Development of an Integrated Design and Simulation Environment for Concurrent Base-Arm Motion Control of Space Manipulators

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1. Introduction

- Close to 1500 active (man-made) satellites are currently orbiting the Earth (NORAD Catalog).

- Nearly 300 new satellites were sent into the orbit in 2014.

- Typical lifetime of a satellite is between 5–10 years. During this time, the satellite can experience malfunctions such as:
  - Failure to deploy mechanisms
  - Component degradation
  - Premature depletion of fuel supply

Source: Spacecraft Encyclopedia
1. Introduction: Space Manipulators

- Currently used for inspecting, maintaining and upgrading International Space Station (Canadarm2-Dextre)
1. Introduction: Space Manipulators

- In future, easily deployable robotic systems are needed, consisting of a base (spacecraft) and a robotic manipulator, to perform servicing tasks such as:
  - Inspection
  - Repair and Refuel
  - Debris Removal
1. Introduction: Space Manipulators

- Future space manipulators behave as free-floating (or free-flying) multi-body systems:
  - Difficult to control due to the base reacting to manipulator motion
  - Difficult to test on Earth due to gravitational effects
Several methods of simulating micro-gravity conditions of space environment have been developed:

- Neutral Buoyancy
  - Fluid damping and inertia

- Parabolic Flight
  - High cost and short experiment duration

- Suspension System
  - Suspension system dynamics and friction

- Manipulator Emulation
  - Complex mechanism and controller
1. Introduction: Air-Bearing Table

- The air-bearing table is a suitable method for testing motion control schemes for space manipulators
  - Negligible dynamic influence from air-bearing
  - Minimal friction
  - Simple construction
  - Low experiment cost

- Existing air-bearing table systems are limited to specific sets of experiments

- Motion control schemes are studied under vastly different test scenarios and are difficult to compare
1. Introduction: Objectives

- Development of versatile air-bearing table platform that can perform different manipulator motion control experiments such as:
  - Planar/spatial arm control (free base)
  - Base control (manipulator actuated)
  - Concurrent base-arm control

- Development of an Integrated Design and Simulation Environment (IDSE):
  - Implement, verify, and optimize different trajectory planning and motion control schemes in virtual reality simulations
  - Apply various control schemes to the hardware platform for comparative studies
2. Hardware Platform
2. Hardware Platform: Manipulator

- Manipulator characteristics:
  - 6 actuated joints for spatial manipulation and concurrent base-arm motion control
  - Modular
  - Reconfigurable
  - Light and Cheap (COTS)
2. Hardware Platform: Base

- Circular chassis with wide air-bearing footprint for stability

- Air tank capacity sufficient for up to 2 minutes of experiment

- 2×2 m² glass table allows for test scenarios with large base translation
2. Hardware Platform: Manipulator Properties

- Allows for large manipulator motions according to the Dynamically Equivalent Manipulator (DEM) concept

- Geometric and dynamic parameters were designed to properly position and motion of the system center of mass

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Base mass</td>
<td>$m_0$</td>
<td>8.4 kg</td>
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<tr>
<td>Link 1 length</td>
<td>$l_1$</td>
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<tr>
<td>Link 1 mass</td>
<td>$m_1$</td>
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</tr>
<tr>
<td>Link 4 mass</td>
<td>$m_4$</td>
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<tr>
<td>Link 4 mass ratio</td>
<td>$m_4/m_0$</td>
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<tr>
<td>Link 6 mass</td>
<td>$m_6$</td>
<td>0.342 kg</td>
</tr>
<tr>
<td>Link 6 mass ratio</td>
<td>$m_6/m_0$</td>
<td>0.041</td>
</tr>
</tbody>
</table>
2. Hardware Platform: Onboard Instruments

- Actuation
  - MX-T servomotors driven by:
    - Current/torque input
    - Position input via internal PID

- Measurements
  - Absolute encoders
  - ArduIMU inertial measurement unit (IMU)

- Communication
  - CM-700 Motor controller
  - Arduino
2. Hardware Platform: Visual Positioning

- Kinect® module is used to track locations base and end-effector
- Dark green visual mark is selected to be distinguished from the red color of the test-bed
- Color matching and blob detection are used to locate the marks in the world frame
- IR depth sensor provide height measurements of the mark location
3. Software Platform: Physical Model

- CAD Drawing of each individual component is created in SolidWorks®
- Modules are assembled from components
- Dynamic properties are computed in SolidWorks®
- Complete model is imported into SimMechanics™ (and SimElectronics™)
3. Software Platform: Actuators

- Servomotor dynamics are modeled in Simulink™ to include:
  - Back Emf
  - Rotor Damping
  - Rotor Inertia
  - Gear ratio

- Model used to design and optimize PID gains for the servomotors
4. Integrated Design and Simulation Environment
4. IDSE: Design Process

Start

Configure hardware/software platforms

Construct joint trajectory generator

Generate joint trajectory

Select target base/arm trajectory

Trajectory feasible?

Results meaningful?

Preview manipulator behavior

Y

Preview manipulator behavior

Conduct experiment

END

N

Implement control scheme

Optimize controller
4. IDSE: Trajectory Generator

- For an end-effector trajectory, the joint trajectory can be computed from the kinematic equations using the Generalized Jacobian Matrix (GJM):

  \[
  \dot{q}_m = J^e(q_b, q_m)^{-1} \begin{bmatrix} \nu_e \\ \omega_e \end{bmatrix}, 
  \tag{1}
  \]

  \[
  J^e(q_b, q_m) = \begin{bmatrix} J_t^e \\ J_r^e \end{bmatrix} = \begin{bmatrix} J_{mt}^e \\ J_{mr}^e \end{bmatrix} - \begin{bmatrix} J_{bt}^e \\ J_{br}^e \end{bmatrix} M_b^{-1} M_m, 
  \tag{2}
  \]

- The rotation of the base can be obtained from momentum conservation equations:

  \[
  \begin{bmatrix} \omega_{bx} \\ \omega_{by} \\ \omega_{bz} \end{bmatrix} = \begin{bmatrix} -(M_b^{-1} M_m)_x \\ -(M_b^{-1} M_m)_y \\ -(M_b^{-1} M_m)_z \end{bmatrix} \begin{bmatrix} \dot{q}_{m1} \\ \dot{q}_{m2} \\ \vdots \\ \dot{q}_{m6} \end{bmatrix}, 
  \tag{3}
  \]
4. IDSE: Trajectory Generator

In the case of concurrent base-arm motion control, the kinematic equations become:

\[
\begin{bmatrix}
\dot{q}_{m1} \\
\dot{q}_{m2} \\
\vdots \\
\dot{q}_{m6}
\end{bmatrix}
= \begin{bmatrix}
J_{mtx}^e - J_{btx}^e M_b^{-1} M_m \\
J_{mty}^e - J_{bty}^e M_b^{-1} M_m \\
J_{mtz}^e - J_{btz}^e M_b^{-1} M_m \\
J_{tx}^0 \\
J_{ty}^0 \\
\left[-M_b^{-1} M_m\right]_z
\end{bmatrix}^{-1}
\begin{bmatrix}
\nu_{ex} \\
\nu_{ey} \\
\nu_{ez} \\
\nu_{bx} \\
\nu_{by} \\
\omega_{bz}
\end{bmatrix}, \quad (4)
\]
5. Experiment Design

- How to simulate 3-D base motion using a planar test setup?
- How to select suitable trajectories to test various control tasks?
- How to define, measure, and compare important performance metrics?
- How to ensure that:
  - Manipulator’s estimated geometric/dynamic properties are sufficiently accurate?
  - Hardware is capable of implementing different control schemes?
  - Simulation and experiment results are comparable?
5. Experiment Design

- Some trajectory selection considerations include:
  - Large end-effector motions to distinguish tracking error from measurement error
  - Trajectories that greatly disturb an uncontrolled base to test zero-disturbance control

- Performance criteria need to be quantified for analysis and comparison using methods such as $t$-statistics

$$ t = \frac{\bar{y}_A - \bar{y}_B - \delta}{\sigma \sqrt{\frac{1}{n_A} + \frac{1}{n_B}}}, \quad (5) $$

- Further experiment design to be conducted to overcome the planar base limitation of the air-bearing table
6. Case Study

- PID joint controllers are used to track a horizontal XY trajectory of end-effector point

- Manipulator is locked in a planar configuration

- A feasible straight line trajectory is selected to be the reference

- PID gains are optimized using Simulink™ PID Tuner and loaded directly onto the servomotors

- No feedback of end-effector point position
6. Case Study
6. Case Study: Results

Using $t$-statistic with 90% confidence level, it is shown that joint displacements of the experiment and simulation are statistically identical.
6. Case Study: Results

The base orientation from experiment and simulation are statistically identical. Simulation error for base position has a mean of 5.2 mm and standard deviation of 8.9 mm.

<table>
<thead>
<tr>
<th>Base Orientation</th>
<th>Base X</th>
<th>Base Y</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.155 deg</td>
<td>3.5 mm</td>
<td>6.9 mm</td>
<td>0.092</td>
</tr>
<tr>
<td>2.9</td>
<td>8.5</td>
<td>3.97</td>
<td>3.97</td>
</tr>
<tr>
<td>2.22</td>
<td></td>
<td></td>
<td>2.22</td>
</tr>
</tbody>
</table>
Simulation error for end-effector point position has a mean of 13 mm and standard deviation of 14 mm
7. Conclusion

- A versatile air-bearing table hardware platform for testing space manipulators is presented. This hardware platform features:
  - Sufficient actuation for spatial and/or concurrent base-arm motion control
  - Large end-effector motion and base rotation, with limited base translation

- The integrated design and simulation environment (IDSE) for the hardware platform is developed and used to
  - Generate joint trajectories from end-effector/base trajectories
  - Design and optimize controllers for hardware and software platforms
  - Study manipulator behavior in simulation and experiment concurrently

- The platform is ready for the experiment design phase and comparative studies
Thank You!  Questions?