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

<table>
<thead>
<tr>
<th>SMALL, DEXTEROUS MANIPULATORS</th>
<th>LARGE, CRANE-LIKE MANIPULATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>dynamics</strong></td>
<td><strong>controls</strong></td>
</tr>
<tr>
<td>Lumped compliance due to actuator gearing</td>
<td>Active damping of gearing mode is achieved with either analog/digital colocated rate feedback or analog output torque feedback.</td>
</tr>
<tr>
<td>Distributed flexibility in the links</td>
<td>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.</td>
</tr>
<tr>
<td>Rigid &amp; elastic payloads with lightly damped vibration modes</td>
<td>No general control approach developed yet. Conventional robot controllers can be tuned to act as vibration absorber for elastic payloads. Robot controller acts as a colocated controller for the elastic payload.</td>
</tr>
<tr>
<td>Compliant base or free-flying base</td>
<td>Important effect for dexterous arms mounted on a spacecraft or on a stabilizer arm or at the end of a long, flexible RMS-like manipulator.</td>
</tr>
</tbody>
</table>

CSI Issues in Space Robotics

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Control of Elastic Payloads: 1-DOF Example

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

\[
\begin{align*}
\text{Arm} & \quad \text{Payload} \\
\mathbf{M}_A & \quad \mathbf{M}_{P_1} \quad \mathbf{M}_{P_2} \\
\mathbf{F} & \quad \mathbf{F}_P \\
\mathbf{X}_A & \quad \mathbf{X}_P \\
\mathbf{K}_P & \quad \mathbf{K}_P
\end{align*}
\]

- \( \mathbf{M}_A = \text{Arm Mass} \)
- \( \mathbf{M}_P = \mathbf{M}_{P_1} + \mathbf{M}_{P_2} = \text{Payload Mass} \)
- \( B_P \) is small (lightly damped elastic mode)

- Payload dynamics can be defined by its dynamic stiffness:

\[
\mathbf{Z}_P(s) = \mathbf{F}_P(s) = \mathbf{M}_P s^2 + 2\zeta\mathbf{\omega}_P s + \mathbf{\omega}_P^2
\]

\[
\mathbf{X}_P(s) = \mathbf{F}_P(s)
\]

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

\[
\begin{align*}
\mathbf{X}_A(s) &= \mathbf{X}_P(s) \\
\mathbf{F}_P(s) &= \mathbf{Z}_P(s)
\end{align*}
\]

- Assume standard PD control for robot arm:

\[
u = -k_A(x_A - x^c) - k_R x_A
\]

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

\( \Rightarrow \) ELASTIC MODE ALWAYS STABLE

- Payload closed-loop elastic mode is a function of the ratio

\[
\frac{\mathbf{\omega}_A}{\mathbf{\omega}_P} = \text{Rigid Arm Closed-Loop Bandwidth}
\]

\[
\frac{\mathbf{\Omega}_P}{\mathbf{\mathbf{\omega}_P}} = \text{First Cantilevered Vibration Frequency of the payload}
\]

Arm Acts as a:

- free-flying base
- vibration absorber
- inertially fixed base
Control of Elastic Payloads: 1-DOF Example (cont'd)

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

\[
\text{PD Control Arm Payload} \quad \text{Impedance Control}
\]

\[
\begin{align*}
\text{We Have:} & \quad x_p \equiv x_p^c \quad (\text{High-Gain PD Control}) \\
& \quad x_p = \frac{-F_p}{B_1 s + K_1} \quad (\text{Impedance Control}) \\
\therefore \quad F_p &= -(B_1 s + K_1) x_p
\end{align*}
\]

- Root-Locus vs. Force Sensor Gain:

\[
\begin{array}{c}
\text{With proper choice of } [K_1, B_1] \\
\text{gains, payload elastic mode is actively damped!}
\end{array}
\]
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:

\[
\begin{bmatrix}
M_{rr} & M_{re} \\
M_{re}^T & M_{ee}
\end{bmatrix}
\begin{bmatrix}
\dot{q}_r \\
\dot{q}_e
\end{bmatrix}
+ \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & D_{ee}
\end{bmatrix}
\begin{bmatrix}
q_r \\
q_e
\end{bmatrix}
+ \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & K_{ee}
\end{bmatrix}
\begin{bmatrix}
q_r \\
q_e
\end{bmatrix}
= \begin{bmatrix}
F_p \\
0
\end{bmatrix}
\]

\[
q_r = \begin{bmatrix}
x_r \\
y_r \\
\phi_r
\end{bmatrix}
\text{ rigid interface DOFs}
\quad
F_p = \begin{bmatrix}
F_x \\
F_y \\
T_\phi
\end{bmatrix}
\text{ external forces/torque exerted on payload by arm.}
\]

- In summary:

\[
\begin{bmatrix}
F_x(s) \\
F_y(s) \\
T_\phi(s)
\end{bmatrix}
= Z_p(s)
\begin{bmatrix}
x_c(s) \\
y_c(s) \\
\phi_c(s)
\end{bmatrix}
\]

where \(Z_p(s) = \text{DYNAMIC STIFFNESS of ELASTIC PAYLOAD}\)

- Arm dynamics linearized around given configuration:

\[
M(\Theta_0) \ddot{\Theta} = \mathcal{T}_A + \mathcal{T} \left( \Theta_0 \right) \mathcal{F}_C
\]

\[
M(\Theta_0) = 3 \times 3 \text{ inertia matrix}
\]

\[
\mathcal{J} \left( \Theta_0 \right) = \text{Jacobian matrix expressed in end-effector frame}
\]

Can be transformed in terms of end-effector coordinates \(x_c\):

\[
M(x_0) \dot{x}_C = \mathcal{T} \left( \Theta_0 \right) \mathcal{T}_A + \mathcal{F}_C
\]

\[
M(x_0) = "\text{Cartesian" inertia matrix}
\]

\[
= \mathcal{T} \left( \Theta_0 \right) M(\Theta_0) \mathcal{T} \left( \Theta_0 \right)
\]

- Coupled arm / payload dynamics:
Control of Elastic Payloads: Planar Arm Example
Control of Elastic Payloads: Planar Arm Example

- System Block Diagram:

![Block Diagram Image]

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

<table>
<thead>
<tr>
<th></th>
<th>F1 (Hz)</th>
<th>F2 (Hz)</th>
<th>F3 (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm Joints Locked</td>
<td>1.2</td>
<td>14.0</td>
<td>42.2</td>
</tr>
<tr>
<td>Arm Joints Free</td>
<td>2.1</td>
<td>14.3</td>
<td>42.3</td>
</tr>
</tbody>
</table>

- Arm Mass Properties:

<table>
<thead>
<tr>
<th>Link</th>
<th>Mass (kg)</th>
<th>Center of Mass (m)</th>
<th>MOI (kg-m^2)</th>
<th>Link Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>13.8</td>
<td>0.406</td>
<td>0.77</td>
<td>0.56</td>
</tr>
<tr>
<td>Elbow</td>
<td>10.1</td>
<td>0.37</td>
<td>0.607</td>
<td>0.56</td>
</tr>
<tr>
<td>Wrist</td>
<td>13.7</td>
<td>0.14</td>
<td>0.106</td>
<td>0.254</td>
</tr>
</tbody>
</table>

- Payload Mass Properties:

<table>
<thead>
<tr>
<th>Part</th>
<th>Mass (kg)</th>
<th>Center of Mass (m)</th>
<th>EI (N-m^2)</th>
<th>Link Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>0.4</td>
<td>0.38</td>
<td>7.28</td>
<td>0.765</td>
</tr>
<tr>
<td>Tip Mass</td>
<td>0.7</td>
<td>___</td>
<td>___</td>
<td>___</td>
</tr>
</tbody>
</table>
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:
    \[ T_a = M_r(\theta) \left[ -K_p(\theta - \theta_c) - K_r \dot{\theta} \right] \]
    
    - 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:

  \[ \omega_A = \text{Rigid Arm Closed-Loop Bandwidth} \]

  \[ \Omega_P = \text{First Clamped Vibration Frequency of the Payload} \]

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:

\[
\begin{align*}
\phi & \equiv \frac{c}{\phi} \quad \text{(High-Gain PD Control)} \\
\phi = \frac{-T_\phi}{B_\phi s + K_\phi} \quad \text{(Impedance Control)}
\end{align*}
\]

\[
T_\phi \equiv - (B_\phi s + K_\phi) \phi
\]

⇒ Torque \(T_\phi\) applied to payload acts as a virtual spring/damper selected by the user !!

Experimental time responses for an initial payload elastic deformation:

<table>
<thead>
<tr>
<th>Impedance controller:</th>
<th>Arm acts as a rigid base:</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{\omega_A}{\Omega_p} = 2)</td>
<td>(\frac{\omega_A}{\Omega_p} = 2)</td>
</tr>
<tr>
<td>sensed (\lambda_g) (Nm)</td>
<td>sensed (\lambda_g) (Nm)</td>
</tr>
<tr>
<td>(0)</td>
<td>(0)</td>
</tr>
<tr>
<td>(1)</td>
<td>(1)</td>
</tr>
<tr>
<td>(2)</td>
<td>(2)</td>
</tr>
<tr>
<td>(0)</td>
<td>(0)</td>
</tr>
<tr>
<td>(1)</td>
<td>(1)</td>
</tr>
<tr>
<td>(2)</td>
<td>(2)</td>
</tr>
<tr>
<td>(d\phi) (deg)</td>
<td>(d\phi) (deg)</td>
</tr>
<tr>
<td>(-1)</td>
<td>(-1)</td>
</tr>
<tr>
<td>(-2)</td>
<td>(-2)</td>
</tr>
<tr>
<td>(-1)</td>
<td>(-1)</td>
</tr>
<tr>
<td>(-2)</td>
<td>(-2)</td>
</tr>
<tr>
<td>time (sec)</td>
<td>time (sec)</td>
</tr>
</tbody>
</table>
Control of Elastic Arms: Testbed Description
Control of Elastic Arms: Testbed Description (cont'd)

- System Block Diagram:

![System Block Diagram Image]

- 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:

\[
\begin{bmatrix}
M_{rr}(\theta_r) & M_{re}(\theta_r) \\
M_{re}(\theta_r) & M_{ee}
\end{bmatrix}
\begin{bmatrix}
\ddot{X}_r \\
\ddot{X}_e
\end{bmatrix}
+ \begin{bmatrix}
D_{rr} & D_{re} \\
D_{re} & D_{ee}
\end{bmatrix}
\begin{bmatrix}
\dot{X}_r \\
\dot{X}_e
\end{bmatrix}
+ \begin{bmatrix}
0 & 0 \\
0 & K_{ee}
\end{bmatrix}
\begin{bmatrix}
X_r \\
X_e
\end{bmatrix}
= \begin{bmatrix}
I_2 \\
0
\end{bmatrix}
\begin{bmatrix}
\dot{T}_s \\
\dot{T}_e
\end{bmatrix}
+ \begin{bmatrix}
\dot{\theta}_r \\
\dot{\theta}_e
\end{bmatrix}
\begin{bmatrix}
F_{Tx} \\
F_{Ty}
\end{bmatrix}
\]

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 No. | \(\theta_r = 0^\circ\) | \(\theta_r = 90^\circ\) | \(\theta_r = 0^\circ\) | \(\theta_r = 90^\circ\) |
| 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:

\[
T_s = - \left[ k_{ps}(\theta_r - \dot{\theta}_r) + k_{ps} \dot{\theta}_r \right] L_{2s}(s)
\]

\[
T_e = - \left[ k_{pe}(\theta_e - \dot{\theta}_e) + k_{pe} \dot{\theta}_e \right] L_{2e}(s)
\]

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

\[
L_2(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}
\]

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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:

![Diagram of arm configuration](a)

- $P_1 = (2.1, -2.0) \text{ m}$
- $P_2 = (2.1, -2.4) \text{ m}$

(a)
Experimental Time Responses for Slew Maneuver

Cartesian End Point Responses

Tip Sensor Responses

Control Torques

Time (sec)

X (m)

Y (m)
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 to Tip 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.