ROBUST PRECISION POINTING CONTROL OF LARGE SPACE PLATFORM PAYLOADS

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LSS CONTROLLER DESIGN STRATEGY

- INHERENT DAMPING PLAYS A VERY IMPORTANT ROLE IN STABILITY. THEREFORE IT IS HIGHLY DESIRABLE TO ENHANCE INHERENT DAMPING USING A SECONDARY CONTROLLER.

- DESIGN PRIMARY CONTROLLER FOR CONTROLLING RIGID-BODY MODES AND POSSIBLY SOME SELECTED STRUCTURAL MODES.

SECONDARY CONTROLLER - VELOCITY FEEDBACK

- FLEXIBLE PART OF DYNAMICS:

$$\underset{n_q \times 1}{\ddot{q}} + D\dot{q} + \Lambda q = \underset{n_q \times n_f}{\Phi^T} f$$

$$D = D^T \geq 0 \quad , \quad \Lambda = diag(\omega_1^2, \omega_2^2, \cdots, \omega_{n_q}^2)$$

- SENSOR OUTPUT:

$$y_r = \Phi \dot{q}$$

CONTROL LAW:

$$f = -K_r y_r = -K_r \Phi \dot{q}$$

- WITH PERFECT (LINEAR, INSTANTANEOUS) ACTUATORS/SENSORS:
  - STABLE IF $K_r \geq 0$
  - ASYMPTOTICALLY STABLE (AS) IF

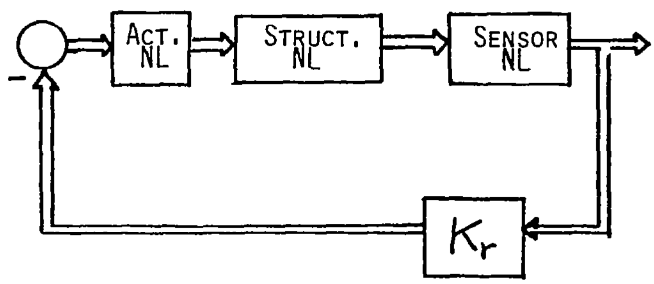
$K_r > 0$ AND (Λ, Φ^T) CONTROLLABLE

- WHAT IS THE EFFECT OF

  NONLINEARITIES

  ACTUATOR/SENSOR DYNAMICS

EFFECT OF SENSOR/ACTUATOR NONLINEARITIES:



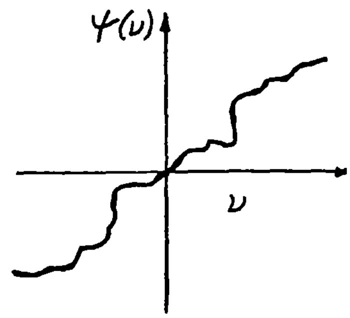
ACTUATOR NONLINEARITIES: LET $\psi_a(0) = 0$ $[\psi_a(a) = \text{ACTUATOR}]$

a) ORIGIN STABLE IF $\nu^T K_r^{-1} \psi_a(\nu) \geq 0$

b) ORIGIN ASIL* IF $\nu^T K_r^{-1} \psi_a(\nu) > 0$ for $\nu \neq 0$

AND (Λ, Φ^T) CONTROLLABLE

(FOR DIAGONAL K_r, $\nu_i \psi_{a_i}(\nu_i) > 0$)



NONLINEARITIES IN ACTUATORS AND SENSORS:

LET K_r BE DIAGONAL

a) ORIGIN STABLE IF $\sigma\psi(\sigma) \geq 0$ FOR EACH ACTUATOR AND SENSOR

b) ORIGIN ASIL* IF $\sigma\psi(\sigma) > 0$ " "

AND (Λ, Φ^T) IS CONTROLLABLE

CONSIDER ACTUATOR/SENSOR DYNAMICS GIVEN BY

$$\mu \dot{x}_a = A_a x_a + B_a u_a$$

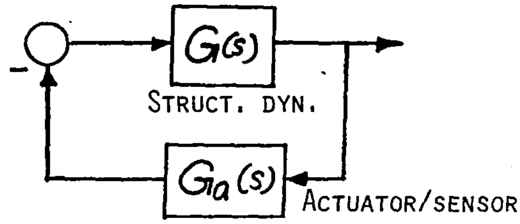
WHERE $\mu > 0$, SMALL; A_A STRICTLY HURWITZ

- IF THE CLOSED-LOOP SYSTEM WITH PERFECT ACTUATORS/SENSORS IS AS, THEN THE TRAJECTORY WITH FINITE-BANDWIDTH ACTUATORS/SENSORS IS $O(\mu)$ CLOSE TO TRAJECTORY WITH PERFECT ACTUATORS/SENSORS (REF. 1).

  HOW TO DETERMINE μ THAT WILL GUARANTEE STABILITY?

*ASYMPTOTICALLY STABLE IN THE LARGE

- CONSIDER THE SINGLE-INPUT SINGLE-OUTPUT CASE (SISO)



ASSUME SIMPLE STRUCTURAL MODE FREQUENCIES, NO DAMPING, AND NO POLE-ZERO CANCELLATIONS (I.E. CONTROLLABILITY)

- <u>THEOREM</u> THE CLOSED-LOOP SYSTEM IS AS FOR SUFFICIENTLY SMALL $K_r > 0$ IF

$$-90^\circ < \phi_a(\omega) < 90^\circ$$

AT $\omega = \omega_i \quad (i = 1, 2, \cdots, n_q)$

WHERE $\phi_a(\omega) = \angle G_a(j\omega)$

  - ALWAYS STABLE FOR 1ST ORDER $G_a(s)$
  - WHEN ACTUATOR/SENSOR HAVE n_a REAL POLES AT $s = -\sigma_a$ AND NO ZEROS. THE SYSTEM IS AS FOR SMALL $K_r > 0$ IF

$$\sigma_a > \frac{\omega_{MAX}}{\tan(\pi/2n_a)}$$

GIVES SOME INSIGHT INTO ACTUATOR/SENSOR BANDWIDTH REQUIREMENTS. ADDITIONAL INVESTIGATION NEEDED FOR OBTAINING MORE USEFUL RESULTS.

n_a	σ_a/ω_{MAX} (MIN. REQD.)
1	0
2	1
3	1.73
4	2.48
5	3.09
6	3.76
7	4.4
8	5.07

CONTROL OF PPS/LSS

- ATTITUDE AND VIBRATION CONTROL OF LSS
- POINTING CONTROL OF EACH PPS
- SINCE THE MASS OF EACH PPS MAY BE OF THE SAME ORDER AS THAT OF LSS, INSTABILITY IS POSSIBLE IF CONTROL SYSTEMS ARE DESIGNED INDEPENDENTLY.

SECONDARY CONTROLLER USING ANNULAR MOMENTUM CONTROL DEVICES (AMCD'S)

ASSUMPTIONS

- AMCD RIMS ARE RIGID
  - RIM DIA ≈ 2 M (SMALL COMPARED TO LSS)
- ACTUATORS AND SENSORS PERFECT
  - ELECTROMAGNETIC ACTUATORS AND POSITION SENSORS ARE ALMOST PERFECTLY LINEAR IN THE OPERATING RANGE. BANDWIDTH IS SEVERAL HUNDRED Hz.
- ACTUATORS/SENSORS COLLOCATED
  - INHERENT DESIGN CHARACTERISTIC OF AMCD

- CONTROL LAW:

$$f = K_p \delta + K_r \dot{\delta}$$

WHERE δ IS THE ACTUATOR CENTERING ERROR VECTOR

- STABLE IF $K_p > 0$, $K_r \geq 0$

ASYMPTOTICALLY STABLE (AS) IF

a) $K_p > 0$, $K_r > 0$

b) LSS STRUCTURAL MODEL STABILIZABLE

c) NO UNDAMPED LSS MODES AT $2j\Omega_i$ (Ω_i = SPIN FREQ.)

d) $\sum_{1}^{\nu} H_i \neq 0$

PRIMARY ATTITUDE CONTROLLER (PAC)

- USING TORQUE ACTUATORS
  - COLLOCATED ACTUATORS/SENSORS
  - NONCOLLOCATED ACTUATORS/SENSORS
- USING AMCD'S

PAC USING TORQUE ACTUATORS

- SEVERAL TORQUE ACTUATORS AT VARIOUS POINTS OF LSS
  - COLLOCATED ACTUATORS/SENSORS:
  - EQUATIONS OF MOTION:

$$A_s \ddot{x}_s + B_s \dot{x}_s + C_s x_s = \Gamma T$$

$$x_s = (\phi_s, \theta_s, q^T)^T$$

- COLLOCATED ACTUATORS/SENSORS

MEASUREMENTS CONSIST OF:

- ATTITUDE VECTOR: $\alpha = \Gamma^T x_s$
- ATTITUDE RATE VECTOR: $\dot{\alpha} = \Gamma^T \dot{x}_s$

CONTROL LAW: $T = -(G_p \alpha + G_r \dot{\alpha})$

- STABLE IF $G_p > 0$, $G_r \geq 0$
  - AS IF $G_p > 0$, $G_r > 0$, (C_s, Γ^T) CONTROLLABLE

- CONTROL LAW MINIMIZES

$$J = \int_0^{\infty} (x_s^T, \dot{x}_s^T, T^T) \begin{bmatrix} Q_1 & 0 & S \\ 0 & Q_2 & 0 \\ S^T & 0 & R \end{bmatrix} \begin{pmatrix} x_s \\ \dot{x}_s \\ T \end{pmatrix} dt$$

- EFFECT OF ACTUATOR/SENSOR DYNAMICS

  SISO CASE, NO REPEATED FREQS., CONTROLLABLE

  Let $\phi_a(\omega) = \angle G_a(j\omega)$, $\phi_a(0) = 0$

  $G_p = k g_p$, $G_r = k g_r$

  - AS FOR SMALL $k > 0$ IF

$$-\phi_{zi} < \phi_a(\omega_i) < 180^\circ - \phi_{zi}$$

  WHERE ϕ_{zi} IS A FUNCTION

  OF ω_i AND POSITION RATE GAINS

- ADDITIONAL INVESTIGATION IS NEEDED

- IF TORQUE ACTUATORS AND ATTITUDE/RATE SENSORS ARE NOT COLLOCATED
  - STABILITY NOT GUARANTEED
  - MUST USE LQG-BASED APPROACHES INVESTIGATED EARLIER
    - KNOWLEDGE OF FREQUENCIES AND MODE-SHAPES REQUIRED
    - ▲ TRUNCATION: "RESIDUAL" MODES IGNORED IN THE DESIGN PROCESS

▲ MODEL ERROR SENSITIVITY SUPPRESSION (REF. 2), "SPILLOVER" IS INCLUDED IN THE QUADRATIC PERFORMANCE FUNCTION:

$$\dot{x}_c = A_c x_c + B_c u$$

$$\dot{x}_r = A_r x_r + B_r u$$

$$J = \int_0^{\infty} \left\{ x_c^T Q x_c + u^T R u + (B_r u)^T Q_r (B_r u) \right\} dt$$

- IT CAN BE SHOWN THAT THE SAME AMCD'S CAN BE USED FOR PRIMARY CONTROL
- ATTITUDE AND RATE SENSORS LOCATED ON LSS AT MIDPOINTS OF AMCD ACTUATORS
- APPROXIMATES TORQUE ACTUATORS AND COLLOCATED SENSORS— PROVEN TO BE STABLE
- CLOSED-LOOP RIGID-BODY BANDWIDTH DEPENDS ON TOTAL MOMENTUM, ALLOWABLE GAPS, ETC.

PRELIMINARY MATH MODEL OF LSS/MPPS

- ASSUME LUMPED POINT-MASSES AT POINTS OF ATTACHMENT OF PPS'S (FOR LSS MODEL)
- ALL PPS RIGID
- EACH PPS CONSISTS OF GIMBALS AND TORQUERS (ONLY X-AXIS GIMBAL ASSUMED IN PRELIMINARY STUDY).

- MATH MODEL GIVEN BY:

$$A\ddot{x} + B\dot{x} + Cx = \Gamma f$$

$$x = (\phi_s, \theta_s, \phi_1, \phi_2, \cdots, \phi_p, q^T)^T \quad \leftarrow n_q \times 1$$

$$A = \begin{bmatrix} A_{11} & 0 \\ 0 & I_{n_q} \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 \\ 0 & D \end{bmatrix} \quad C = \begin{bmatrix} 0 & 0 \\ 0 & \Lambda \end{bmatrix}$$

$$\Lambda = diag(\omega_1^2, \omega_2^2, \cdots, \omega_{nq}^2)$$

$$f = (T_1^T, T_2^T, \cdots, T_m^T, T_{g1}, T_{g2}, \cdots, T_{gp})^T$$

$$T_i = (T_{xi}, T_{yi})^T$$

OBSERVATIONS

- INERTIAL ATTITUDE AND RATE SENSORS ON EACH PPS PAYLOAD
- m INERTIAL ATTITUDE AND RATE SENSORS ON LSS (COLLOCATED WITH LSS TORQUE ACTUATORS)
- SENSORS FOR MEASURING RELATIVE ANGLE BETWEEN EACH GIMBAL AND LSS

CONTROL OF MULTIPLE PRECISION - POINTED STRUCTURES (MPPS) MOUNTED ON LSS

- MPPS USED FOR COMMUNICATIONS, ASTRONOMY, EARTH RESOURCES, AND WEATHER PAYLOADS

- ADVANTAGES:
  - LESS ORBITAL SLOT SPACE AT GEO
  - SAVINGS IN POWER, CYROGENICS, GROUND DATA LINKS, AND SMALLER GROUND TERMINALS

CONTROL LAWS

- CONTROL LAW I: DECENTRALIZED CONTROL OF LSS/PPS:
  - USE LSS ATTITUDE AND RATE SIGNALS AND DESIGN LSS CONTROL LAW (COLLOCATED ACTUATORS/SENSORS)
  - USE PPS ATTITUDE AND RATE SIGNALS AND DESIGN CONTROL LAW (TO GENERATE DESIRED GIMBAL TORQUER TORQUES)
  - THE RESULTING CLOSED-LOOP SYSTEM CAN BE UNSTABLE
- CONTROL LAW II: ROBUST COMPOSITE CONTROL
  - USE INERTIAL PPS AND LSS SENSORS, AND ALSO GIMBAL-ANGLE SENSORS AND COMBINE THE SIGNALS TO OBTAIN

$$y = \Gamma^T x$$

  - CONTROL LAW:

$$f = -K_p y - K_r \dot{y}$$

  - CLOSED-LOOP SYSTEM LYAPUNOV-STABLE *if* $K_p > 0, K_r \geq 0$
  - ASYMPTOTICALLY STABLE (AS) IF $K_p, K_r > 0$, AND LSS STRUCTURAL MODEL STABILIZABLE, REGARDLESS OF NUMBER OF MODES AND NUMBER OF PPS. THEREFORE, CONTROLLER IS ROBUST.

NUMERICAL RESULTS

- 100′ x 100′ x 0.1″ COMPLETELY FREE ALUMINUM PLATE
- TWO PPS EACH WITH MASS ≈ LSS MASS
- THREE LSS TORQUE ACTUATORS WITH COLLOCATED ATTITUDE AND RATE SENSORS
- CONTROL LAW I: DECENTRALIZED CONTROL
  - LSS BW ≈ 0.05 rad/sec
  - PPS BW INCREASED GRADUALLY - A STRUCTURAL MODE WAS DRIVEN UNSTABLE FOR PPS BW > 0.1 rad/sec
- CONTROL LAW II: COMPOSITE CONTROL
  - LSS BW ≈ 0.05 rad/sec
  - PPS BW OF 1 rad/sec ($\rho \approx 0.7$) WAS EASILY OBTAINED WITHOUT SIGNIFICANT EFFECT ON CLOSED-LOOP LSS STRUCTURAL MODES

CONCLUDING REMARKS

- TWO-LEVEL LSS CONTROL IS STABLE AND ROBUST AND OFFERS PROMISE
- FURTHER INVESTIGATION NEEDED ON EFFECTS OF ACTUATOR/SENSOR BANDWIDTH
- COMPOSITE LSS/MPPS CONTROLLER IS STABLE AND ROBUST

PLANS FOR CONTINUED RESEARCH

- COMPLETE INVESTIGATION OF LSS/MPPS COMPOSITE CONTROL, INCLUDING PERFORMANCE EVALUATION
- INVESTIGATE ANNULAR SUSPENSION AND POINTING SYSTEM (ASPS) FOR PPS CONTROL ACTUATION
- START INVESTIGATION OF HOOP-COLUMN ANTENNA CONTROL

REFERENCES

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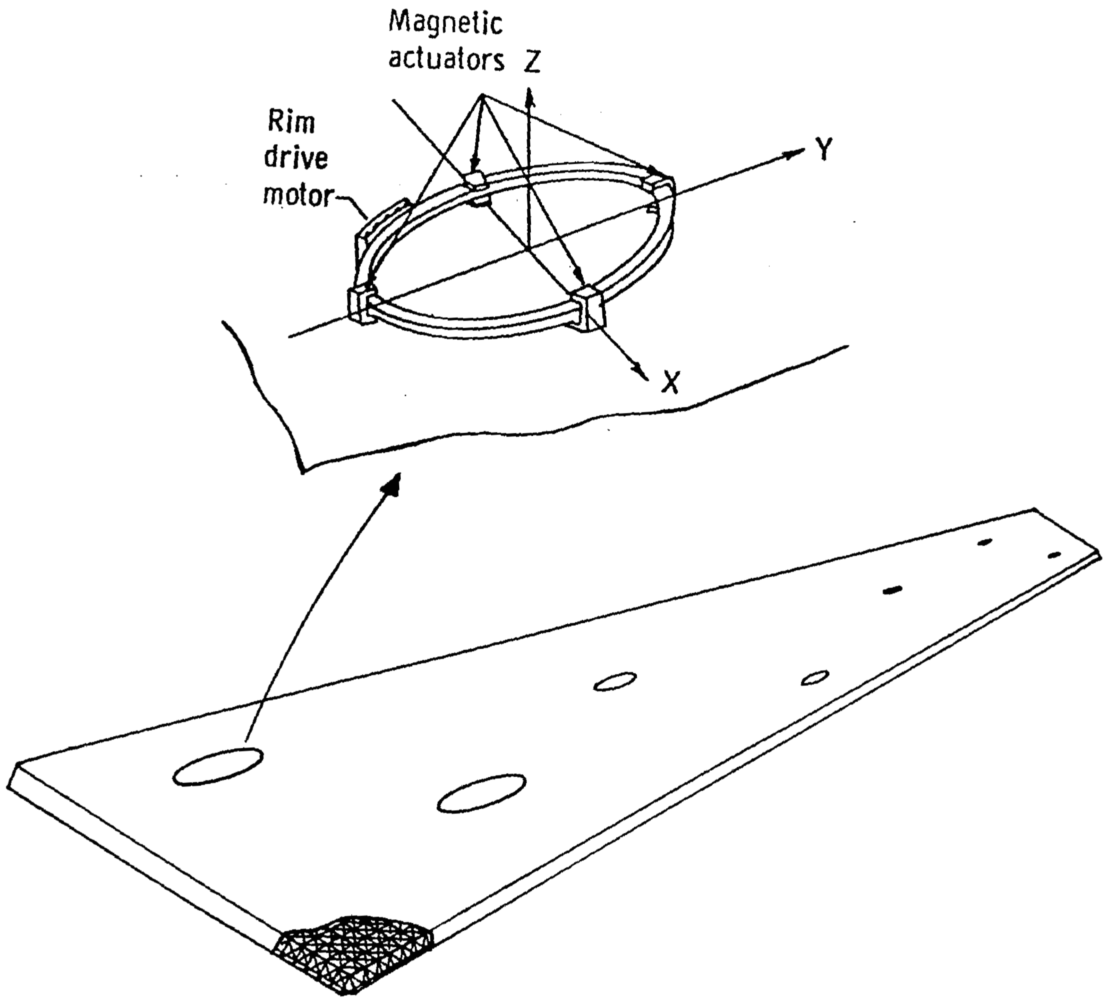
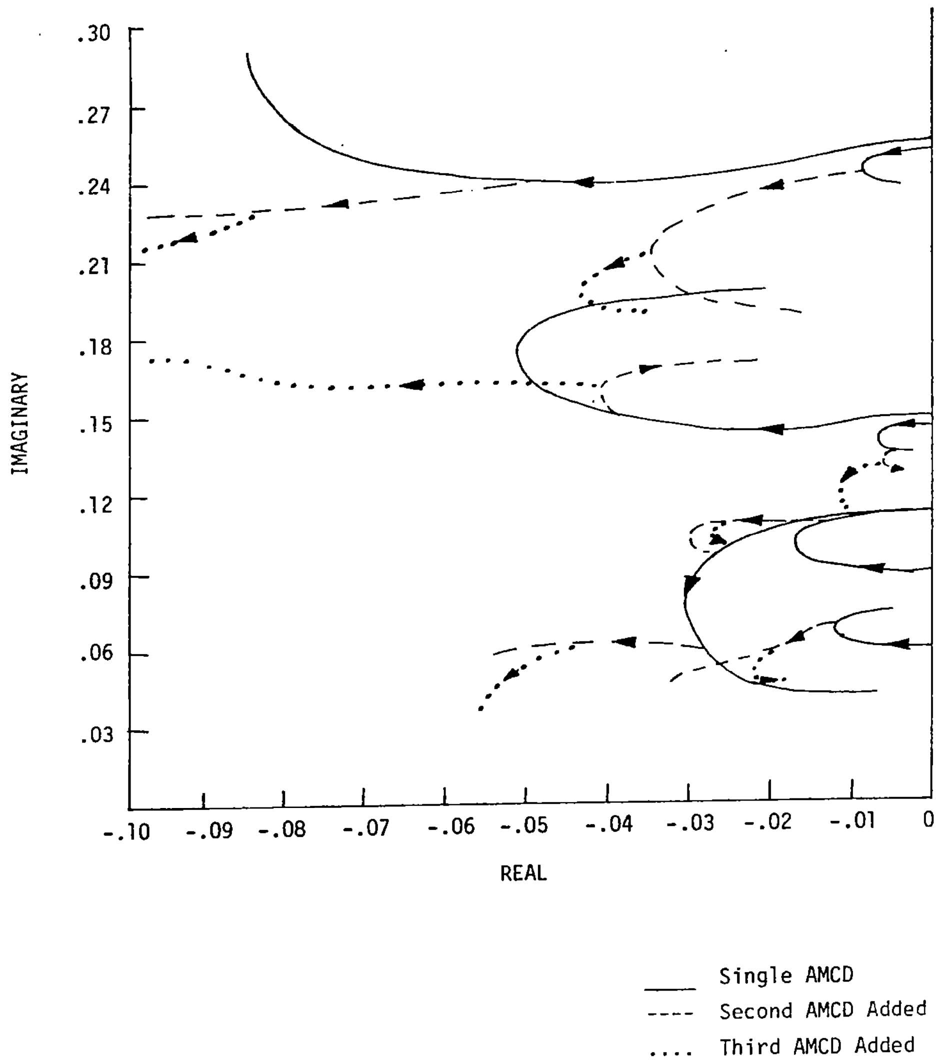
2. SESAK, J. R.; LIKENS, P. W.; AND CORADETTI, T.: FLEXIBLE SPACECRAFT CONTROL BY MODEL ERROR SENSITIVITY SUPPRESSION (MESS). J. ASTRONAUT. SCI., VOL. 27, NO. 2, PP. 131-156.



AMCD/ LSS CONFIGURATION



SECONDARY CONTROLLER ROOT LOCI