in the performance of these devices has, in general, been poor. Poor performance primarily is in short life and high noise.
2) Spacecraft continued growth places a demand on increased storage capacity and redundancy.

## Recommendation

There is no recommendation in the area of electromechanical new technology design. The belief of the committee is that these devices will ultimately be replaced by passive electrical devices and all new development effort should point in that direction.

## SUMMARY OF RECOMMENDATIONS

The recommendations made by the panel for each of the technology deficiencies or technology problem areas are summarized in the following paragraphs.

### Magnetic Bearings

1) Conduct flight demonstration of momentum wheels with magnetic bearings.

2) Apply magnetic bearing technology to scanning instruments and instrument package platforms.

3) Investigate use of magnetic suspension at cryogenic temperatures.

4) Develop magnetically suspended nutation damper.

### Lubrication

1) Develop forced feed lubrication system for ball bearings.

2) Develop sensors to determine need for re-lubrication.

3) Investigate lubricants and materials for bearings and gears to be operated after extended storage in orbit, and/or operation at cryogenic temperatures.

### Signal and Power Transfer Devices

1) Conduct comparative evaluation of existing technology to select candidate approaches.

2) Develop brassboards and test prime candidates.

3) Space qualify best candidates.

## Servo Sensing Devices

1) Evaluate and improve existing sensors.

2) Develop new sensors, such as:

   a) Active magnetic suspension that will support an encoder with minimum runout and yield accuracies to less than an arc-second

   b) Zero ripple torque motor

   c) Encoder with scanned array

   d) Monolithic IC sensors

## Deployment and Retraction Mechanisms

1) Develop universal deployment mechanism concepts.

   a) Testable in 1G environment

   b) Optimum from overall system standpoint

2) Fabricate, test and space qualify representative configurations.

## Cryogenic Devices

1) Characterize materials and electronic devices at cryogenic temperatures.

2) Continue development of mechanical cooler.

3) Develop technology for operating at cryogenic temperatures.

   a) Superconducting motors and control devices

   b) Actuators and suspension devices

   c) Thermal switches

## Digital Servo Electronics

1) Fabricate and qualify:

   a) Motor commutation and stepper logic circuits in monolithic form using power FET's and fast diode technology.

   b) Programmable digital servo compensation IC's with feedback sensor compatibility.