ADVANCED MAGNETIC SUSPENSIONS for VIBRATION ISOLATION and FAST-ATTITUDE CONTROL of SPACE-BASED GENERIC POINTING MOUNTS

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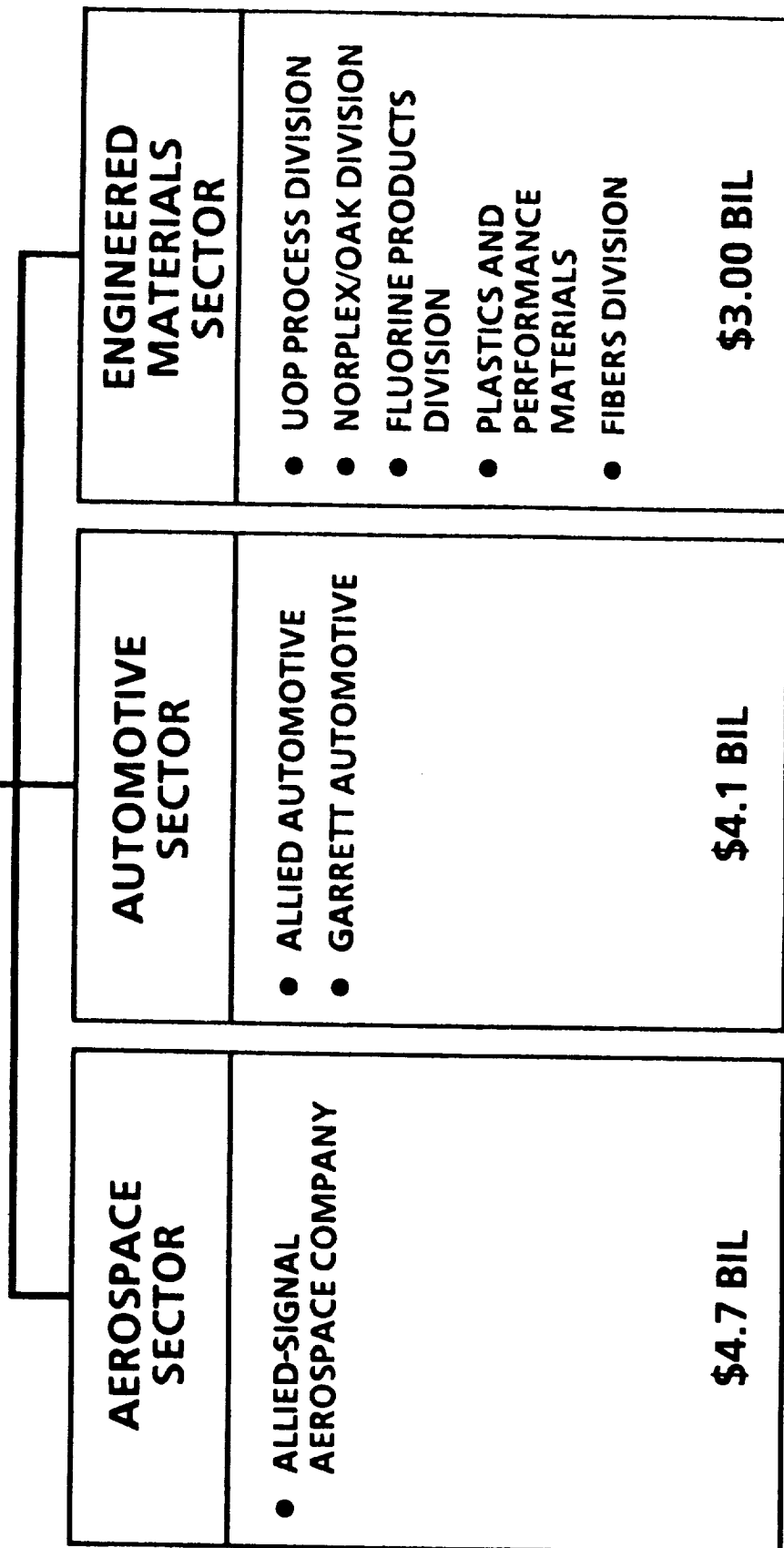
Torrance

CA 90509-2960

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ALLIED SIGNAL, INC
1988 SALES $11.9 BIL

EMPLOYEES   110,000

LISTED IN FORTUNE'S TOP
50 U.S. INDUSTRIAL COMPANIES

AN ADVANCED TECHNOLOGY
COMPANY WHOSE PRIMARY
BUSINESSES ARE IN
AEROSPACE/ELECTRONICS,
AUTOMOTIVE, AND ENGINEERED
MATERIALS

AEROSPACE SECTOR

- ALLIED-SIGNAL
  AEROSPACE COMPANY

$4.7 BIL

AUTOMOTIVE SECTOR

- ALLIED AUTOMOTIVE
- GARRETT AUTOMOTIVE

$4.1 BIL

ENGINEERED MATERIALS SECTOR

- UOP PROCESS DIVISION
- NORPLEX/OAK DIVISION
- FLUORINE PRODUCTS DIVISION
- PLASTICS AND PERFORMANCE MATERIALS
- FIBERS DIVISION

$3.00 BIL

B-12112
FG-02086

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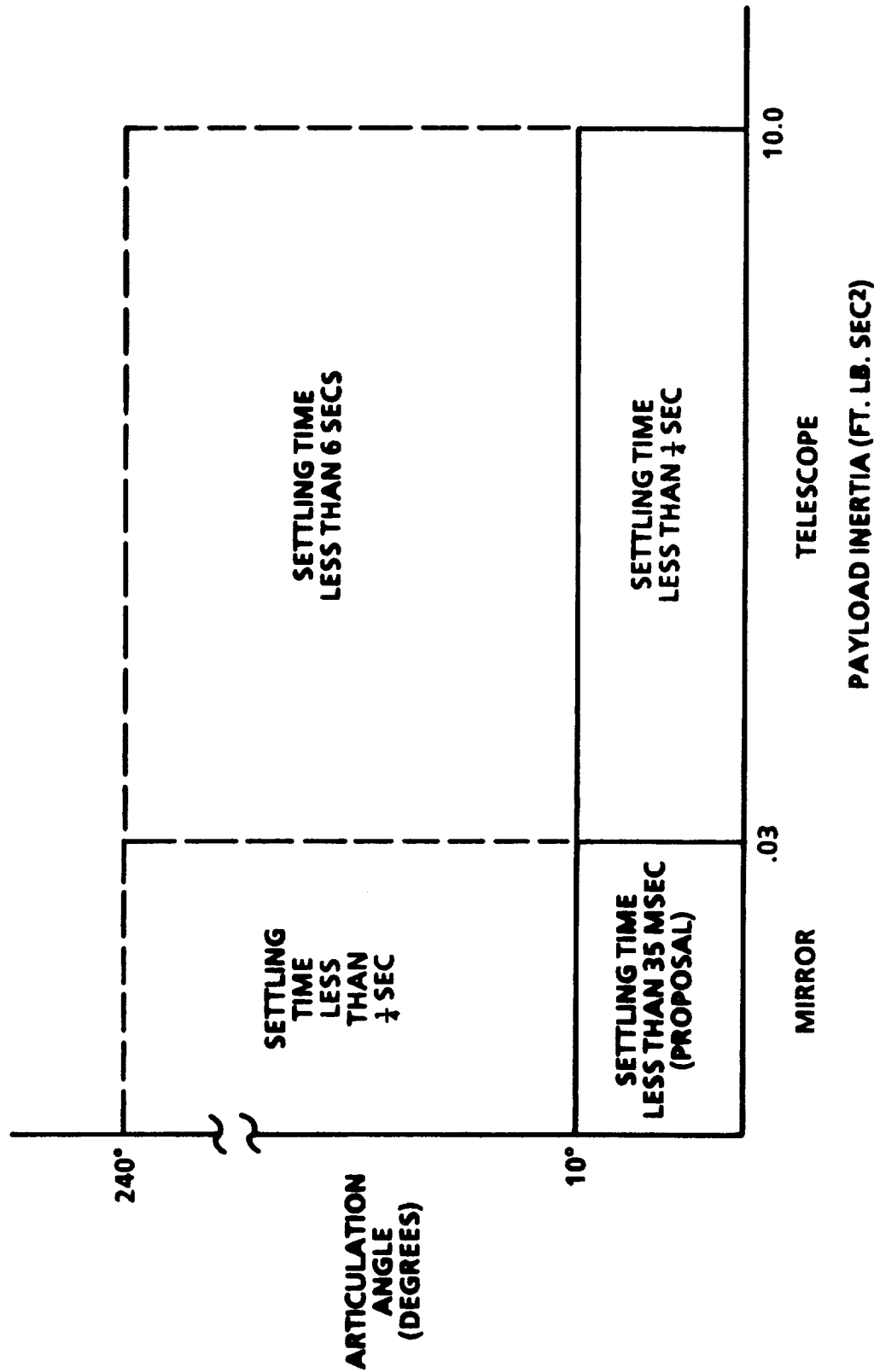
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DESIGN CRITERIA FOR GENERIC POINTING MOUNTS

- **POINTING PAYLOAD:**
  - SMALL (ounces)
  - LARGE (tons)

- **AUTOMATICALLY ADAPT SERVO SYSTEM CONTROL LAWS TO INTERCHANGEABLE PAYLOADS**

- **CONTINUOUSLY ADAPT CONTROL LAWS TO POINTING ERRORS (POSITION, VELOCITY & ACCELERATION)**

- **ARTICULATION ANGLES UP TO 240 DEGREES**

- **TRANSMIT POWER/COMMANDS/DATA TO PAYLOAD WITHOUT CABLES**

- **MINIMIZE DATA RATE REQUIREMENT FOR INTERFACING WITH SPACE CRAFT**

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DESIGN CRITERIA FOR GENERIC POINTING MOUNTS

THE GENERIC POINTING MOUNT IS DESIGNED TO AIM A VARIETY OF INTERCHANGEABLE POINTING
PAYLOADS USING MAGNETIC SUSPENSION AND ADAPTIVE CONTROL TECHNOLOGIES.   TO CHANGE PAYLOADS
REQUIRES ONLY THE MECHANICAL DETACHMENT OF THE OLD PAYLOAD AND THE ATTACHMENT OF THE NEW
PAYLOAD.   THE MOUNT'S SERVO SYSTEM AUTOMATICALLY SENSES THE CHANGE IN THE PAYLOAD AND
MEASURES THE MULTIAXIS INERTIAS AND RESONANT CHARACTERISTICS OF THE NEW PAYLOAD.   THE
SERVO SYSTEM AUTOMATICALLY AND CONTINUOUSLY ADAPTS THE SERVO CONTROL LAWS TO OPTIMIZE THE
ISOLATION OF THE PAYLOAD FROM SPACECRAFT VIBRATIONS, TO OPTIMIZE THE DAMPING OF PAYLOAD
RESONANCES, AND TO MINIMIZE THE POINTING ERROR SETTLING TIMES FOR EACH INTERCHANGEABLE
PAYLOAD AND AS THE VARIOUS MULTIAXIS POINTING ERRORS CHANGE WITH TIME.   THE TRANSMISSION
OF POWER AND COMMANDS TO THE PAYLOAD AND THE TRANSMISSION OF DATA FROM THE PAYLOAD ACROSS
THE MAGNETIC SUSPENSION GAP IS ACCOMPLISHED WITHOUT THE USE OF CABLES.   ARTICULATION IN
TIP, TILT AND ROLL AXES ALLOWS 75% OF THE SPHERICAL SKY TO BE WITHIN THE MOUNTS AIMING
CONE.   DATA COMMUNICATION RATES BETWEEN THE POINTING MOUNT AND THE SPACECRAFT ARE
MINIMIZED BY USE OF ARTICULATED AND NON ARTICULATED INERTIAL MEASUREMENT UNITS (IMU'S)
COUPLED TO SPACECRAFT ORBIT AND ATTITUDE COMPUTATIONAL UNITS.

WHY IS THE PROPOSED DESIGN GENERIC?

ARTICULATION ANGLE (DEGREES)

240°

SETTLING TIME LESS THAN ¼ SEC

SETTLING TIME LESS THAN 6 SECS

10°

SETTLING TIME LESS THAN 35 MSEC (PROPOSAL)

SETTLING TIME LESS THAN ¼ SEC

MIRROR   .03   TELESCOPE   10.0

PAYLOAD INERTIA (FT. LB. SEC2)

*SETTLING TIME IS FOR SIX ORDERS OF MAGNITUDE ERROR REDUCTION

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WHY IS THE PROPOSED DESIGN GENERIC?

THE PROPOSED MOUNT IS GENERIC IN THAT IT CAN AIM EITHER LOW OR HIGH INERTIA PAYLOADS OVER REQUIRED ARTICULATION ANGLES THAT CAN RANGE FROM A FEW DEGREES TO 240 DEGREES. VARYING PAYLOAD INERTIA OR ARTICULATION ANGLE DOES AFFECT POINTING ERROR SETTLING TIME BUT DOES NOT AFFECT POINTING ACCURACY OR STABILITY. POINTING ERRORS CAN BE REDUCED BY SIX ORDERS OF MAGNITUDE FOR A MIRROR PAYLOAD HAVING AN INITIAL POINTING ERROR OF 10 DEGREES IN ONLY 35 MILLISECONDS. AS SHOWN, THE SETTLING TIME FOR THE MOST DEMANDING CONDITION (HIGH INERTIA, LARGE ARTICULATION ANGLE) DOES NOT EXCEED 6 SECONDS.

GENERIC POINTING MOUNT SYSTEM FEATURES

MEASURING PAYLOAD MECHANICAL IMPEDANCES	AUTOMATIC
CHANGING CONTROL LAWS TO MATCH PAYLOAD	STANDARD (IN SPACE)
VIBRATION ISOLATION	MASS DAMPING
VIBRATION DAMPING APPROACH	INERTIA VELOCITY ANTI-NODAL DAMPING FOR ALL PAYLOAD RESONANT MODES
MAXIMUM ARTICULATION ANGLE (TIP & TILT)	240°
POWER TRANSMISSION TO PAYLOAD	MICROWAVE
COMMANDS TO AND DATA FROM PAYLOAD	OPTICAL
GIMBALS	MAGNETIC
NUMBER OF PIVOT POINTS	ONE

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GENERIC POINTING MOUNT SYSTEM FEATURES

MOST OF THE FEATURES DESCRIPTIONS ARE SELF-EXPLANATORY, EXCEPT FOR VIBRATION ISOLATION AND VIBRATION DAMPING. CONVENTIONAL MAGNETIC SUSPENSIONS USE A PSEUDO VELOCITY SIGNAL (DERIVED BY LIMITED GAIN DIFFERENTIATION OF THE MEASURED GAP ACROSS THE SUSPENSION) IN THEIR CONTROL LOOPS TO ACHIEVE DAMPING OF STRUCTURAL RESONANT MODES. THEY ALSO USE SINGLE POINT IMPEDANCE CONTROL. THE GENERIC POINTING MOUNT USES THE INERTIALLY REFERENCED VELOCITY OF THE PAYLOAD TO ACHIEVE DAMPING AND USES AN APPROACH THAT EFFECTIVELY DAMPS ALL MODES AT THEIR ANTINODES REGARDLESS OF MODE SHAPE.

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GENERIC POINTING MOUNT
PERFORMANCE CHARACTERISTICS

PARAMETER	
SETTLING TIME: (10 TO 3X10^{-6} DEG)	0.0463 SEC
NUMBER OF CYCLES TO STEADY STATE	0.50 CYCLE
SLEW RATE	26.2 RAD/SEC
__BANDWIDTH__	
TRANSLATION RELATIVE TO INERTIAL FRAME	100 HZ
TRANSLATION RELATIVE TO PLATFORM	0.02 HZ
TIP	47.7 TO 450 HZ
TILT	47.7 TO 450 HZ

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GENERIC POINTING MOUNT
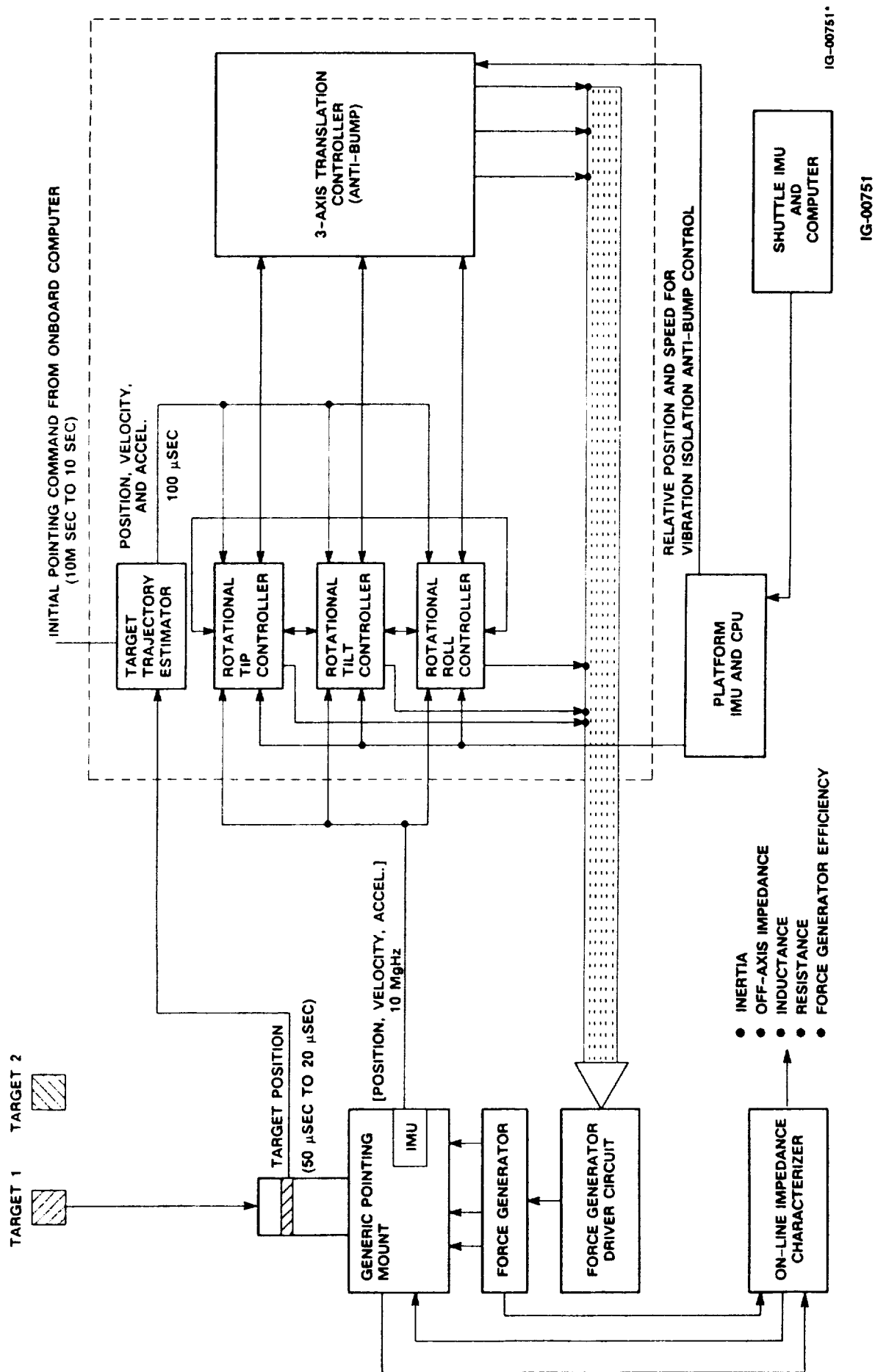# FUNCTIONAL BLOCK DIAGRAM

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IG-00751

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GENERIC POINTING MOUNT FUNCTIONAL BLOCK DIAGRAM

THE GENERIC POINTING MOUNT USES A SIX AXIS SERVO CONTROL TO ACHIEVE THE PROPER POINTING ANGLES AND TO PREVENT TRANSMISSION OF VIBRATION TO THE PAYLOAD. IT REQUIRES AN ARTICULATED IMU THAT MOVES WITH THE PAYLOAD. TO MINIMIZE THE NEED FOR SPACECRAFT ORBITAL AND ATTITUDE DATA, AN NON-ARTICULATED IMU IS USED. A MULTIDIMENSIONAL TARGET TRAJECTORY ESTIMATOR IS USED TO SPEED UP THE POINTING CONTROL LOOPS. SYSTEM PARAMETERS MAY CHANGE WITH TIME AND THE SERVOSYSTEM CAN BECOME NONLINEAR DUE TO MANY FACTORS (E.G., FORCE COIL VOLTAGE APPROACHING SUPPLY BUSS VOLTAGE). THEREFORE THE SERVOCONTROL MEASURES SYSTEM PARAMETERS ON-LINE WITH AN IMPEDANCE CHARACTERIZER TO PREDICT NONLINEARITIES BEFORE THEY ARE ENCOUNTERED.

GENERIC POINTING MOUNT
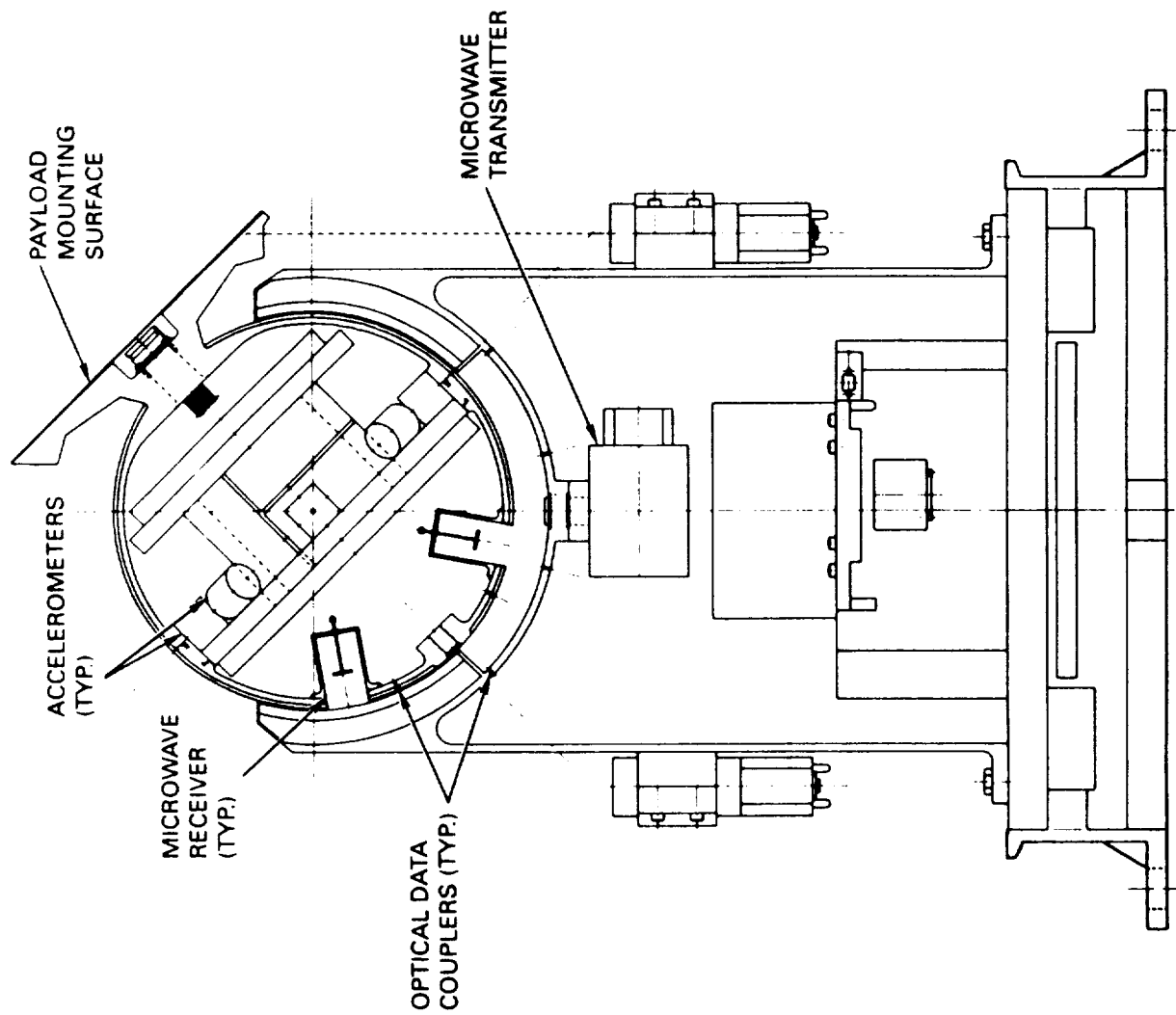
PAYLOAD
MOUNTING
SURFACE

MICROWAVE
TRANSMITTER

ACCELEROMETERS
(TYP.)

MICROWAVE
RECEIVER
(TYP.)

OPTICAL DATA
COUPLERS (TYP.)

B 16139

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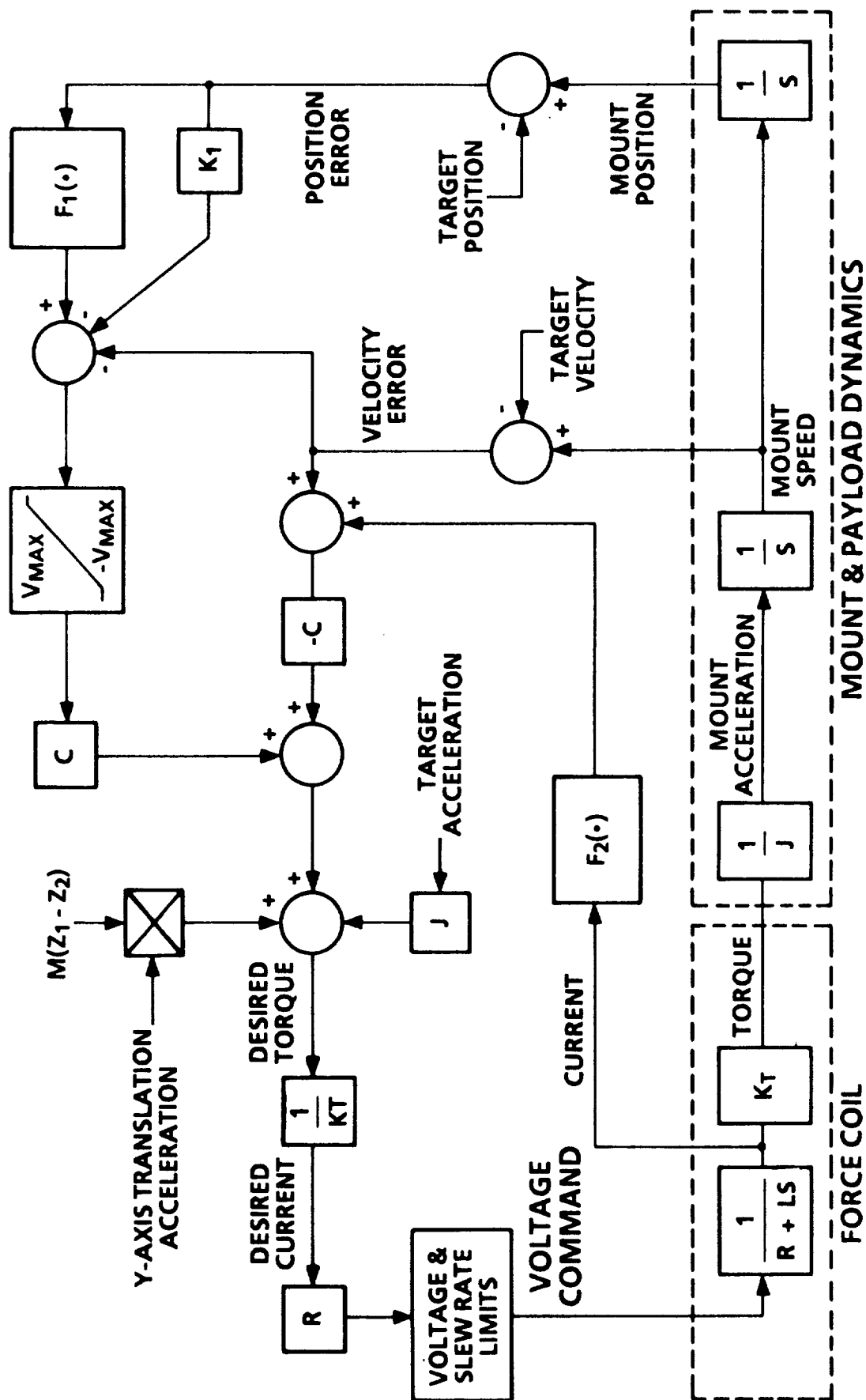
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GENERIC POINTING MOUNT

THE GENERIC POINTING MOUNT USES A SPHERICAL MAGNETIC FORCE/TORQUE GENERATOR TO APPLY
TORQUES IN THREE AXES AND TRANSLATIONAL FORCES IN THREE AXES TO A 10" SPHERE ATTACHED TO A
PAYLOAD MOUNTING SURFACE. THE SPHERE CAN ARTICULATE 120 DEGREES IN THE TIP AND TILT AXES
AND CAN ROTATE WITHOUT LIMIT IN THE ROLL AXIS. BY MOUNTING THE PAYLOAD AT A 60 DEGREE
ANGLE RELATIVE TO THE MOUNT AXIS, ROLLING THE PAYLOAD CAN ALLOW IT TO "LOOK OVER THE
HORIZON" AND THUS OBTAIN AN EFFECTIVE 240 DEGREE OF TIP AND TILT ARTICULATION. RING LASER
GYROSCOPES AND ACCELEROMETERS ARE USED BY BOTH IMU'S. POWER IS TRANSMITTED ACROSS THE
MAGNETIC SUSPENSION GAP BY MICROWAVES. COMMANDS AND DATA ARE TRANSMITTED ACROSS THE GAP
BY OPTICAL LINK ARRAYS. AUTO COLLIMATORS ARE USED TO CALIBRATE THE IMU'S. THE DESIGN IS
SCALABLE FOR LARGER SIZE PAYLOADS.

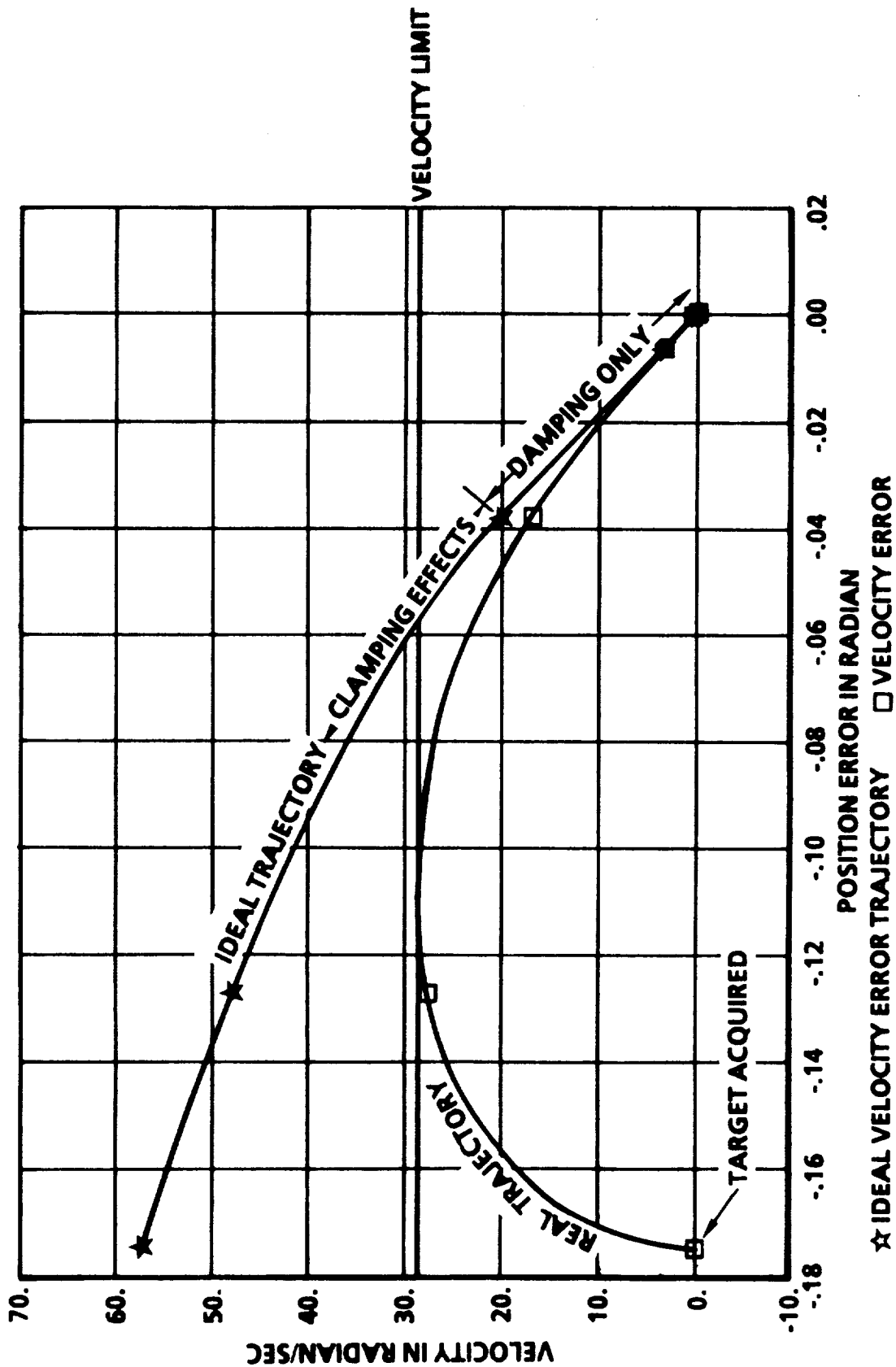# TIP AXIS ROTATIONAL CONTROL AND PLANT BLOCK DIAGRAM

POSITION ERROR

$F_1(\cdot)$

K_1

TARGET POSITION

MOUNT POSITION

$\frac{1}{S}$

VELOCITY ERROR

TARGET VELOCITY

MOUNT SPEED

V_{MAX} / $-V_{MAX}$

$-C$

C

TARGET ACCELERATION

$\frac{1}{S}$

$F_2(\cdot)$

MOUNT ACCELERATION

$\frac{1}{J}$

MOUNT & PAYLOAD DYNAMICS

$M(z_1 - z_2)$

Y-AXIS TRANSLATION ACCELERATION

DESIRED TORQUE

J

$\frac{1}{KT}$

DESIRED CURRENT

R

VOLTAGE & SLEW RATE LIMITS

VOLTAGE COMMAND

CURRENT

TORQUE

K_T

$\frac{1}{R + LS}$

FORCE COIL

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TIP AXIS ROTATIONAL CONTROL
AND PLANT BLOCK DIAGRAM

CONVENTIONAL MAGNETIC SUSPENSIONS CAN BE CHARACTERIZED AS MASS-SPRING-DAMPING RESONANT
SERVOSYSTEMS WHERE THE MASS IS PRIMARILY DUE TO THE PHYSICAL INERTIA OF THE SUSPEND
OBJECT, AND THE SPRING AND DAMPING ARE ESTABLISHED BY THE SERVOSYSTEMS SENSORS, CIRCUITRY
AND MAGNETIC FORCE GENERATORS. THE SERVOSYSTEM DAMPING CAN USUALLY BE EFFECTIVELY
ACHIEVED ONLY OVER A LIMITED FREQUENCY RANGE IF VELOCITY IS DERIVED BY DIFFERENTIATION.
IN CONTRAST, THE GENERIC POINTING MOUNT CAN BE CHARACTERIZED AS A MASS-DAMPING SYSTEM WITH
NO "CLASSICAL" SPRING. AN IDEAL VELOCITY ERROR IS CONTINUOUSLY DETERMINED AND SET AS A
SERVOSYSTEM OBJECTIVE FUNCTION TO ASSURE THAT ZERO ERROR FOR POSITION VELOCITY,
ACCELERATION, AND JERK CAN BE ACHIEVED SIMULTANEOUSLY. THIS ASSURES MINIMUM SETTLING
TIME. THE CALCULATION OF THE IDEAL VELOCITY HAS TO ACCOUNT FOR CLAMPS AND NONLINEARITIES
(E.G., LIMITED BUSS VOLTAGE, VELOCITY LIMITS ON GYROSCOPES, ETC.) THAT WILL BE ENCOUNTERED
DURING THE ENTIRE (FUTURE) PERIOD. THE SERVOSYSTEM APPLIES TORQUES AND FORCES TO PREVENT
POINTING ERRORS DUE TO FUTURE OFF-AXIS DISTURBANCES. THIS IS PRIMARILY DUE TO
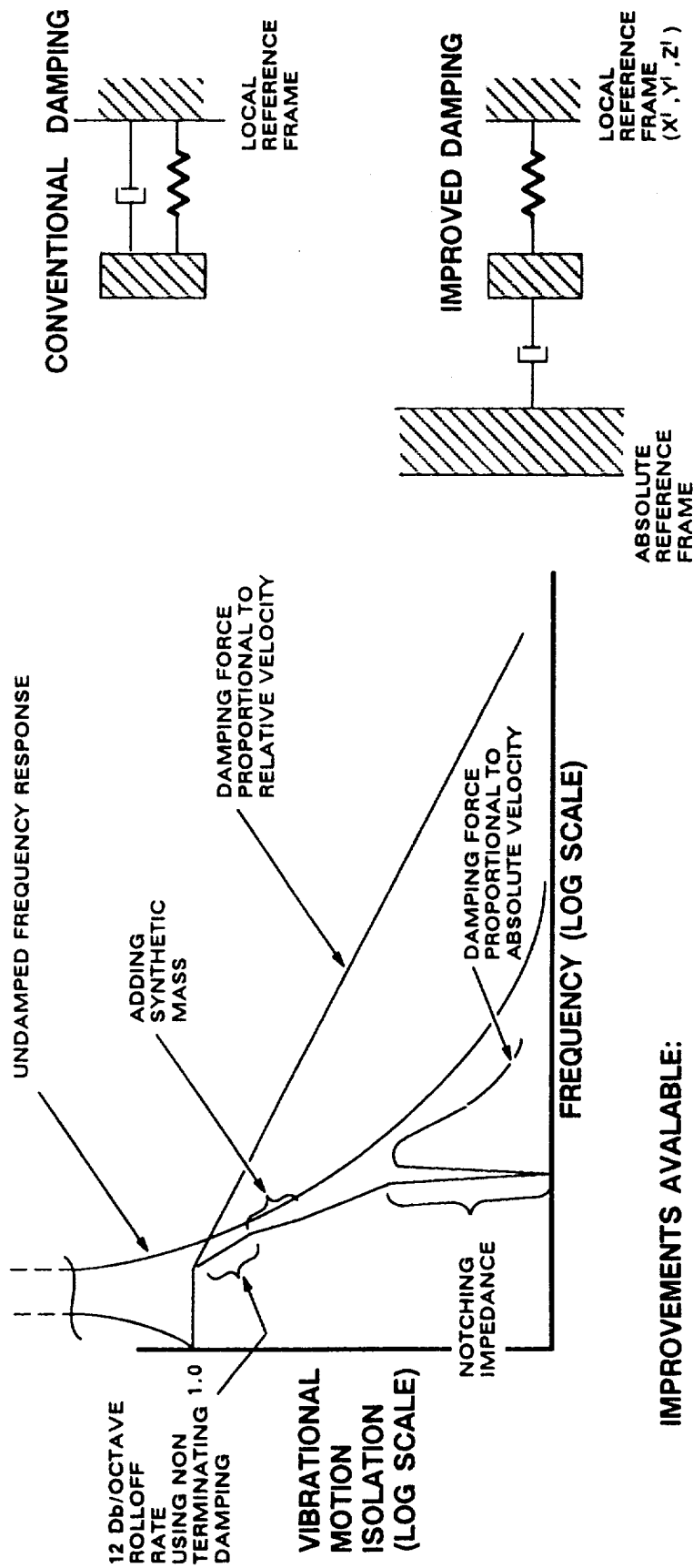NON-SYMMETRIES BETWEEN THE INERTIAS IN THE VARIOUS PAYLOAD AXES.

VELOCITY TRAJECTORY PLANNER

VELOCITY LIMIT

VELOCITY IN RADIAN/SEC

POSITION ERROR IN RADIAN

☆ IDEAL VELOCITY ERROR TRAJECTORY   □ VELOCITY ERROR

IDEAL TRAJECTORY — CLAMPING EFFECTS

DAMPING ONLY

REAL TRAJECTORY

TARGET ACQUIRED

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VELOCITY TRAJECTORY PLANNER

AT ANY GIVEN TIME, THE POINTING MOUNT AND PAYLOAD WILL HAVE MULTIPLE POINTING ERRORS
(POSITION, VELOCITY, ACCELERATION, JERK, VOLTAGE/CURRENT/FREQUENCY) IN BOTH THE TIP AND
TILT AXIS. SIMILAR ERRORS WILL ALSO EXIST IN THE ROLL AND THREE TRANSLATIONAL AXES. IT
IS DESIRABLE TO REDUCE ALL OF THESE ERRORS TO ZERO AT THE SAME TIME AND AS QUICKLY AS
POSSIBLE WITHOUT OSCILLATIONS. FOR A MASS-DAMPING SYSTEM THERE IS AN IDEAL RATIO OF
VELOCITY ERROR TO POSITION ERROR THAT WILL ZERO OUT ALL ERRORS AT THE SAME TIME. THIS
RATIO IS A FUNCTION OF THE INERTIA AND THE DAMPING CONSTANT. IF POSITION ERRORS ARE
SMALL, THE SERVOSYSTEM CAN OPERATE LINEARLY AND THE IDEAL VELOCITY ERROR WILL BE
PROPORTIONAL TO THE POSITION ERROR BUT WITH OPPOSITE SIGN. IF POSITION ERRORS ARE LARGE,
MANY NONLINEARITIES (E.G., VELOCITY OR VOLTAGE CLAMPS) CAN CAUSE THE IDEAL VELOCITY ERROR
TO BE A NONLINEAR FUNCTION OF POSITION ERROR. IF THE IDEAL VELOCITY IS EXCEEDED,
OVERSHOOT WILL OCCUR IN POSITION ERROR. IF THE VELOCITY PROFILE IS WELL BELOW THE IDEAL
TRAJECTORY, IT WILL CAUSE EXCESSIVE SETTLING TIMES.

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IMPROVED VIBRATION ISOLATION AND DAMPING

CONVENTIONAL DAMPING

LOCAL REFERENCE FRAME

IMPROVED DAMPING

LOCAL REFERENCE FRAME (X¹,Y¹,Z¹)

ABSOLUTE REFERENCE FRAME

UNDAMPED FREQUENCY RESPONSE

ADDING SYNTHETIC MASS

DAMPING FORCE PROPORTIONAL TO RELATIVE VELOCITY

DAMPING FORCE PROPORTIONAL TO ABSOLUTE VELOCITY

12 Db/OCTAVE ROLLOFF RATE USING NON TERMINATING 1.0 DAMPING

VIBRATIONAL MOTION ISOLATION (LOG SCALE)

NOTCHING IMPEDANCE

FREQUENCY (LOG SCALE)

IMPROVEMENTS AVALABLE:

- NOTCHED IMPEDANCE

- ANTI-NODAL DAMPING FOR ILL MODES

- ORTHOGONAL MODAL DAMPING

- INERTIAL MASS ENHANCEMENT

- FORCE REFLECTION

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IMPROVED VIBRATION ISOLATION AND DAMPING

MANY ADVANCED TECHNOLOGIES ARE AVAILABLE TO ISOLATE VIBRATION AND DAMP RESONANCES WITH MAGNETIC SUSPENSIONS. THESE INCLUDE:

● NOTCHING THE SUSPENSION IMPEDANCE TO ZERO AT THE FREQUENCIES OF KNOWN RESONANCES.

● DAMPING FLEXURAL CRITICALS SO AS TO SIMULATE ANTINODAL DAMPING REGARDLESS OF MODE SHAPE.

● CONTROLLING THE SUSPENSION IMPEDANCES TOTALLY INDEPENDENTLY FOR EACH RESONANCE. THIS CANNOT BE ACHIEVED WITH SINGLE POINT IMPEDANCE SUSPENSIONS.

● ENHANCE THE "APPARENT" INERTIAL MASS FOR SUSPENDED OBJECTS BY APPLYING MAGNETIC FORCES PROPORTIONAL TO ACCELERATION.

● REFLECT VIBRATIONAL FORCES THAT PASS THROUGH A SUSPENSION BACK TO THE SOURCE.

● INCREASE ROLL OFF RATE OF SUSPENSION ISOLATION VERSUS FREQUENCY BY USING INERTIALLY REFERENCED VELOCITY RATHER THAN RELATIVE VELOCITY FOR DAMPING.

POSITION RESPONSE NOMINAL CONDITIONS WITH TRAJECTORY PLANNER & LIMITERS
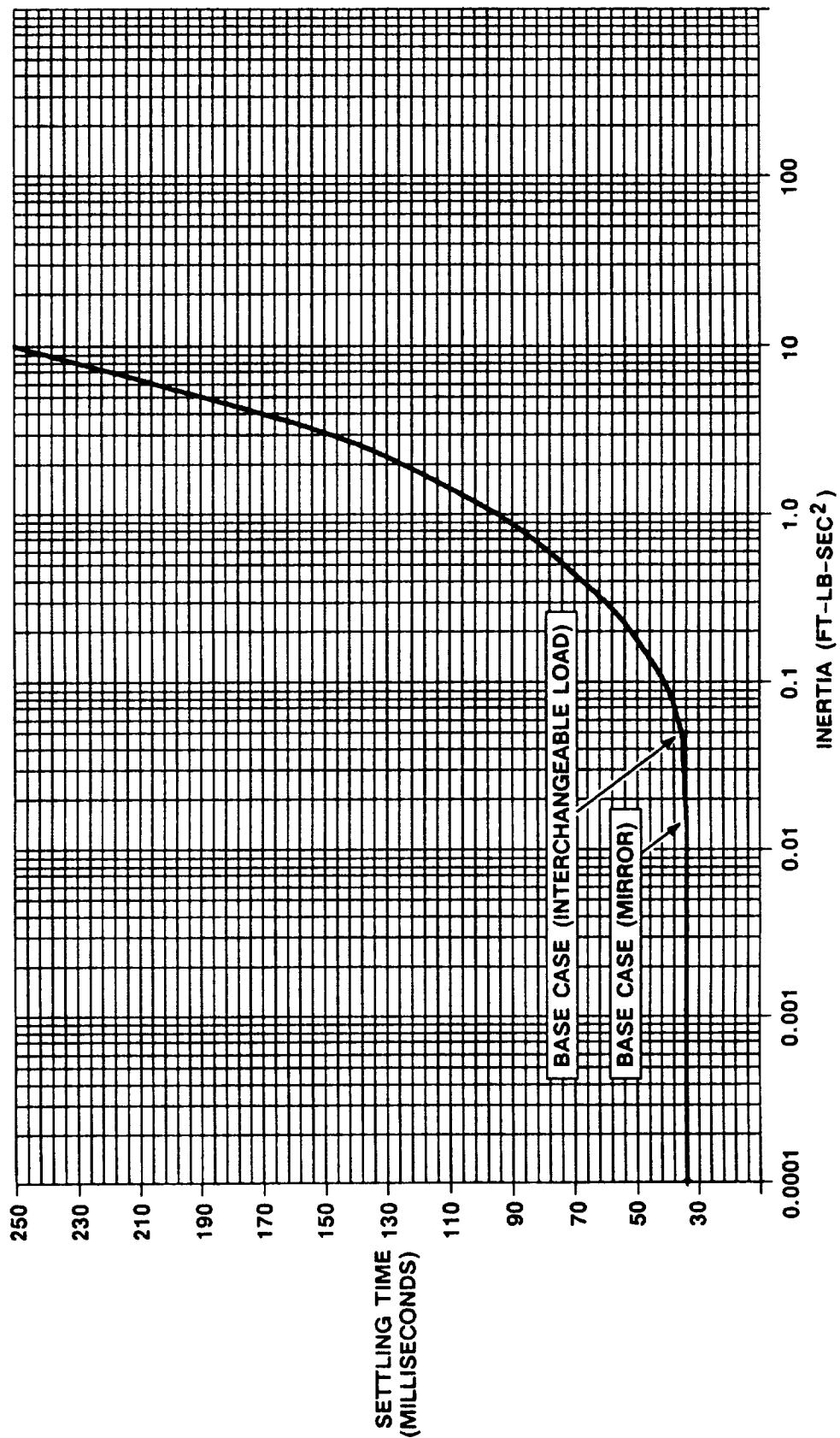

POSITION ERROR IN RADIANS

TIME IN SECONDS
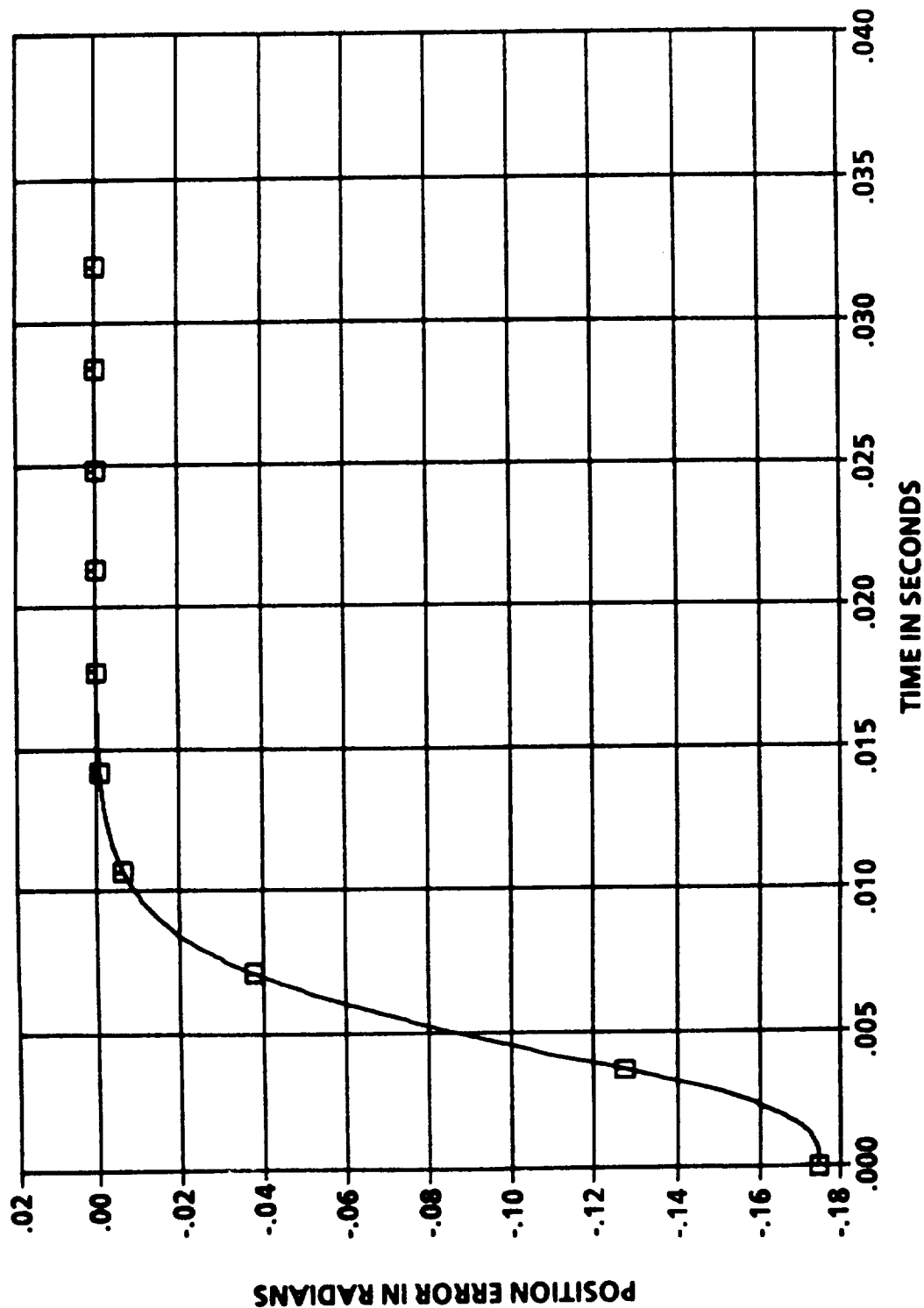
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POSITION RESPONSE NOMINAL CONDITIONS WITH
TRAJECTORY PLANNER & LIMITERS

THE GENERIC POINTING MOUNT CAN REDUCE POINTING ERRORS BY SIX ORDERS OF MAGNITUDE IN LESS
THAN 35 MILLISECONDS IF PRECISE AND ACCURATE SENSORS ARE UTILIZED.

SETTLING TIME VERSUS INERTIA

SETTLING TIME VERSUS INERTIA

BASE CASE (INTERCHANGEABLE LOAD)

BASE CASE (MIRROR)

INERTIA (FT–LB–SEC^2)

SETTLING TIME (MILLISECONDS)

SETTLING TIME VERSUS INERTIA

(FOR AN INITIAL 10 DEGREE POINTING ERROR)

INCREASING PAYLOAD INERTIA DOES NOT INCREASE SETTING TIME (FOR 6 ORDERS OF MAGNITUDE ERROR
REDUCTION) UNTIL THE MAGNETIC TORQUE GENERATOR BECOMES SATURATED. THE SETTLING INCREASES
NON-LINEARITY BEYOND THIS POINT

SETTLING TIME VERSUS INITIAL POSITION ERROR BASELINE CASE (MIRROR)

NOMINAL POINTING ERROR

SETTLING TIME (MILLISECONDS)

190
170
150
130
110
90
70
50
30
10

0.0001   0.001   0.01   0.1   1.0   10   100

INITIAL POSITION ERROR (DEGREES)
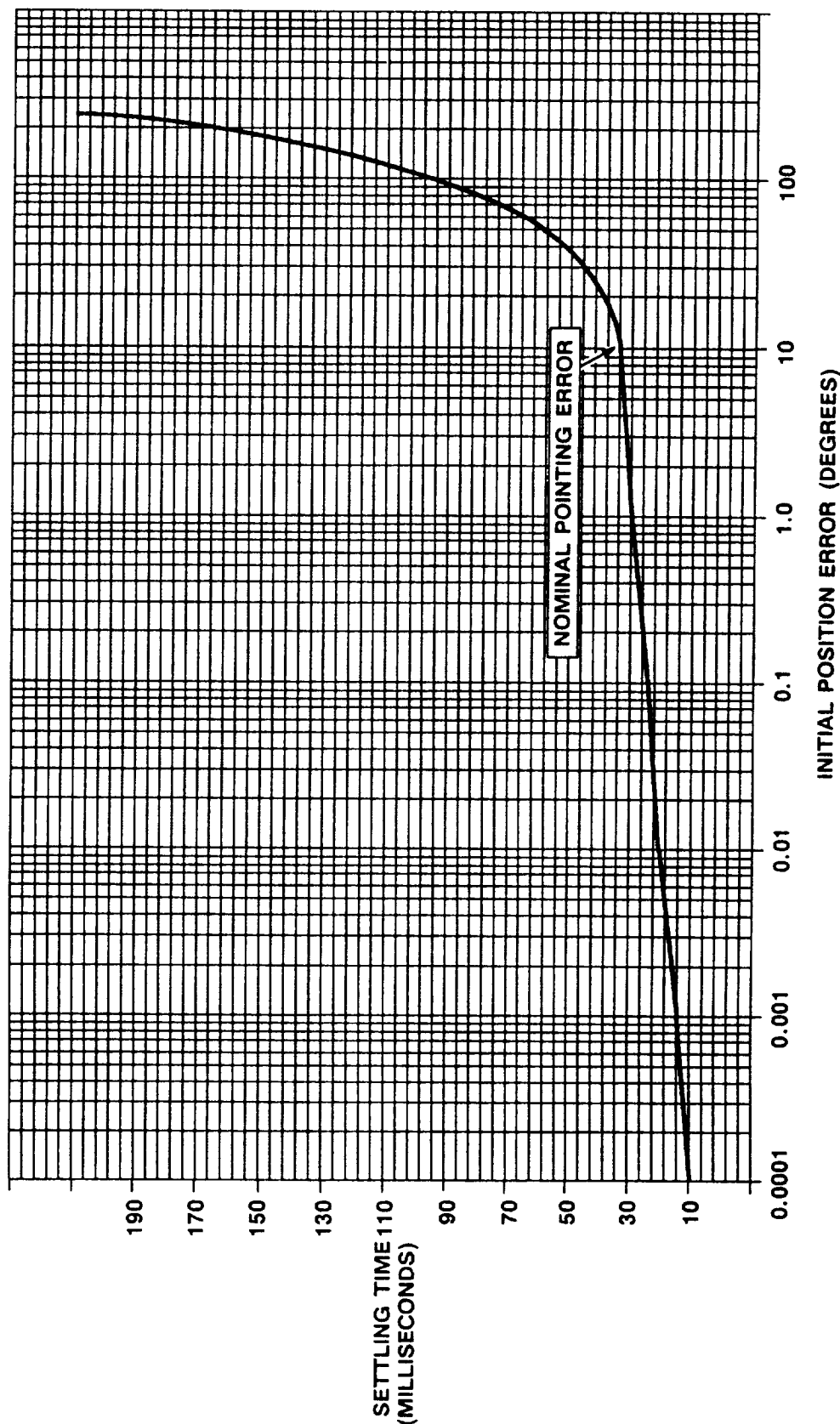
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SETTLING TIME VERSUS INITIAL POSITION ERROR
BASELINE CASE (MIRROR)

SETTLING TIME INCREASES ONLY AS A FUNCTION OF THE SQUARE ROOT OF INITIAL POSITION ERROR
UNTIL THE MAGNETIC TORQUE GENERATOR IS SATURATED. IT IS NON-LINEAR BEYOND THIS POINT.

SUMMARY OF SYSTEM FEATURES

- GENERIC POINTING MOUNT FOR INTERCHANGEABLE PAYLOADS

- SYSTEM AUTOMATICALLY ADAPTS CONTROL LAWS TO EACH PAYLOAD

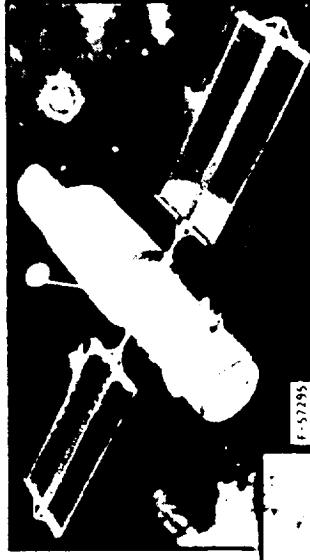- POINTING CONTROL IN THREE AXES AROUND A SINGLE PIVOT POINT

- 240-DEG ARTICULATION ANGLES
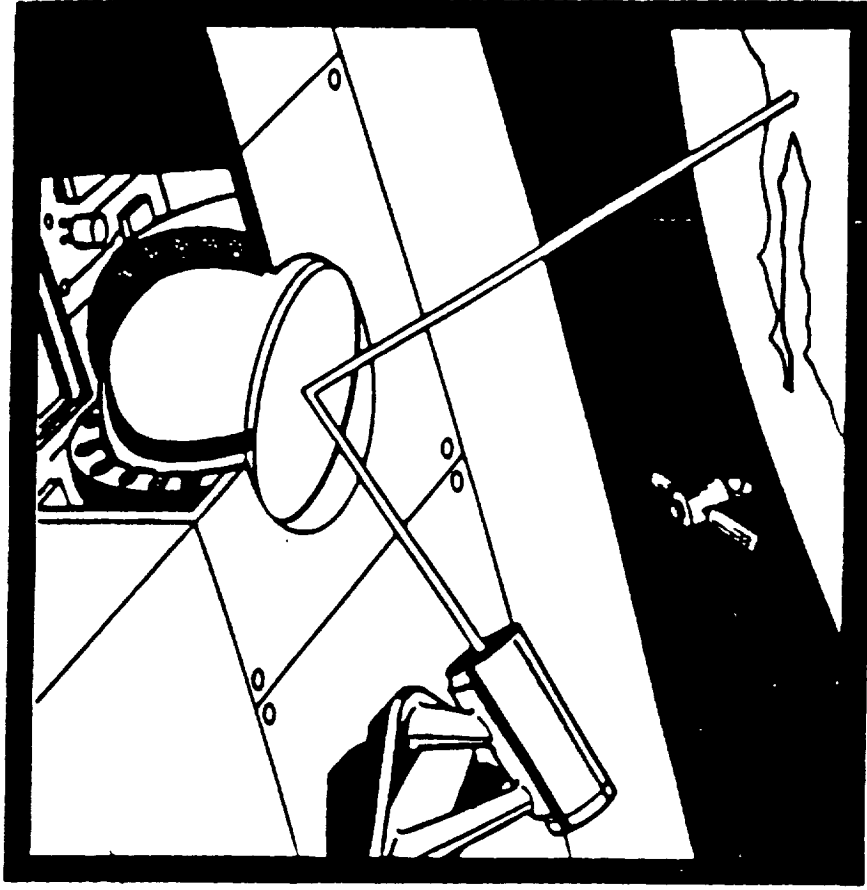
OTHER APPLICATIONS FOR GENERIC MAGNETIC SUSPENSION TECHNOLOGIES

MAGNETIC SUSPENSIONS PROVIDE IMPROVED:

- **ISOLATION AND POINTING**

- **VIBRATION CANCELLATION**

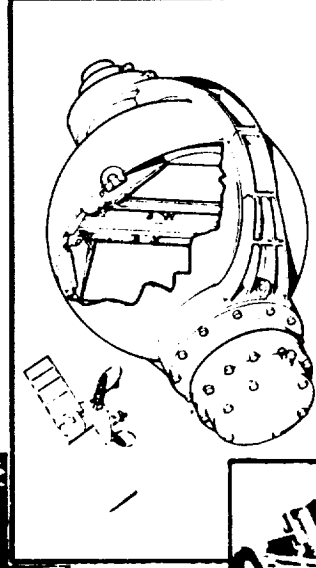- **BEARINGS**

SPACE TELESCOPES

F-57295

SHORT ROTORS

F-55795-E

SUBMARINES

F-57296

LONG ROTORS

A-96857

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