Simulink® helps PNNL create vibration-free robotic control system

The Challenge
To develop control strategies to compensate for oscillation and vibration in a flexible, 30-foot-long robotic arm built to handle nuclear waste.

The Solution
Use MATLAB® and Simulink® to create a comprehensive, dynamic model of the arm and evaluate control options. Use the model to produce optimized linear transfer functions based on the step response of the robotic system.

The Results
Using the model created with tools from The MathWorks, engineers were able to design an optimized, vibration-free control system for the arm in a fraction of the time required for traditional control system design.

Richland, Washington-based Pacific Northwest National Laboratory (PNNL) was contracted by the U.S. Department of Energy to develop a robotic arm to break up sediment in nuclear waste. The waste was stored in tanks 40 feet underground. Because access was limited to a 42-inch hole in the top of the tank, the movable end of the robotic arm had to be long and thin, with relatively flexible links and low natural frequencies. This design made the arm prone to vibration and oscillation.

The Challenge: Control system difficult to model and test with conventional design tools

PNNL engineers settled on a design concept that included a long-reach manipulator (LRM), used for coarse positioning, with a lighter-duty short-reach manipulator (SRM) mounted on its tip. With sensors and control computers in place to provide feedback control for oscillation damping, the basic idea was to alter the intended command trajectory of the short arm to take advantage of the arm's own inertial forces. The movement would cancel oscillations while still meeting the normal requirements of stability, robustness, and reliability.

This highly nonlinear system would be difficult to model with conventional design tools.

Testing a physical prototype could take years

PNNL engineers built a prototype of the proposed design in half scale. The test bed was a steel beam 15 feet long, one foot high, and 0.75 inches thick. The beam was fixed at one end and free to move in a horizontal plane at the other. The free end was supported by an air bearing that provided a low-friction interface with the floor while restricting any torsion about the longitudinal axis of the beam. A six-degree-of-freedom hydraulic manipulator was mounted on the beam at the free-floating end to represent the SRM.

While the physical prototype could be used to evaluate many control strategies, engineers could spend years in this physical testing environment in a search for the optimal approach.

The Solution: Computer simulation

PNNL engineers chose MATLAB® and Simulink® to evaluate alternative control strategies. Computer simulation allowed them to consider many operational parameters, such as the position, velocity, and acceleration of every point at each time step in the simulation. That data was then used in analysis routines to calculate optimal control equations.

The MathWorks Inc.

"[These] modern engineering modeling tools allow engineers to create realistic simulations of controlled mechanical systems. This approach frees engineers from the time-consuming and error-prone process of manually writing their own equations of motion."

— Carl Baker, PNNL

PNNL engineers used DADS (Dynamic Analysis and Design System) 3-D mechanical system simulation software from Computer Aided Design Software, Inc., to model the mechanics. This software, which interfaces with MATLAB and Simulink, allowed engineers to quickly model, simulate, and animate the basic test bed system. The model included open- and closed-loop control systems and realistic hydraulic valve and actuator properties. It also incorporated finite element results that accurately modeled the flexible link.

The tools had met the biggest simulation challenge—accurately reflecting physical reality. Once linearized, the model was used to develop the constant-coefficient differential equations that drive the controller design models (CDMs), the mathematical models that compute the actuator responses needed to dampen vibrations. The step functions developed from the simulation output were applied to the azimuth angle of the SRM, and the LRM tip response signals were measured.

PNNL engineers analyzed those responses to produce optimized linear transfer functions based on the step response of the robotic system. The analysis was performed under a variety of loading conditions to obtain a family of transfer functions.

The Results

- **Realistic, time-saving simulations.** With tools from The MathWorks, PNNL engineers were able to create a comprehensive, computer-based, dynamic model of the robot that led to the design of an optimized, vibration-free control system for the arm in a fraction of the time required for traditional physical testing.
- **Quick, accurate feedback.** The simulation, using MATLAB, Simulink, and DADS, showed that the control system provided the required level of vibration damping, stability, robustness, and reliability.
- **Reliable measurements of performance.** The next step was to implement the control and test its performance on the prototype robot. The physical test results matched those achieved on the simulation very closely and again demonstrated the damping capabilities and robustness of the CDMs.

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