CSI Related Dynamics and Control Issues in Space Robotics

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Outline

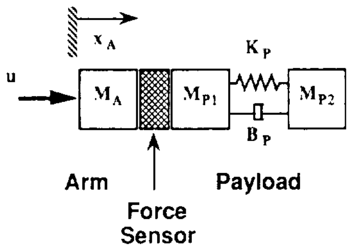
- CSI issues in space robotics
- Control of elastic payloads:
  - 1-DOF example
  - 3-DOF Harmonic Drive arm with elastic beam
- Control of large space arms with elastic links:
  - Testbed description
  - Modelling
  - Experimental implementation of colocated PD and end-point tip position controllers
- Conclusions

CSI MODELLING AND CONTROL ISSUES	SMALL, DEXTEROUS MANIPULATORS		LARGE, CRANE-LIKE MANIPULATORS	
	dynamics	*controls*	*dynamics*	*controls*
Lumped compliance due to actuator geartrain	Dominant Effect (free-free resonance modes in the 10-30 Hz range, ζ=0.1 for FTS-like arms with Harmonic Drive gearings)	Active damping of geartrain mode is achieved with either analog/digital colocated rate feedback or analog output torque feedback.	Effect is as or more important than distributed flexibility (lowest locked joint frequency for RMS in the 0.1 to 2 Hz range, depending on load)	RMS control system is based on analog/digital colocated rate control (PI). Active CSI controller using links and wrist-mounted sensors have been demonstrated in the lab.
Distributed flexibility in the links	No significant effect except for lumped compliances arising from mechanical interfaces, actuator housing and end-effectors.	Control system should include active filters to gain stabilize flexible modes due to lumped compliances. Other approach is to use passive damping if it is feasible.	Significant effect, especially for the cases of very large payloads (RMS dominant elastic mode in the 0.03 to 0.4 Hz range, depending on load.	RMS control system based on colocated rate feedback damps out elastic modes but at the expense of rigid-body bandwidth. Laboratory systems are currently testing CSI-based controllers using links and wrist-mounted sensors. Future space arms will have control modes based on proximity/vision sensing systems.
Rigid & elastic payloads with lightly damped vibration modes	Important effect as dexterous robots will be used for spacecraft servicing (dominant payload frequencies can be inside or outside the robot control system nominal bandwidth) (typically, ω= 1 to 3 Hz)	No general control approach developed yet. Conventional robot controllers can be tuned to act as vibration absorber for elastic payload. Robot controller acts as a colocated controller for the elastic payload.	For each flown payload detailed pre-flight simulations are run for the RMS. Special studies need to be run to assess dynamic coupling when payload fundamental vibration mode (clamped interface) is below 0.5 Hz. Future RMS-like arm will need to handle massive and elastic systems.	No general control approach yet developed. As for rigid arms, conventional colocated rate controllers will not destabilize the payload elastic modes. For performance, additional sensors will be needed to increase active damping on dominant payload modes as necessary. A general approach will have to consider the cooperative use of the payload attitude control system together with the arm controller.
Compliant base or free-flying base	Important effect for dexterous arms mounted on a space station node or on a stabilizer arm or at the end of a long, flexible RMS-like manipulator.	Practical engineering solutions will have to be developed. Use of wrist mounted or body-mounted sensors for active feedback of base mode will be key to effective control. Passive energy dissipation mechanisms (friction brakes, viscoelastic mounts) will need to be designed.	The Space Shuttle/RMS system is the first free-flyer servicing spacecraft. Free-flying base effect becomes more important as payload mass becomes comparable to Shuttle mass/inertia. Compliance of Space-Station RMS mount on truss needs to be accounted for in design. Cooperative use of the base and the arm controllers will be needed for future autonomous operations.	Effect of base compliance shows up as pairs of lightly damped poles and zeroes in each joint open-loop transfer function. Effective damping of these modes can be increased through a combination of colocated control and wrist/base-mounted sensors (accelerometers and/or inertial position sensors)

CSI Issues in Space Robotics

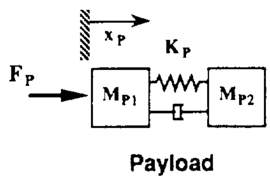
Control of Elastic Payloads: 1-DOF Example

- 1-DOF rigid arm with 1-DOF elastic payload:



- M_A = Arm Mass
- $M_P = M_{P1} + M_{P2}$ = Payload Mass
- B_P is small (lightly damped elastic mode)

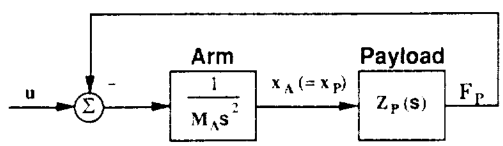
- Payload dynamics can be defined by its dynamic stiffness:



$$Z_P(s) = \frac{F_P(s)}{x_P(s)} = M_P s^2 \frac{s^2 + 2\zeta\omega_P s + \omega_P^2}{s^2 + 2\zeta'\Omega_P s + \Omega_P^2} \frac{\Omega_P^2}{\omega_P^2}$$

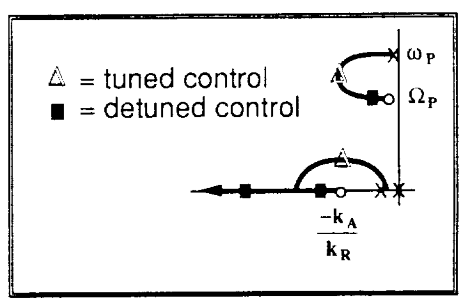
$$\omega_P^2 = K_P\left[\frac{1}{M_{P1}} + \frac{1}{M_{P2}}\right] \qquad \Omega_P^2 = \frac{K_P}{M_{P2}}$$

- Equations of motion for arm/payload system can be expressed in terms of the INDIVIDUAL arm & payload dynamics:



- Assume standard PD control for robot arm:

$$u = -k_A(x_A - x_A^c) - k_R x_A$$



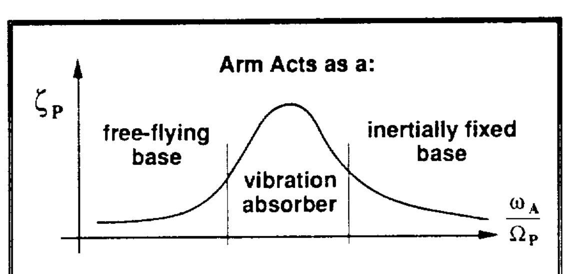
- Arm is acting as a colocated actuator/ sensor pair for payload.

  ⇒ ELASTIC MODE ALWAYS STABLE

- Payload closed-loop elastic mode is a function of the ratio $\frac{\omega_A}{\Omega_P}$ where:

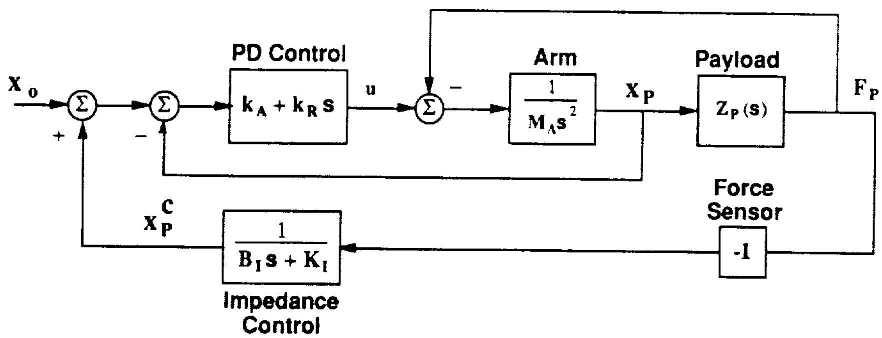
  ω_A = Rigid Arm Closed-Loop Bandwidth

  Ω_P = First Cantilevered Vibration Frequency of the payload



Control of Elastic Payloads: 1-DOF Example (cont'd)

- For cases where arm controller is "detuned" ($\omega_A >> \Omega_P$), we can implement an additional IMPEDANCE control law to actively damp the payload's elastic mode:



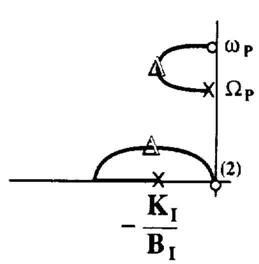
- We Have: $x_P \cong x_P^c$ (High-Gain PD Control)

$$x_P^c = \frac{-F_P}{B_I s + K_I} \quad \text{(Impedance Control)}$$

$$\left.\begin{matrix} \\ \\ \end{matrix}\right\} F_P = -(B_I s + K_I)\, x_P$$

> $\Rightarrow$ Force F_P applied to payload acts as a <u>virtual</u> spring/damper selected by the user !!

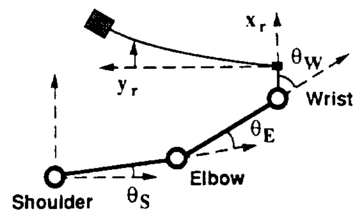
- Root-Locus vs. Force Sensor Gain:



$\Rightarrow$ With proper choice of $[K_I, B_I]$ gains, payload elastic mode is <u>actively</u> damped !

Control of Elastic Payloads: Planar Arm Example

- **Three DOF Arm with Elastic Beam Payload:**



- **Payload linearized dynamics model is obtained from FEM techniques applied to elastic body on moving base:**

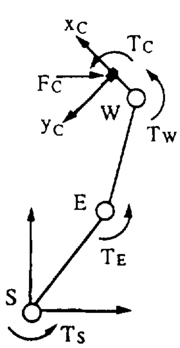
$$\begin{bmatrix} M_{rr} & M_{re} \\ M_{re}^{t} & M_{ee} \end{bmatrix} \begin{bmatrix} \ddot{q}_r \\ \ddot{q}_e \end{bmatrix} + \begin{bmatrix} \underline{0}_{3} & \underline{0}_{3n} \\ \underline{0}_{n3} & D_{ee} \end{bmatrix} \begin{bmatrix} \dot{q}_r \\ \dot{q}_e \end{bmatrix} + \begin{bmatrix} \underline{0}_{3} & \underline{0}_{3n} \\ \underline{0}_{n3} & K_{ee} \end{bmatrix} \begin{bmatrix} q_r \\ q_e \end{bmatrix} = \begin{bmatrix} F_p \\ \underline{0} \end{bmatrix}$$

$q_r = \begin{bmatrix} x_c \\ y_c \\ \phi_c \end{bmatrix}$ = rigid interface DOFs $\qquad F_p = \begin{bmatrix} F_x \\ F_y \\ T_\Phi \end{bmatrix}$ = external forces/torque exterted on payload by arm.

- **In summary:**

$$\begin{bmatrix} F_x(s) \\ F_y(s) \\ T_\Phi(s) \end{bmatrix} = Z_p(s) \begin{bmatrix} x_c(s) \\ y_c(s) \\ \phi_c(s) \end{bmatrix} \text{ where } Z_p(s) = \textbf{DYNAMIC STIFFNESS of ELASTIC PAYLOAD}$$

- **Arm dynamics linearized around given configuration:**



$$M(\underline{\theta}_0)\,\ddot{\underline{\theta}} = \underline{T}_A + J^{T}(\underline{\theta}_0)\,\underline{F}_C \quad \text{with}$$

$\underline{\theta} = \begin{bmatrix} \theta_S \\ \theta_E \\ \theta_W \end{bmatrix}$ $\quad \underline{T}_A = \begin{bmatrix} T_S \\ T_E \\ T_W \end{bmatrix}$ $\quad \underline{F}_C = \begin{bmatrix} T_{xC} \\ T_{yC} \\ T_{\phi C} \end{bmatrix}$

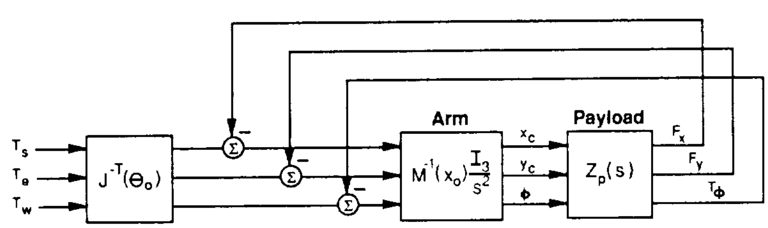
$M(\underline{\theta}_0)$ = 3x3 inertia matrix

$J(\underline{\theta}_0)$ = Jacobian matrix expressed in end-effector frame

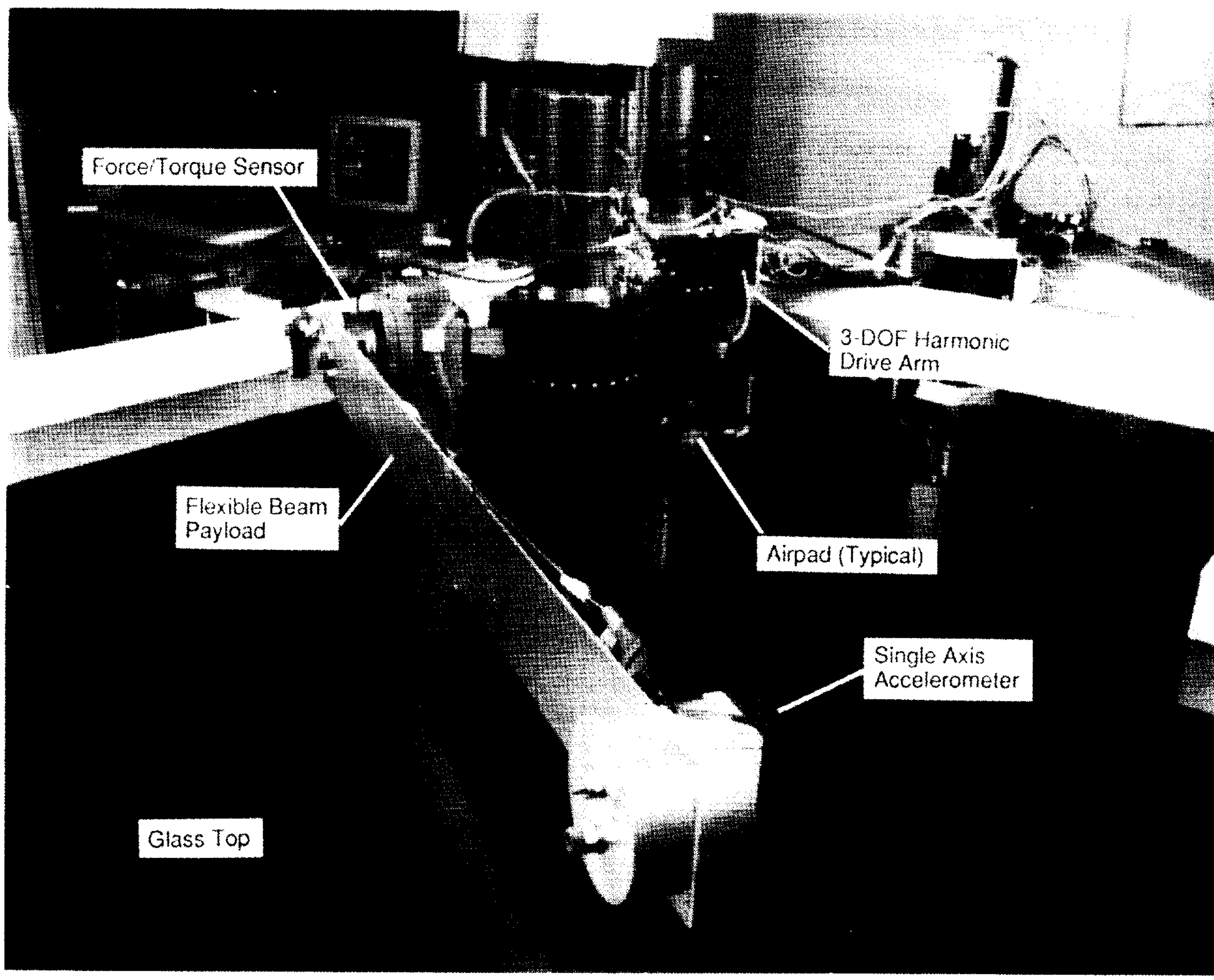
Can be transformed in terms of end-effector coordinates xc:

$$M(\underline{x}_0)\,\underline{x}_C = J^{-T}(\underline{\theta}_0)\,\underline{T}_A + \underline{F}_C \quad \text{with} \quad M(\underline{x}_0) = \text{"Cartesian" inertia matrix} = J^{-T}(\underline{\theta}_0)\,M(\underline{\theta}_0)\,J^{T}(\underline{\theta}_0)$$

- **Coupled arm / payload dynamics:**



Control of Elastic Payloads: Planar Arm Example



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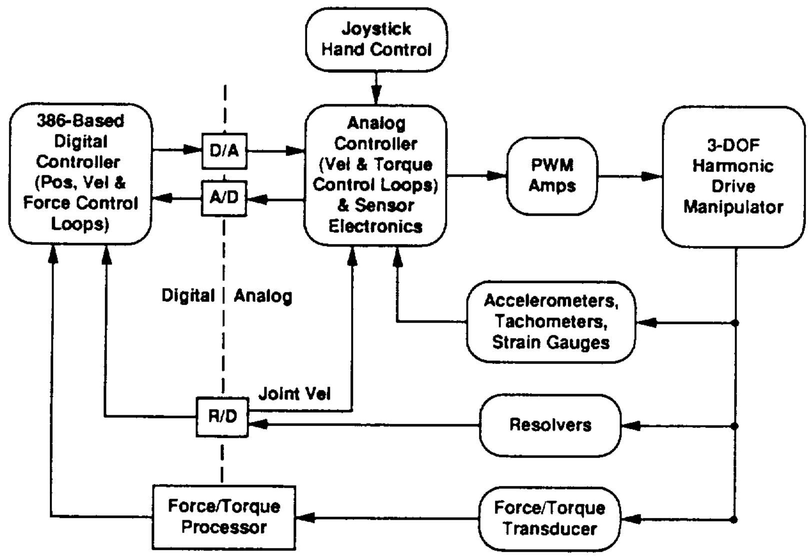
Control of Elastic Payloads: Planar Arm Example

- System Block Diagram:



- Characteristic frequencies for 3-DOF Arm & Payload dynamic system (derived using TREETOPS multi-body software):

	F_1 (Hz)	F_2 (Hz)	F_3 (Hz)
Arm Joints Locked	1.2	14.0	42.2
Arm Joints Free	2.1	14.3	42.3

- Arm Mass Properties:

Link	Mass (kg)	Center of Mass (m)	MOI (kg-m ^{2})	Link Length (m)
Shoulder	13.8	0.406	0.77	0.56
Elbow	10.1	0.37	0.607	0.56
Wrist	13.7	0.14	0.106	0.254

- Payload Mass Properties:

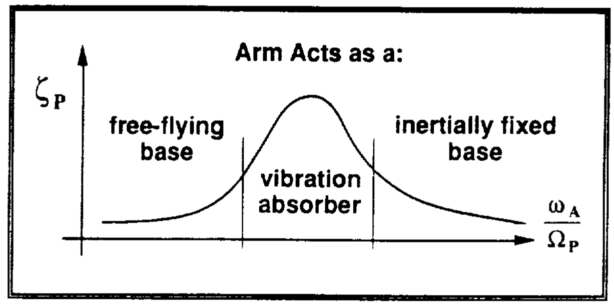
Part	Mass (kg)	Center of Mass (m)	EI (N-m ^{2})	Link Length (m)
Beam	0.4	0.38	7.28	0.765
Tip Mass	0.7	-----	-----	-----

Control of Elastic Payloads: Planar Arm Example (cont'd)

- **Arm controller is designed assuming a rigid payload:**
  - Independent analog torque loop controllers (elastic gearmotors behave as direct drive actuators)
  - Standard nonlinear control law: $T_a = M_{rr}(\theta)\left[-K_P(\theta - \theta^c) - K_R\dot{\theta}\right]$
    - For a rigid arm, closed-loop dynamics is approximated by 3 decoupled second-order integrators.
    - For a rigid arm with elastic payload, arm can be treated as a virtual cartesian 3-dof colocated actuator/sensor pair.
- **Dominant payload closed-loop elastic mode is a function of the ratio $\frac{\omega_A}{\Omega_P}$ where:**

ω_A = Rigid Arm Closed-Loop Bandwidth

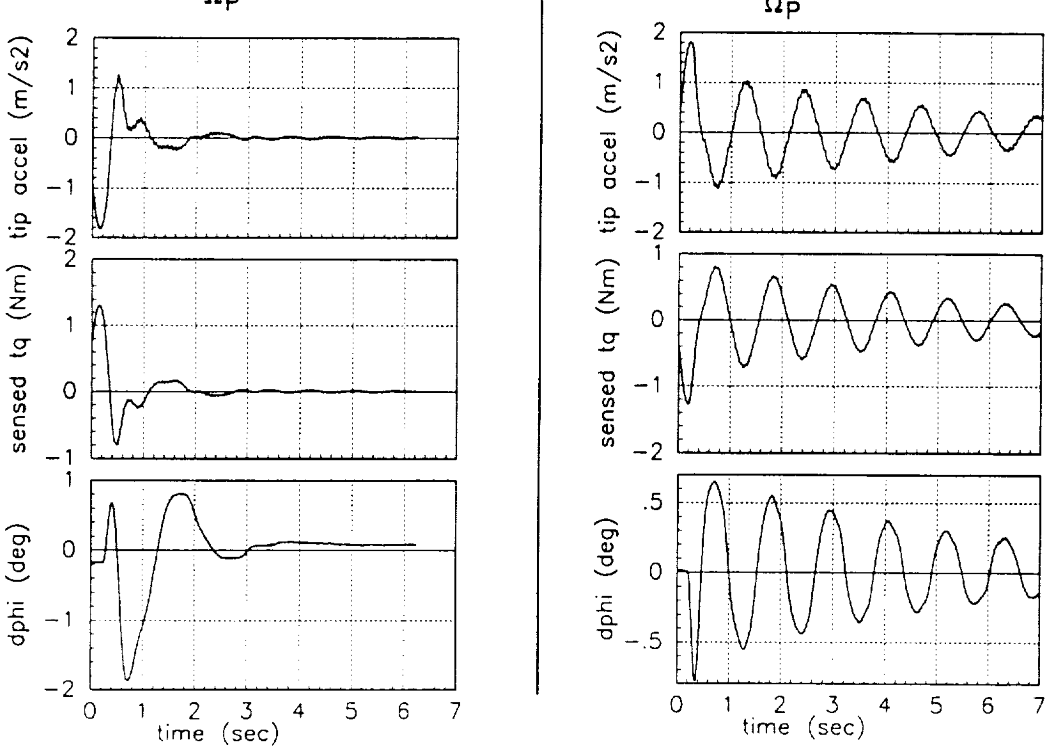
Ω_P = First Clamped Vibration Frequency of the Payload



Experimental time responses for an initial payload elastic deformation:

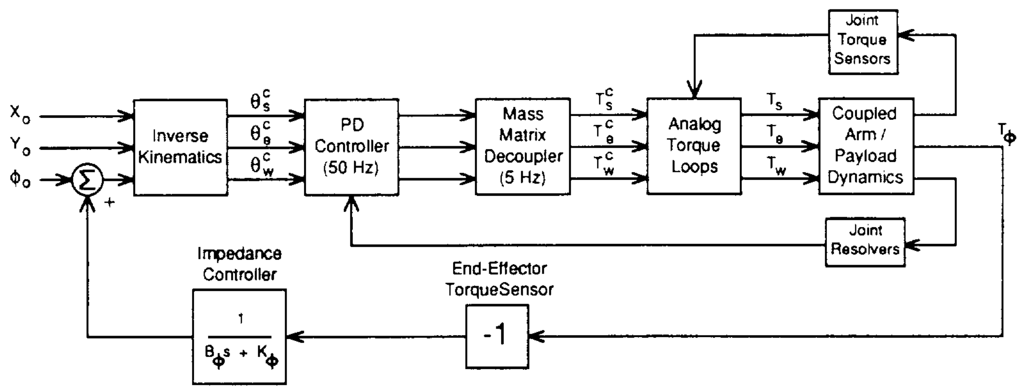
Arm acts as a vibration absorber: $\frac{\omega_A}{\Omega_P} = 1$

Arm acts as a rigid base: $\frac{\omega_A}{\Omega_P} = 2$



Control of Elastic Payloads: Planar Arm Example (cont'd)

- **For cases where arm controller is detuned ($\omega_a > \Omega_p$), we can implement an impedance control law to actively damp dominant payload elastic modes:**



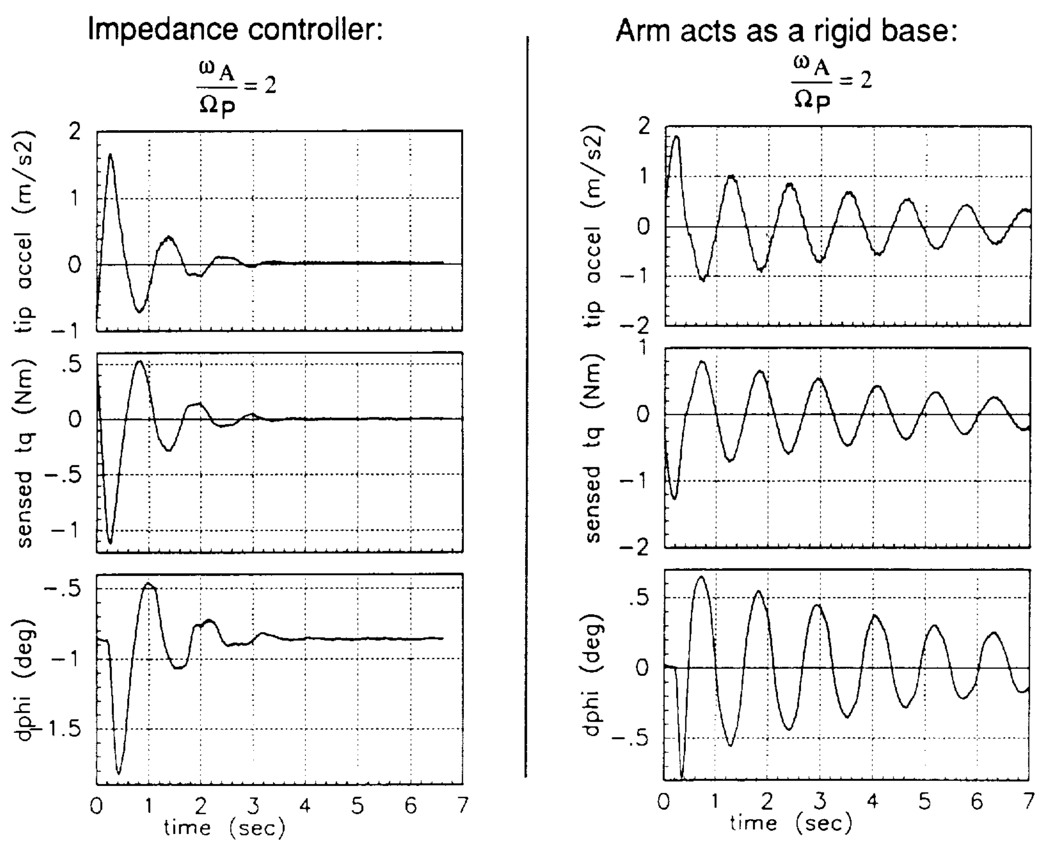
• **We Have:** $\phi \cong \phi^c$ (High-Gain PD Control)

$$\phi^c = \frac{-T_\phi}{B_\phi s + K_\phi} \quad \text{(Impedance Control)}$$

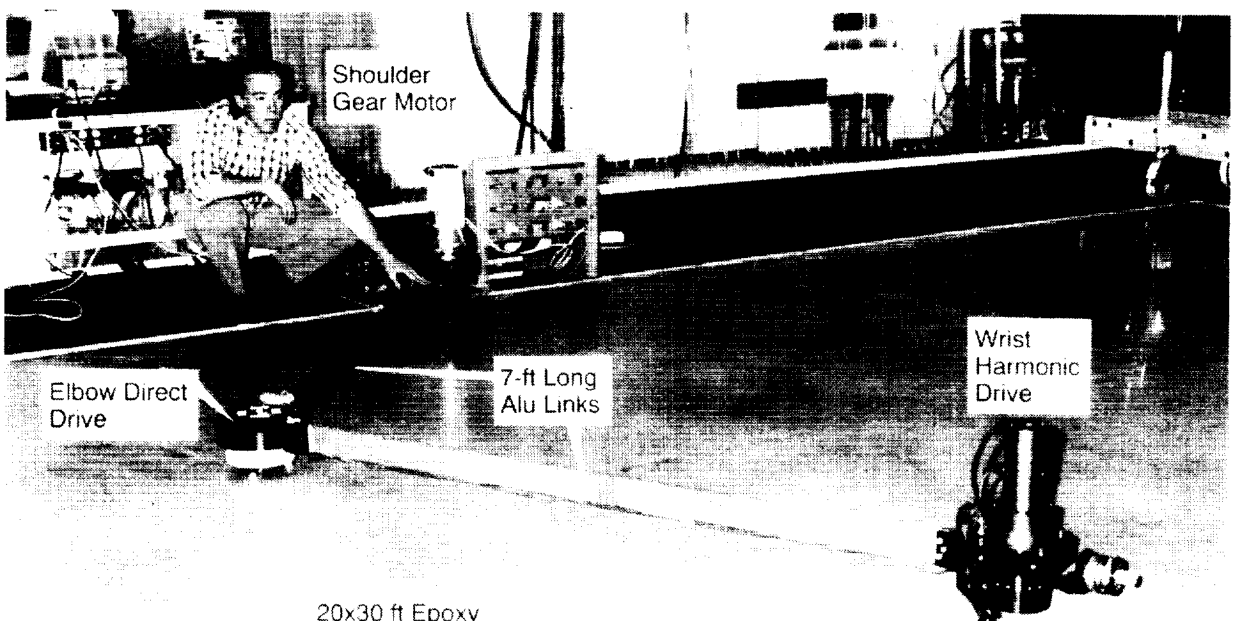
$$\Big\} \; T_\phi \cong -(B_\phi s + K_\phi)\,\phi$$

> ⇒ **Torque T_ϕ applied to payload acts as a <u>virtual</u> spring/damper selected by the user !!**

Experimental time responses for an initial payload elastic deformation:

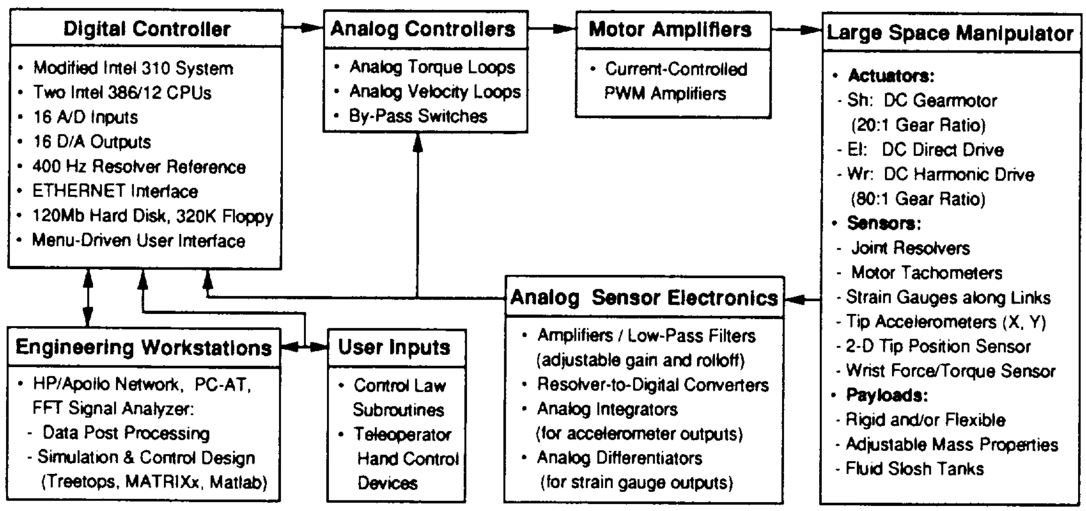


Control of Elastic Arms: Testbed Description



Control of Elastic Arms: Testbed Description (cont'd)

- **System Block Diagram:**



Control of Elastic Arms: Dynamic Modelling

- **Modelling tool is the multi-flexible body dynamic analysis code TREETOPS:**
  - Code developed by Dynacs for NASA-MSFC can simulate controlled dynamics of a general chain of articulated rigid and elastic bodies.
  - Preprocessor generates finite element mass, damping and stiffness matrices for each link with user-selectable end boundary conditions.
  - Linearized models can be loaded in the control analysis software packages MATLAB and MATRIXx.
  - Nonlinear TREETOPS simulation can be run with the MATRIXx/System-Build nonlinear simulator. This allows to easily design and simulate control laws with the TREETOPS-generated dynamic models.

- **Simple analytical models have also been derived to understand the basic characteristics of the system to control: linear and nonlinear models for a 1-DOF, and 2-DOF planar slender elastic arms with a rigid payload and with nonlinear or linear geared actuators.**

Control of Elastic Arms: Dynamic Modelling (cont'd)

- **Equations of motion for 2-DOF elastic arm numerically assembled by TREETOPS:**

$$\begin{bmatrix} M_{rr}(x_r) & M_{re}(x_r) \\ M_{re}^{t}(x_r) & M_{ee} \end{bmatrix}\begin{bmatrix}\ddot{X}_r \\ \ddot{X}_e\end{bmatrix} + \begin{bmatrix} D_{rr} & \underline{0}_{2n} \\ \underline{0}_{n2} & D_{ee}\end{bmatrix}\begin{bmatrix}\dot{X}_r \\ \dot{X}_e\end{bmatrix} + \begin{bmatrix}\underline{0}_{22} & \underline{0}_{2n} \\ \underline{0}_{n2} & K_{ee}\end{bmatrix}\begin{bmatrix}X_r \\ X_e\end{bmatrix} = \begin{bmatrix} I_2 \\ \underline{0}_{n2}\end{bmatrix}\begin{bmatrix}T_s \\ T_e\end{bmatrix} + \begin{bmatrix}\mathcal{J}_{RR}^{t} \\ \mathcal{J}_{ee}^{t}\end{bmatrix}\begin{bmatrix}F_{Tx} \\ F_{Ty}\end{bmatrix}$$

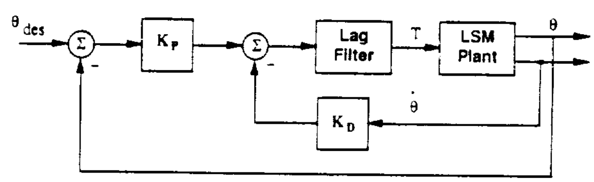
where X_r and X_e are respectively the joint angles and the generalized elastic coordinates

- **Equations of motion are linearized around a given arm configuration. A state-space model is derived with the two control actuators as inputs. The model outputs are the joint angles, motor rates and linearized tip displacements (dx,dy).**
- **Characteristic System frequencies: JL= free joints FF = joint locked.**

System Frequencies (Hz) for No Payload Configuration				
Mode	$\theta_e = 0°$		$\theta_e = 90°$	
No.	JL	FF	JL	FF
1	0.29	5.12	0.36	5.00
2	1.50	6.70	0.94	6.54
3	7.53	18.3	7.27	18.2
4	14.5	25.3	14.3	25.1
5	27.1	40.9	26.6	40.9
6	38.7	63.2	38.6	63.1

Control of Elastic Arms: Colocated PD Control

- Closed-loop system block diagram:



- **PD controller with joint position and motor velocity feedback:**

$$T_s = -\left[k_{Ps}(\theta_s - \theta_s^c) + k_{Rs}\dot{\theta}_s \right] L_{2s}(s)$$

$$T_e = -\left[k_{Pe}(\theta_e - \theta_e^c) + k_{Re}\dot{\theta}_e \right] L_{2e}(s)$$

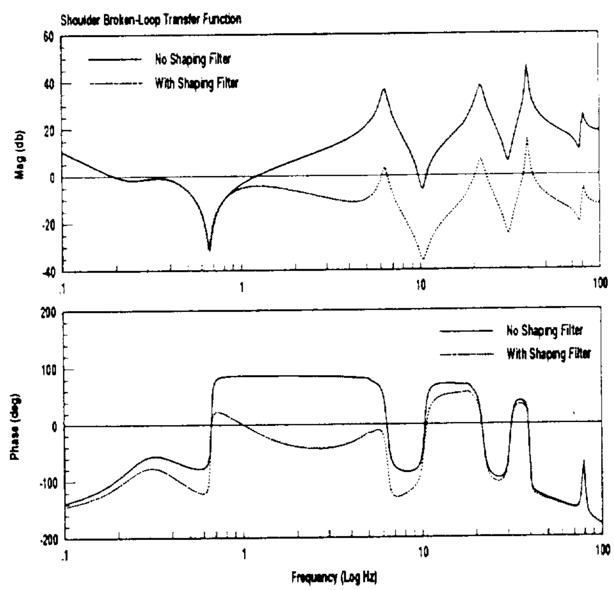
where L_{2s} and L_{2e} are two second-order lag filters:

$$L_2(s) = \frac{S^2 + 2\zeta_z \omega_z s + \omega_z^2}{S^2 + 2\zeta_p \omega_p s + \omega_p^2}\,\frac{\omega_p^2}{\omega_z^2}$$

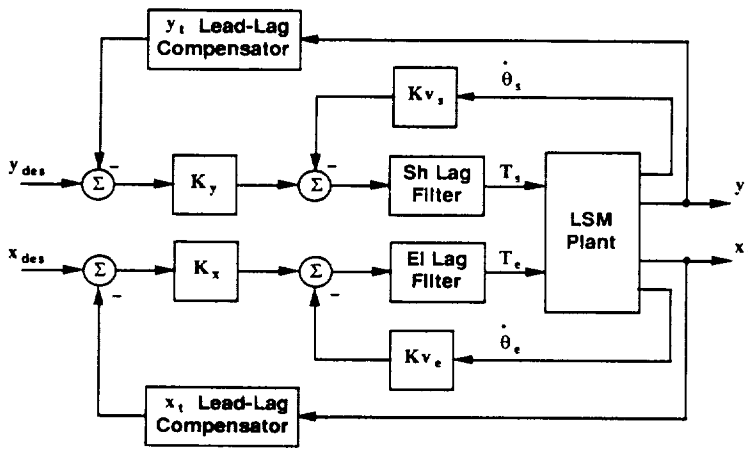
Control of Elastic Arms: Colocated PD Control (cont'd)

- **Example of gain-stabilization of the 4th vibration mode (85 Hz) with PD controller implemented at 200 Hz. Second-order lag filter provides high-frequency roll-off in compensator:**

Open-loop shoulder transfer function G (s) K (s)



Control of Elastic Arms: End-point Controller



- **End-point controller is designed for configurations with the elbow angle nearly equal to 90 degrees:**
  - Tip sensor Xt channel is fed back to elbow actuator.
  - Tip sensor Yt channel is fed back to shoulder actuator.
- **For each channel, the tip controller consists of a second-order lead compensator with motor rate feedback:**

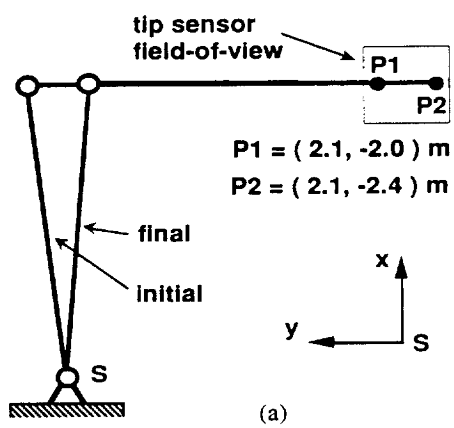
$$T_i = - \left[k_{Pi} \frac{(s+a)}{(s+b)(s+c)} (z_i - z_i^c) + k_{Ri} \dot{\theta}_i \right] L_{2i}(s)$$

with $\{a << b \;\&\; c\}$ and L_{2i} is a second-order lag filter.

Control of Elastic Arms: PD Control vs End-point Control

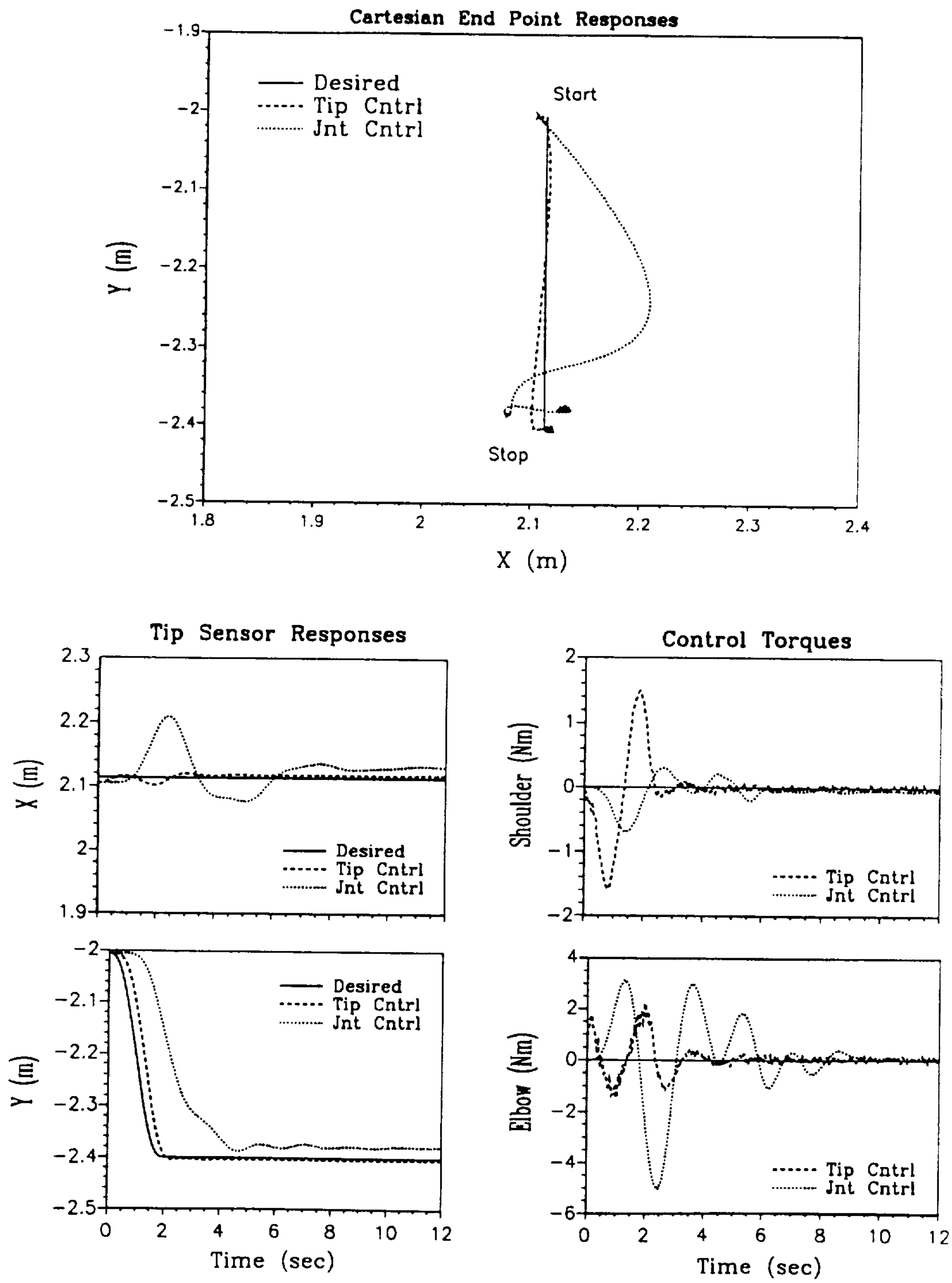
- **Arm is commanded to move along a straight line in the y-direction:**
  - A fifth-order spline command profile is used for the tip position command
  - For the independent joint controller, equivalent joint command profiles are computed using inverse kinematics (assuming arm is rigid).

- **Arm configuration for reference slew maneuver:**



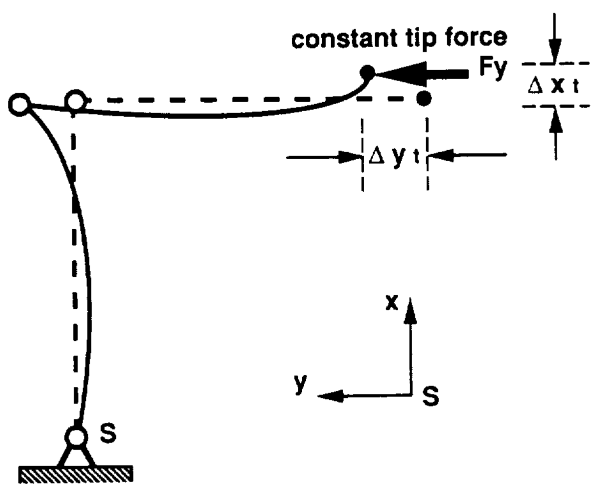
(a)

Experimental Time Responses for Slew Maneuver



Control of Elastic Arms: Disturbance Response to Tip Forces

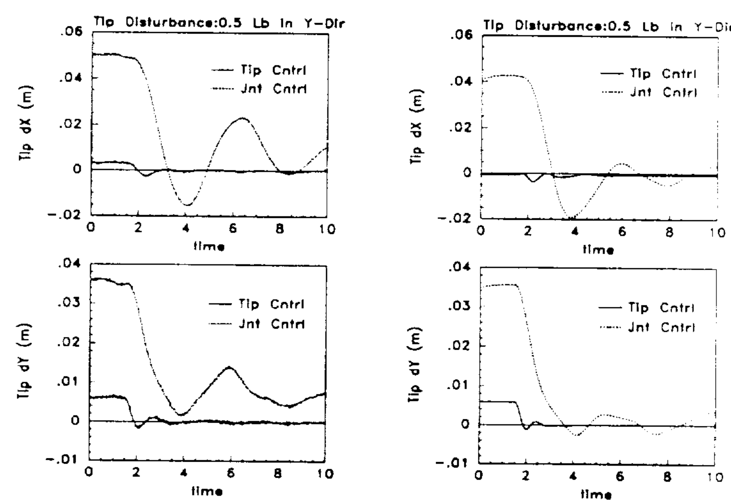
- Experimental set-up:



- The arm is under closed-loop control in a given configuration (joint or tip control).
- A constant force is applied at the tip using a force gage.
- After steady-state has occurred, tip force is removed.

Control of Elastic Arms: Disturbance Response toTip Forces (cont'd)

Experimental Data for 0.5 Lb Tip Force Applied along Y axis:



- Effective cartesian stiffness with tip position control is one order of magnitude larger than with joint feedback.
- With joint control, tip disturbance forces excite fundamental low-frequency and the lightly-damped elastic mode of the arm (0.5 Hz frequency). With tip controller, transient response is well damped.

Conclusions

- **With additional sensing capability, simple and robust control laws can be used for active damping of space robots:**
  - wrist-mounted force/torques sensors can be used to damp out large elastic payload vibration modes with a simple impedance control law.
  - sensors which directly sense the wrist motion can be used to damp out link elastic modes for RMS-class arms.
  - output torque sensors can also be used to damp out gearmotor elastic modes.

- **Experimental testbeds have been designed to validate modelling techniques and to demonstrate in 2-D the feasibility of new control/sensing implementation for FTS/SPDM-class and RMS-class manipulators. These testbeds are useful as a complement to 3-D simulation studies.**

- **Space-based experiments should be planned to demonstrate CSI-technology for FTS/SPDM-class and RMS-class manipulators.**