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Model of Rotary-Actuated Flexible Beam With Notch Filter Vibration Suppression Controller and Torque Feedforward Load Compensation Controller*

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DISCLAIMER

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ABSTRACT

This paper describes Oak Ridge National Laboratory's (ORNL's) development of an environment for the simulation of robotic manipulators. Simulation includes the modeling of kinematics, dynamics, sensors, actuators, control systems, operators, and environments. Models will be used for manipulator design, proposal evaluation, control system design and analysis, graphical preview of proposed motions, safety system development, and training. Of particular interest is the development of models for robotic manipulators having at least one flexible link. As a first application, models have been developed for the Pacific Northwest Laboratory's Flexible Beam Test Bed (PNL FBTB), which is a 1-Degree-of-Freedom, flexible arm with a hydraulic base actuator. ORNL transferred control algorithms developed for the PNL FBTB to controlling IGRIP models. A robust notch filter is running in IGRIP controlling a full dynamics model of the PNL test bed. Model results provide a reasonable match to the experimental results (quantitative results are being determined) and can run on ORNL's Onyx machine in approximately realtime. The flexible beam is modeled as six rigid sections with torsional springs between each segment. The spring constants were adjusted to match the physical response of the flexible beam model to the experimental results. The controller is able to improve performance on the model similar to the improvement seen on the experimental system. Some differences are apparent, most notably because the IGRIP model presently uses a different trajectory planner than

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the one used by ORNL on the PNL test bed. In the future, the trajectory planner will be modified so that the experiments and models are the same. The successful completion of this work provides the ability to link C code with IGRIP, thus allowing controllers to be developed, tested, and tuned in simulation and then ported directly to hardware systems using the C language.

DOE PROJECT RELATED

Since the late 1940s and early 1950s one of the primary missions of the Department of Energy (DOE) and its predecessor agencies, the Atomic Energy Commission and the U.S. Energy Research and Development Agency, has been the production of strategically important radioactive materials. Each production facility handling radioactive materials generated waste by-products, and one of the most common disposal approaches for liquid and sludge waste streams was storage in large, single-shell steel, underground storage tanks or in large, reinforced concrete, above-ground silos. This approach was viewed as a temporary solution since the storage tanks were typically designed for 20- to 50-year life cycles. Unfortunately many of these tanks are still in use and have developed leaks. As a result, DOE is currently engaged in an aggressive effort to reduce the generation of radioactive waste by-products and to remediate contaminated sites and facilities. One of the highest priority remediation areas is waste storage tanks and, in particular, those tanks suspected of or documented as leaking. Many of the concepts envisioned for deployment of remediation tools in waste storage tanks rely on long-reach, high-capacity manipulator systems. Construction of prototype arms or experimental test beds is cost prohibitive and time consuming. The ability to evaluate concepts and proposed designs through simulation is essential. In addition, once systems are deployed, training of operators is necessary and simulation will be an important component of the typical training systems.

SIMULATION NEED

Simulation, including the modeling of kinematics, dynamics, sensors, actuators, control systems, operators, and environments can be used for manipulator design, proposal evaluation, control system design and analysis, graphical preview of proposed motion, safety systems, and training. Of particular interest to Oak Ridge National Laboratory's (ORNL's) robotics programs is the development of models for high-aspect ratio, long-reach robotic manipulators having at least one flexible link; modeling hydraulic components such as actuators and valves; simulation of nonlinearities in robots such as nonlinear drive-train compliance, nonlinear friction, and nonlinear gear boxes.

Besides the aforementioned uses, simulation can also provide a deeper understanding of the physical phenomena governing a system. In simulation, for example, it is easy to vary physical parameters, thereb, allowing one to investigate the cause-and-effect relationship in a physical system. The goal of this simulation was to see if it was possible to construct a realistic model of the Pacific National Laboratory's Flexible Beam Test Bed (PNL

FBTB) and to couple the model with the input shaping filter controller. A future goal is to use the model to investigate the physical effects of particular parameters.

Preliminary results indicate that the PNL FBTB can be accurately simulated using IGRIP at least when the significant vibration characteristics are considered. Agreement between experimental test data and simulated data for the first two natural frequencies is within a few percent.

MODELING

The IGRIP model consists of a 413.3-lb, 164 in.-long steel beam with a 375-lb platform on the end. On the platform is mounted a single Schilling Titan II arm. In the IGRIP model the joints on the Schilling arm are locked. The beam is modeled as six rigid parts connected together with five rotational joints. The following sketch gives a detailed picture of the model and the location of the joints.

Beam kinematics are rotation about the Z axis at each of the joints. The platform has an air bearing support that prevents rotation about other axis. Mass properties which include the weight, center of gravity, and moments of inertia were added to the beam, platform, and the Schilling arm for the dynamic simulation.

MODELING IN IGRIP

The beam using a Graphic Simulation Language program. The spring values were input to the model and compared with data from the PNL the beam simulates a lumped mass system with springs at the joint locations on the beam. Spring stiffness was assigned to each joint of the best bed. When the IGRIP beam frequency responded similarly to the test bed, another joint was added as the actuator joint. The generic Porportional Intergral Derivative (PID) controller using Device/Sim/Pipeline/Controller was used to understand what input and output IGRIP would accept. Then, using the shared library capability in IGRIP, a C-routine controller similar to one used on the PNL test bed was added to the IGRIP model.

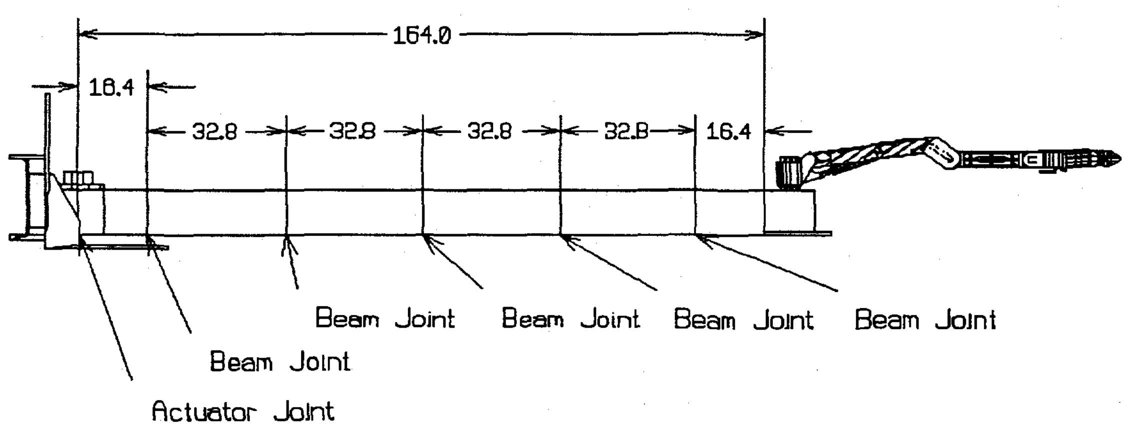

Figure 1. IGRIP Model of Pacific Northwest Laboratory Flexible Beam Test Bed

FEEDBACK CONTROLLER

The PID controller has been designed by modifying the IGRIP example C-routine "dyn_cont_ex.c" of the shared library. The PID gains are carefully tuned to represent the experimental system's feedback servo-loop characteristics such as the servo bandwidth and the damping ratio.

ROBUST INPUT SHAPING FILTER

For a trajectory planner, the IGRIP default trajectory planner has been used. Since it is using the third order polynomial for the joint position trajectory, the acceleration profile exhibits very steep slopes that generate a torque profile with high-frequency components. In order to prevent these high-frequency components from exciting the resonant frequency of the manipulator system, various input shaping filters have been proposed such as a robust notch filter, an impulse shaping filter, a feedforward simulation filter, and a fuzzy shaping filter. [Kwon 94] Among them the robust notch filter has been applied to the IGRIP simulation model by being modified to be called from the PID controller C-routine.

The transfer function $F(s)$ of the robust notch filter [Jansen 92] is given by the cascade of the two notch filters to filter the first and second resonant frequency component.

The robust notch filter introduces zeros at the resonant frequecy of ω_{zi} and adds critically damped poles at the frequency of ω_{pi}. The parameter α_i was set, by trial, to 1.6 to obtain the fastest possible system response without excessive oscillatory joint motion. By having higher-order poles, the filter has a low-pass filter effect. For an initial test, the filter of $n = 1$ was applied. To make it more robust to variations in the plant, the order of filter n can be increased at the cost of slow response, as is the case for the impulse shaping filter. [Kwon 94]

TORQUE FEEDFORWARD LOOP

For better tracking, the required torque calculated based on the rigid body assumption has been added as another feedforward loop. The feedforward torque has been calculated with the acceleration profile that is filtered with the above shaping filter.

$$F(s) = \frac{\left[\left(\frac{s}{\omega_{z1}}\right)^2 + 1\right]^n \left[\left(\frac{s}{\omega_{z2}}\right)^2 + 1\right]^n}{\left[\left(\frac{s}{\omega_{p1}}\right)^2 + 2\frac{\zeta_{p1}}{\omega_{p1}}s + 1\right]^n \left[\left(\frac{s}{\omega_{p2}}\right)^2 + 2\frac{\zeta_{p2}}{\omega_{p2}}s + 1\right]^{n+1}}$$

where ω_{z1}, ω_{z2} = first and second resonant frequency of the closed loop system;

ω_{pi} = ith low-pass filter natural frequency,

$$\omega_{pi} = \alpha_i \omega_{zi} \quad (\alpha_i = 1 \sim 2);$$

ζ_{pi} = damping ratio of the ith filter (set to 1 to achieve a critically damped response).

CLAMPED SYSTEM NATURAL FREQUENCY

The model's actuator joint was locked (kinematics not added), and the first joint of the beam was jogged and released to obtain the natural frequency of the beam. The IGRIPs charting capability was used to determine the beam's oscillation frequency as spring values were adjusted. When the model responded with a first and second natural frequency similar to the test bed, the spring coefficients used in IGRIP were checked using calculated values from the equation of motion and the natural frequency.

COMPARISON OF PID CONTROLLERS

Two cases were refined to control the beam in reaching its desired goal. The same gain parameters and bounds were used on each case. The first case was the embedded PID controller in IGRIP which took approximately 70 seconds to reach the desired position. The PID controller allowed the beam to follow the ideal displacement path but overshot the desired position which caused the beam to oscillate as the controller tried to correct to the desired position. The second case was the PID controller with a shaping filter which took 20 seconds to reach the desired position. When the PID with the shaping filter was applied, the beam took longer to reach the desired position but did not significantly overshoot the desired position. Figures 2 and 3 show the two cases.

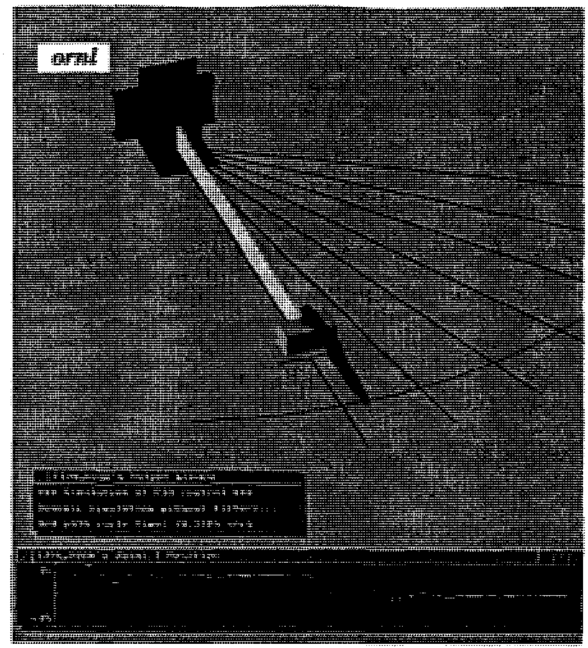

Figure 2. Simulation of PID control without filters

USEFULNESS OF THE IGRIP DYNAMIC SIMULATION

The usefulness of the IGRIP dynamic simulation will be demonstrated as it provides quality simulations of development algorithms allowing quick graphical preview of a design and its controls.

FURTHER EXTENSION

The Robotics and Process Systems Division at ORNL plans to pursue using the IGRIP software on the development of systems that control robotic and telerobotic manipulators. Future tasks that will allow the IGRIP models to respond more like physical reality include adding a customized trajectory planner and adding a hydraulic actuator model.

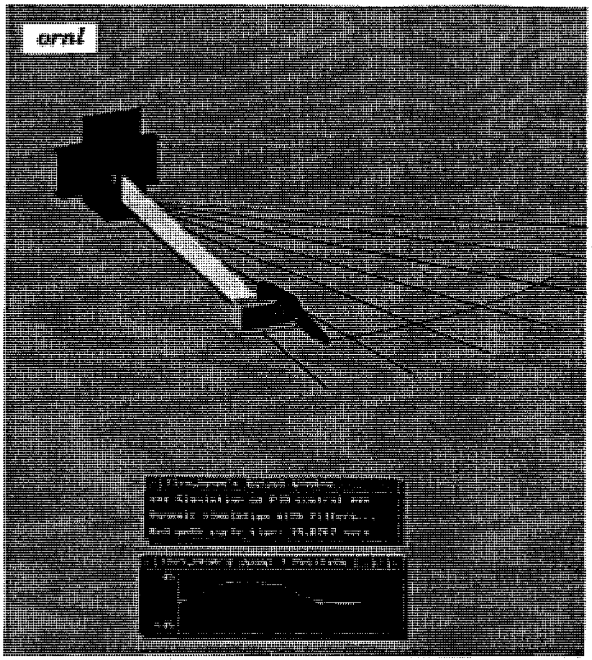

Figure 3. Simulation of PID control with feedback filters

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