

SIMULATION OF ROBOT MANIPULATORS*

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ABSTRACT

This paper describes Oak Ridge National Laboratory'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 Laboratories' Flexible Beam Testbed which is a one-Degree-Of-Freedom, flexible arm with a hydraulic base actuator. Initial results show good agreement between model and experiment.

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INTRODUCTION

General

This paper describes Oak Ridge National Laboratory's (ORNL) development of an environment for the simulation of robotic manipulators and of simple simulation of an experimental manipulator. 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 systems, and training. Of particular interest 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 non-linearities in robots such as non-linear drive-train compliance, non-linear friction, and non-linear gearboxes.

Specific

Since the late 1940's and early 1950's 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 aboveground 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 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 testbeds 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 will be necessary and simulation will be an important component of the typical training systems.

Along with the clean up of waste disposal sites, decontamination and dismantlement of decommissioned facilities is an important problem. Systems such as the Selective Equipment Removal System (SERS)¹ are being developed for this application. These systems not only need to be designed with the aide of simulation but they also need to rely on simulation to help in operational planning, control (especially for collision avoidance between the surrounding hardware and between the multiple arms), and for training.

Brief Literature Review

Examination of recent conference literature reveals the use of simulation in numerous robotic applications. A controller for a Load-Haul-Dump unit is designed and simulated in Goulet et al.² Workcell layout and joint motion constraints were simulated for a plasma spray system in Robinson et al.³ A study of joint characteristics such as compliance, hysteresis, and friction were studied via simulation in Kircanski and Goldberg.⁴ Underwater vehicle dynamics were simulated in McMillan et al.⁵ A simulation technique for use in the design of control architectures for automated workcells is described in Adam and Grant.⁶ A simulation package for the modeling of multi-link robots that interact with objects is detailed in Lee et al.⁷ There are many other examples of the importance and need for accurate simulation of robotic

mechanisms. This paper will present some of the requirements necessary to simulate robotic arms and their environments as well as describe an example simulation.

COMPUTER REQUIREMENTS FOR SIMULATION

The requirements for a typical simulation are determined from the system and environment being modeled. The next sections address the problem of developing a model for the SERS dual arm system described in Noakes et al.¹

Typical Model

A typical modeling problem is the real-time (or near real-time) simulation and control of a multiple arm robotic system mounted on a mobile base working in a detailed environment such as might be present in a chemical processing plant or nuclear power plant. The SERS is an example of such a system. A typical model consists of the following: two 6-Degree-of-Freedom (DOF) arms which might need to be modeled as flexible arms, one 5-DOF base platform, multiple tools such as saws, drills, grinders, torches, portable sensors, etc. This system moves and operates in an environment described by a detailed world model. A typical 6.1 x 6.1 x 6.1 m (20 x 20 x 20 ft) section of world model might contain the following hardware^a: brick wall as background, 4 processing tanks, 50 vertical pipes, 50 horizontal pipes, 100 instrument lines, 50 electrical lines, 25 valves, 10 pressure gauges. This equipment density would be repeated 10-20 times in a typical 30.5 x 15.2 x 15.2 m (100 x 50 x 50 ft) high bay. The multiple arm system maneuvers in this environment and performs tasks such as equipment repair, equipment removal, inspection, and operation. The movement is aided by views from several pan/tilt camera systems. An accurate simulation requires: 1) a graphical description of all of the systems, components, manipulators, and facilities in the high bay; 2) dynamic models of all moving components including manipulator arms, tools, and mobile bases; and 3) moveable descriptions of support systems such as cameras, lights, and deployable sensors.

Computational Requirements

The basic computational requirements for modeling of a manipulator system are described in two references. For dynamic modeling one must calculate accelerations based

^a Based on an examination of hardware in a typical chemical processing high bay located in the Robotics & Process Systems Division of ORNL.

on forces and torques and typical methods are outlined in Walker and Orin.⁸ For control, it is necessary to determine forces and torques required to provide a desired motion and typical approaches are outline in Hollerbach.⁹ For a flexible arm, as many as 100-DOF are expected to be modeled in order to simulate the flexible modes of the system. Choosing the most efficient methods from each reference, considering real-time calculations at 100 Hz for two arms, one can calculate a required computational capacity on the order of 100-300 MFLOPS. Consider Table 1 which presents the computational capability of the Silicon Graphics, Inc. (SGI) family of computers.

Table 1. Computational capability of the SGI family of computers.

Computer	MFLOPS (1000X1000)
Indy R4000SC	28.4
Indigo R4400SC	42.3
Crimson Jurassic Classic	40.0
Challenge R4400SC	42.3
Onyx 100-MHz CPU	119.6
Onyx 150-MHz CPU	175.0

Table 1 shows that computational capacity of this magnitude requires the use of multi-processor platforms such as the Silicon Graphics Onyx-class machines or other manufacturer's multi-processor units such as the SUN SPARCstation 10-class machines.

Graphical Requirements

The basic graphical requirements for the typical model described above can be determined by examining the requirements for similar models developed in the past. A model of a standard industrial robot arm (Schilling Arm) developed by ORNL's Robotics & Process Systems Division requires the use of 1500 polygons. Assuming two arms, a base platform, several other tools, and a very simple background, it can be calculated that the model would require ~35,000 polygons. Updating and displaying this model at the video rate of 30 Hz would require a graphical rate of greater than 1 Million Polygons/second. Table 2 compares the graphical specifications for the SGI Onyx and the SUN SPARC10 computers. Either the SGI or the SUN can handle the 1 Million polygons/second requirement as is evidenced by the 3D Tmesh/s specifications. The real challenge arises, however, when a more complicated model is developed. An example of such a model is given by the University of Tennessee's models

of robots working in simulated nuclear plant environments. In these cases, a complete model requires on the order of 500,000 polygons.¹⁰ Updating and displaying this model

Table 2. Graphical performance comparison between SGI Onyx and SUN SPARC10 four processor systems.

Performance Area	SGI ONYX/4 RE ²	SUN SPARC10 Model 514MP
Resolution (pixels)	1280X1024	1280X1024
Color planes (bits)	192	24
Overlay (bits)	8	24
z-buffer (bits)	32	24
Texture Memory (MB)	16	-
3-D Tmesh/s 50 pixels	1.6 M	3.0 M
3-D Quads/s 100 pixels	500 k	600 k

at the video rate of 30 Hz requires greater than 10 Million Polygons/second capability. These rates dictate a machine that is capable of texturing. Texturing allows for the representation of objects made up of many polygons as a single polygon with a given texture. For example, texturing allows one to represent a brick wall as one polygon with the brick texture as opposed to having one polygon for each brick. This significantly reduces the complexity in terms of numbers of polygons of the ensuing graphical models.

SIMULATION OF PNL FLEXIBLE BEAM TESTBED

Description of Basic Model

An important first application for the simulation system at ORNL is to develop models of robotic arms having high-aspect ratios (large length with respect to cross-sectional dimensions). Such arms are an essential tool in the Tank Waste Retrieval (TWR) task where it is proposed to use high-aspect ratio arms to remove waste from storage tanks having large diameters and limited access. Models have been developed for the Pacific Northwest Laboratories' (PNL) Flexible Beam Testbed (FBTB) which is a 1-DOF, flexible arm with a hydraulic base actuator. This system has been used extensively for the development of control algorithms for flexible robotic arms.

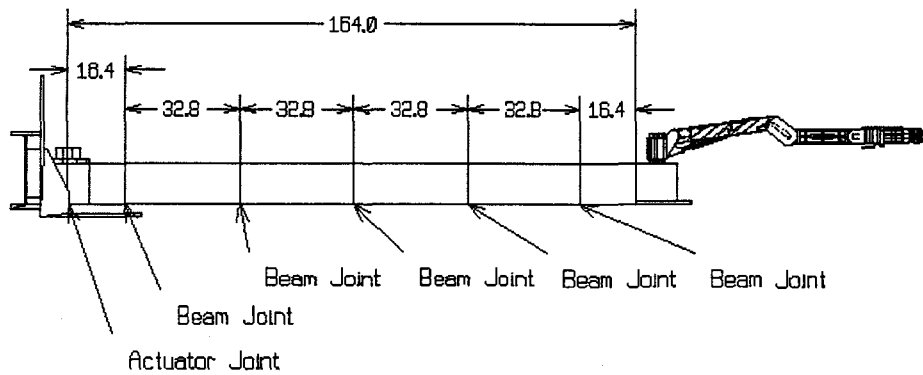


Fig. 1. PNL Flexible Beam Test Bed with base hydraulic actuator, 4.17-m (164-in.) long, 0.30-m (12-in.) tall, 1.91-cm (0.75-in.) thick steel flexible link, and end frame with Schilling Titan II manipulator.

A typical modeling problem is the near real-time simulation and control of the PNL FBTB. Accurately modeling a system such as this requires a model with more than one DOF because of the flexible modes of the beam. As an initial approach, the beam is broken down into segments, and the model and physical agreement is restricted to only a few modes. Thus, the major vibration characteristics are simulated which are the most important characteristics for control algorithm development.

The PNL FBTB was constructed to study the fundamental control issues associated with the structural vibration of a flexible link manipulator. It consists of a 4.17-m (164-in.) long, 0.30-m (12-in.) tall, 1.91-cm (0.75-in.) thick steel beam, weighing approximately 187.7 Kg (413 lbf) with a 170.5 Kg (375 lbf) platform plus a Schilling Titan II arm mounted on the end. The base has a rotary, rack-and-pinion style hydraulic actuator. The PNL FBTB is illustrated graphically in Fig. 1.

The PNL FBTB was modeled using the TELEGRIP software from Deneb Robotics, Inc. For the model, the beam is divided into six major segments: a 0.42-m (16.4-inch) long rigid base, four 0.83-m (32.8-inch) long rigid midsegments, and a 0.42-m (16.4-inch) long rigid end segment and platform. Each of the segments are 0.30-m (12-inches high), 1.91-cm (0.75-inches) thick, and have a density of 7750 Kg/m³ (0.28 lb_m/in³). Masses and inertias are calculated by TELEGRIP using the specified dimensions and mass properties. Each of these rigid body segments are assumed to be connected by torsional spring/dampers at the axes labelled beam joint. Spring constants of 39.5 KN-m/rad (350 Klb_f-in/rad) and damping

coefficients of 90.4 N-m/rad/s (800 lb_f-in/rad/s) are used for each "joint". One can determine the equivalent spring constant of a cantilever beam by equating the torque developed at the beam's base by a force acting perpendicular to the beam located at the beam's end, to the torque generated by an imaginary torsional spring located at the beam's base and deflecting through the angle required to produce the endpoint deflection developed by the applied force (see Fig. 2).

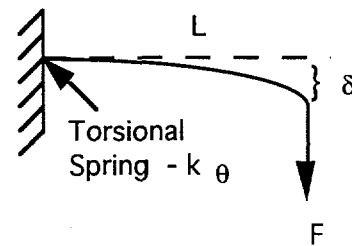


Fig. 2. Equivalent torsional spring model of beam.

The torque developed at the base of the beam by the end force is given by the product of the force and the beam length:

$$\text{Torque} = FL \quad (1)$$

The torque is also given by the product of the torsional spring constant and the angle of deflection:

$$\text{Torque} = k_{\theta} \theta = k_{\theta} \tan^{-1}\left(\frac{\delta}{L}\right) \approx k_{\theta} \frac{\delta}{L} \quad (2)$$

Equating the two expressions for torque from eqs. (1) and (2) one obtains:

$$k_{\theta} = \frac{FL^2}{\delta} \quad (3)$$

The expression for the deflection of a cantilever beam is found in numerous elementary mechanics texts and is:

$$\delta = \frac{FL^3}{3EI} \quad (4)$$

Substituting eq. (4) into eq. (3) produces:

$$k_{\theta} = \frac{3EI}{L} \quad (5)$$

for the equivalent spring constant of a cantilever beam. Calculating the equivalent spring constant for a 0.83-m (32.8-inch) long segment (the length of one of the midsection pieces) and for a 4.17-m (164-inch) long segment (the entire beam length) produces 131.1 KN-m/rad (1160 Klbf-in/rad) and 26.2 KN-m/rad (232 Klbf-in/rad) respectively. The simulated torsional spring constant between each segment was adjusted between these two values to bring the first and second natural frequencies of the model to approximately 0.3 Hz and 2.3 Hz, respectively, which is within a few percent of the actual PNL FBTB system. The simulated joint spring constants were all set to 39.5 KN-m/rad (350 Klbf-in/rad). This value is bracketed by the values determined above, as it should be, since the overall beam 4.17-m long (k_{θ} of 26.2 KN-m/rad) is approximated by a series combination of short segments of 0.83-m (k_{θ} of 131.1 KN-m/rad). The combined set of rigid segments connected by torsional springs should require a spring constant less than the spring constant of the individual segments but certainly greater than the spring constant of the entire beam. The TELEGRIP model consisted of 2678 polygons and is further described in Bills et al.¹¹

Control Algorithm Description

Several controllers were designed and tested on the PNL FBTB including an impulse shaping filter, a robust notch filter, a model-based feed-forward technique, and a fuzzy logic based filter. These are described and experimental results are presented in Kwon et al.¹² For the simulation, the performance of a well-tuned PID controller was compared to the robust notch filter technique described in Kwon et al.¹² The robust notch filter was selected because it requires only knowledge of the dominant vibration frequencies. Robust formulation implies that it is insensitive to variations in the controlled system's dynamics but it achieves this by sacrificing speed of response (this is a result of multiple zeros). The robust notch filter is formulated by the cascade of two notch filters that filter inputs at the first two resonant frequencies.¹³

The transfer function of the robust notch filter is given by¹³:

$$F(s) = \frac{\left[\left(\frac{s}{\omega_{z1}} \right)^2 + 1 \right]^n \left[\left(\frac{s}{\omega_{z2}} \right)^2 + 1 \right]^n}{\left[\left(\frac{s}{\omega_{p1}} \right)^2 + 2 \frac{\zeta_{p1}}{\omega_{p1}} s + 1 \right]^n \left[\left(\frac{s}{\omega_{p2}} \right)^2 + 2 \frac{\zeta_{p2}}{\omega_{p2}} s + 1 \right]^{n+1}} \quad (6)$$

where,

ω_{z1}, ω_{z2} = 1st and 2nd resonant frequency of the closed loop system;

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

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

The robust notch filter introduces zeros at the resonant frequency 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. For the filter to be more robust to variations in the plant, the order of filter n can be increased at the cost of a slower response, as is the case for the impulse shaping filter.¹²

In addition to the robust notch filter, a signal calculated from the torque was used in a feed-forward loop for load compensation. In the experimental system, hydraulic pressure instead of torque was used for the feed forward signal. (Hydraulic pressure will be used in future models when the hydraulic actuator is completely modeled.)

Basic Simulation Results

The controller described in the previous section was applied to the TELEGRIP model of the PNL FBTB. The default TELEGRIP trajectory planner (a third order polynomial fit to the joint position trajectory) was used for simulated movements from 0 to 0.5 rad back to 0, and 0 to 1.0 rad back to 0. The performance of the model agreed to within a few percent of the experimental performance. For step inputs of ~ 0.5 radians, settling times on the order of 1 second are typical of the output from the system with the robust notch filter whereas settling times on the order of 10 seconds are characteristic of the non-filtered response. Both the simulation and the experiment show the same results.

CONCLUSIONS

The capability to simulate robotic systems for manipulator design, proposal evaluation, control system design and analysis, graphical preview of proposed motions, safety system development, and training is essential for more rapid and cost-effective design, implementation, and fielding of robotic systems. An essential feature of high quality modeling is the verification of models with experimental data. ORNL has initiated its robotic simulation efforts by modeling the PNL FBTB system and initial results indicate that good agreement can be achieved between simulation and experiment using physically realistic parameters. Future work will focus on including more of the dynamic elements in the simulation such as hydraulic actuators, multi-DOF flexible links, combined manipulator and end-effector motions, and payload variations; and on the simulation of different robotic and telerobotic systems.

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