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Telerobotic Operations of Structurally Flexible, Long-Reach Manipulators

Dong-Soo Kwon, Dong-Hwan Hwang, and Scott M, Badcock
Robotics & Process Systems Division
Oak Ridge National Laboratory

ABSTRACT

As a part of the Department of Energy's Environmental Restoration and Waste Management Program, long-reach manipulators are being considered for the retrieval of waste from large storage tanks. Long-reach manipulators may have characteristics significantly different from those of typical industrial robots because of the flexibility of long links needed to cover the large workspace. To avoid structural vibrations during operation, control algorithms employing various types of shaping filters were investigated. A new approach that uses imbedded simulation was developed and compared with others. In the new approach, generation of joint trajectories considering link flexibility was also investigated.

1. Introduction

Within the Department of Energy's (DOE's) Environmental Restoration and Waste Management (ER&WM) program, underground storage tank cleanup is one of the most urgent tasks. The use of long-reach manipulators is considered to be one of the most advantageous approaches for the retrieval of waste from large tanks. The development of a tank waste retrieval manipulator system (TWRMS) may be one DOE's most significant robotics projects. The TWRMS will consist of a long-reach manipulator (LRM) including a vertical deployment mast and a short-reach, dexterous manipulator. From preliminary studies [1][2], it is anticipated that the long-reach manipulator will have very low structural natural frequencies, and its structural flexibility will significantly affect the positioning accuracy at the end of the manipulator. Control of the end position of the LRM considering the flexibility will be very important to the performance of the various cleaning processes with the dexterous manipulator.

To study control issues associated with structural vibration of the long reach manipulator, a test-bed was built by Battelle Pacific Northwest Laboratories (PNL). The test-bed has a 15-ft-long flexible beam, with a Shilling hydraulic manipulator at the end of the beam as shown in Figure 1. The flexible beam represents the long-reach manipulator dynamically, and the Shilling manipulator represents the dexterous manipulator. An air bearing supports the end of the flexible beam to ensure planar operation.

The most prominent control methods available can be grouped as impulse shaping filters [4][5], robust notch filters [6], inverse dynamic methods [7][8] , and others including acceleration feedback [9], passive damping treatment [10], and end-position feedback [11]. The impulse shaping filter is effective but introduces a tracking delay. If multiple impulses are used for robust filtering, the increased time delay introduced may be a serious problem for teleoperation and robotic tracking control of a very flexible manipulator that has a very low system bandwidth. The shaping filter method using a robust notch filter is easy to use and practical. Since it has a low-pass filter effect, it is robust to the unwanted high-frequency command. But it also introduces a significant time delay like that of an impulse shaping filter. In this research, the above shaping filter methods were demonstrated and evaluated, and a new method called "feedforward simulation filtering" was proposed and demonstrated. The feedforward simulation filtering method incorporates the advantages of several other methods.

2. Control System

The control software was designed within the framework of the Modular Integrated Control Architecture (MICA) to enhance modularity, graphic user interface, and expandability. MICA is a software package developed at Oak Ridge National Laboratory (ORNL) to provide a framework for robotic manipulator control. MICA provides operational codes that are portable among different manipulators and operating environments [12]. MICA also provides precise operation of multiple processors that have to be coordinated to control manipulators. With the MICA framework, specific aspects of the long-reach manipulator control can be concentrated in the controller development stage.

The hardware for the control system consists of a SUN workstation and a VME bus-based system rack as shown in Figure 2. The SUN workstation is used for the man-machine interface and supervision of the control system. The system rack contains CPU boards and several interface cards for data acquisition. Depending on the computational load, CPU boards can be added and the control software can be adapted easily for multiple processors. The data exchange between the SUN workstation and the system rack is by Ethernet.

3. Modeling

The flexible beam of the PNLs testbed was modeled by using the assumed mode method. To obtain an accurate model with a small number of modes, pinned-pinned boundary conditions with inertia and mass was used for the calculation of mode shaping functions [7]. The testbed was modeled as a single flexible beam with an end mass and a rotational inertia with

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$$[M]\ddot{q}+[D]\dot{q}+[K]q=[B]\tau, \tag{1}$$

where the generalized coordinate is $\begin{Bmatrix} q_0 \\ q_1 \\ \vdots \\ q_n \end{Bmatrix}$.

The inertia matrix $[M]$ is expressed with mode functions:

For $i,j=0,1,\cdots,n$,

$$[M]=\begin{bmatrix} M_{ij} & \cdots \\ \vdots & \ddots \end{bmatrix}, \quad \text{where } M_{ij}=\begin{pmatrix} \rho A\int_0^l \phi_i(x)\phi_j(x)dx \\ +I_h\phi_i'(0)\phi_j'(0) \\ +M_e\phi_i(1)\phi_j(1) \\ +J_e\phi_i'(1)\phi_j'(1) \end{pmatrix}$$

ϕ_i is the mode function, I_h is the hub rotational inertia, M_e is the end mass, and J_e is the rotational inertia.

The damping matrix $[D]$ represents the viscous joint friction, and the input matrix $[B]$ is for the joint torque:

$$[D]=c_0\begin{bmatrix} \phi_i'(0)\phi_j'(0) & \cdots \\ \vdots & \ddots \end{bmatrix}, \qquad [B]=\begin{bmatrix} \phi_i'(0) \\ \vdots \end{bmatrix}$$

The stiffness matrix is,

for $i,j=0,1,\cdots,n,$

$$[K]=\begin{bmatrix} 0 & 0 & \cdots \\ 0 & K_{ij} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}, \text{ where } K_{ij}=EI\int_0^1 \phi_i''(x)\phi_j''(x)dx.$$

4. Approaches and Results

4.1 Impulse shaping filter

The filter was designed to cancel out the dominant vibration mode of the closed-loop system with three impulses [4]. The impulse was digitally convoluted to the desired command.

$$h(t)=\frac{1}{(1+M)^2}\delta(t)+\frac{2M}{(1+M)^2}\delta\Big(t-\frac{\pi}{\omega_n\sqrt{1-\zeta^2}}\Big) + \frac{M^2}{(1+M)^2}\delta\Big(t-\frac{2\pi}{\omega_n\sqrt{1-\zeta^2}}\Big) \tag{2}$$

where $M=e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}}$,

ω_n= undamped natural frequency,

ζ = damping ratio of the dynamic system.

The impulse shaping filter actually introduces zeros where the system's dominant closed-loop poles exist and filters out the frequency content of the command input, which may excite the dominant vibration mode. The filter divides a one-step command into a three-step command. At the first and second steps, the filtered trajectory excites the system; but at the third step, the excited vibration is canceled completely as shown in Figure 4. However, it introduces a time delay that is as long as the duration of the impulses. It is not easy to determine the exact damping ratio.

4.2 Robust notch filter

The transfer function of the robust notch filter [6] is given by

$$F(s)=\frac{\left[\left(\frac{s}{\omega_z}\right)^2+1\right]^n}{\left[\left(\frac{s}{\omega_p}\right)^2+2\frac{\zeta_p}{\omega_p}s+1\right]^{n+1}}, \tag{3}$$

where ω_z = resonant frequency of the system;

ω_p = low-pass filter natural frequency,

$\omega_p=\alpha\omega_z$ (α= 1 ~ 2);

ζ_p = damping ratio (set to 1 to achieve a critically damped response).

The robust notch filter introduces zeros at the damped vibration frequency of ω_z and adds critically damped poles at the frequency of ω_p. Parameter α was set to 1.5 for 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 responsiveness, as is the case for the impulse filter. Figure 5 shows smooth responses without overshoot. However, it also has the same tracking delay problem for slow systems that the impulse shaping filter has.

4.3 Feedforward simulation filter

Since the shaping filter induces a time delay of half the system natural frequency or multiples of that, it was not practical for very slow and very flexible systems. To avoid the tracking delay problem, the inverse dynamic method can be used by pregenerating the feedforward torque profile and the joint trajectory, which give perfect tracking at the end point. But the inverse dynamic method usually gives anticausal solutions for nonminimum phase systems [7]. Its application is limited to robotic operation.

As Cannon [11] indicated, end-position feedback could provide a much higher closed-loop bandwidth (beyond the clamped natural frequency) than that of a joint-based closed-loop feedback system. However, end-position feedback is very sensitive to the parameter variation and the modeling error. It may not be appropriate for practical applications with dynamic systems that are approximately known. The conventional proportional-derivative (PD) joint feedback system usually gives good stability, but the closed-loop bandwidth cannot be greater than the clamped natural frequency. In practical applications, it is usually less than half the fundamental clamped natural frequency [3].

Figure 3 describes a feedforward simulation filtering method that integrates most of the advantages of the above method. Since the higher bandwidth system has less time delay with the shaping filter, the closed-loop system, which has two or three times higher bandwidth than that of the joint feedback loop, was made with the end-position feedback including joint rate feedback. A feedforward torque loop was added to improve tracking. As mentioned above, because the end-position feedback is conditionally stable and sensitive to the modeling errors, it may be difficult to use for actual applications. Therefore, the end-position feedback with a robust notch shaping filter was used in the simulation to generate a joint trajectory that makes the end-position follow the desired filtered trajectory. Since the appropriate joint trajectory was generated, the joint PD controller, even with low gain, gives good tracking performance of the end-position as shown in Figure 6.

5. Conclusions

The impulse shaping filter gives good performance with knowledge of the frequency and the damping ratio of the dominant vibratory mode. The robust notch filter requires only the frequency of the dominant oscillation and gives reasonably good performance. The advantage of the robust notch filter is that it is insensitive to variations in the plant at the cost of responsiveness, as is the impulse filter. The feedforward simulation method gives almost perfect tracking performance at the price of the knowledge of the dynamics and calculation burden. Therefore, the trade-off between the performance and the requirement for prior knowledge of the system and the calculation burden should be considered in the control system design.

Even though the above mentioned filtering methods minimize overshoot and excitation of structural vibration, they must be capable of adapting the varying system frequency for the actual three-dimensional, multilink LRM. ORNL is pursuing the use of a real-time fast Fourier transform to adapt the shaping filter when the varying manipulator's configuration or payload results in significant changes in the system frequency.

References

[1] D.-S Kwon., S. March-Leuba,, S. M. Babcock, and W. R. Hamel, "Parametric Design Studies of Long-Reach Manipulators," *Proceedings of the American Nuclear Society Fifth Topical Meeting on Robotics and Remote Handling*, pp. 265–273, April 1993.

[2] D.-S. Kwon, S. March-Leuba, S. M. Babcock, and W. R. Hamel, *Key Design Requirements for Long-Reach Manipulators*, ORNL/TM-12251, Oak Ridge National Laboratory, drafted on July 14, 1992 (in the process of clearance).

[3] W. J. Book, "Controlled Motion in an Elastic World," *Trans. ASME, Journal of Dynamic Systems, Measurement, and Control*, Vol. 115, pp. 252–261, June 1993.

[4] N. C. Singer and W. P. Seering, "Preshaping Command Inputs to Reduce System Vibration," *Trans. ASME, Journal of Dynamics Systems, Measurement, and Control*, Vol. 112, pp. 76–82, 1990.

[5] D. P. Magee and W. J. Book, "The Application of Input Shaping to a System with Varying Parameters," *Proceedings of ASME Japan–USA Symposium on Flexible Automation*, San Francisco, Vol. 1, pp. 519–26, 1992.

[6] J. F. Jansen, "Control and Analysis of a Single-Link Flexible Beam with Experimental Verification," ORNL/TM-12198, Oak Ridge National Laboratory, December 1992.

[7] D.-S. Kwon and W. J. Book, "An Inverse Dynamic Method Yielding Flexible Trajectories," *Proceedings of 1990 American Control Conference*, pp. 186–93, San Diego, May 1990.

[8] E. Bayo and B. Paden, "On Trajectory Generation for Flexible Robots," *Journal of Robotic Systems*, Vol. 4, pp. 229–35, No. 2, 1987.

[9] P. Kotnik, S. Yurkovich, and Ü. Özgüner, "Acceleration Feedback for Control of a Flexible Manipulator Arm," *Journal of Robotic Systems*, Vol. 5, No. 3, pp. 181–96, 1988.

[10] T. E. Alberts, H. Xia, and Y. Chen, "Dynamic Analysis to Evaluate Viscoelastic Passive Damping Augmentation for Space Shuttle Remote Manipulator System," *Trans. ASME, Journal of Dynamic Systems, Measurement, and Control*, Vol. 114, pp. 468–75, 1992.

[11] R. H. Cannon and E. Schmitz, "Initial Experiments on the End-Point Control of a Flexible One-Link Robot," *The International Journal of Robotic Research*, Vol. 3, No. 3, pp. 62–75, Fall 1984.

[12] P. L. Butler, "An Integrated Architecture for Modular Control Systems," *Robotics and Autonomous Systems*,, Vol. 10, No. 2–3, 1992.

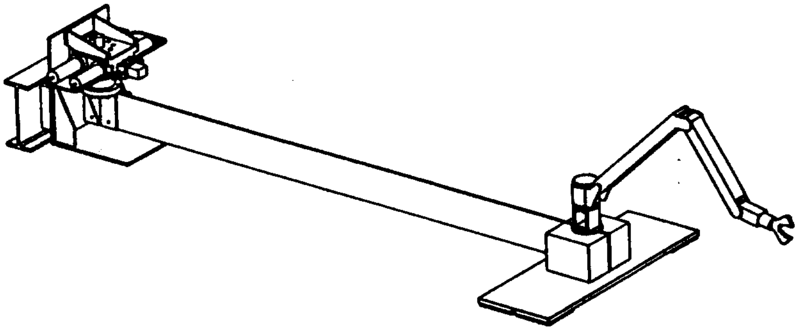


Figure 1. Flexible-beam test-bed built by Battelle Pacific Northwest Laboratories.

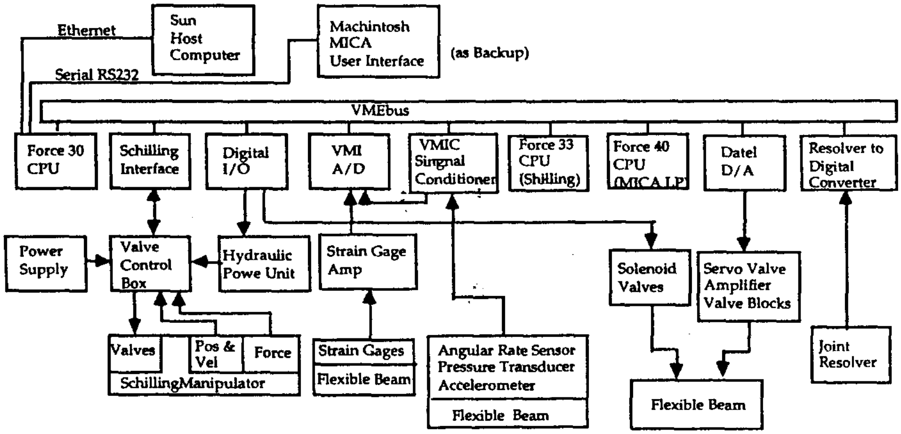


Figure 2. VME system controller for the flexible-beam testbed.

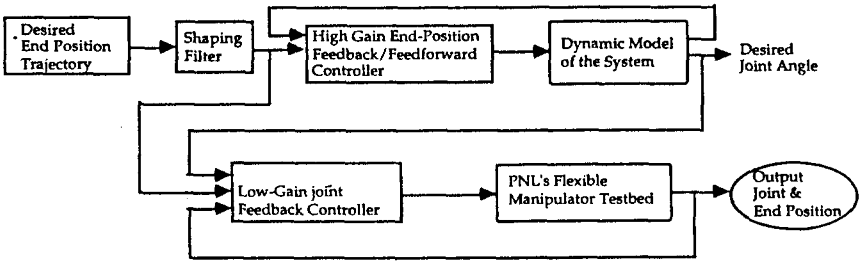
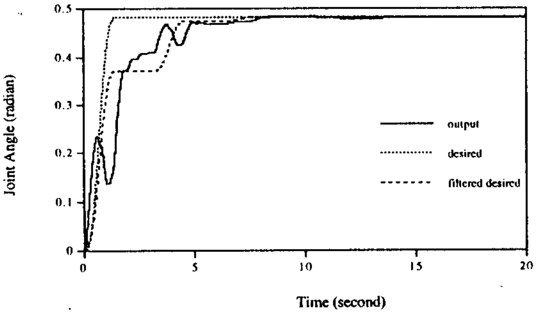
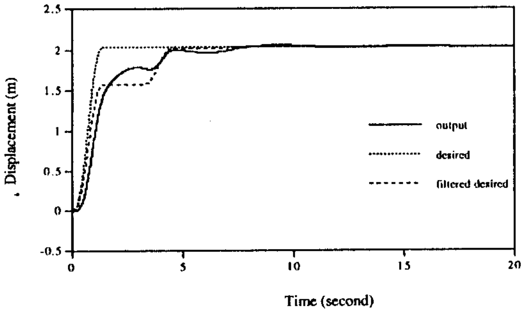


Figure 3. The feedforward simulation filtering method.

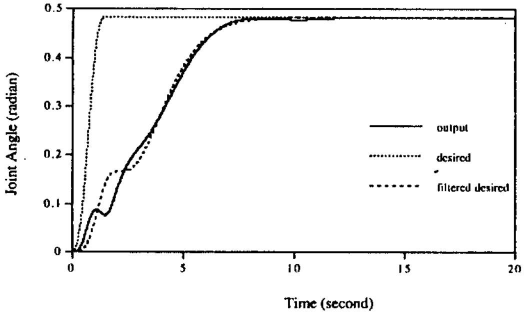


(a) Joint trajectory

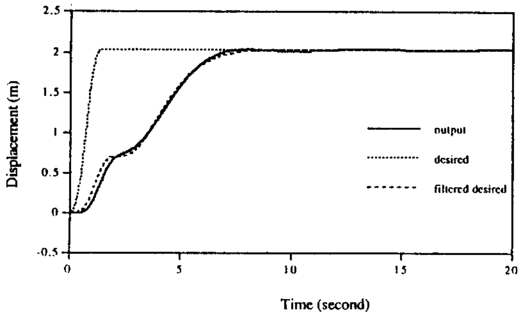


(b) End-position trajectory

Figure 4. Responses of the impulse shaping filter with the joint proportional-derivative controller.

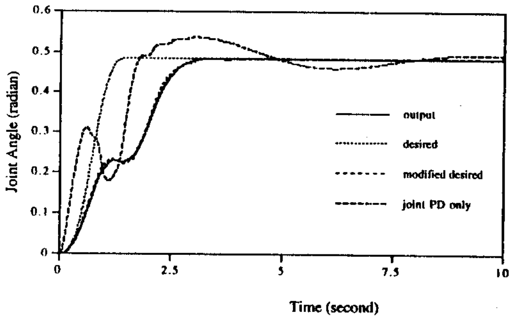


(a) Joint trajectory (alpha=1.5)

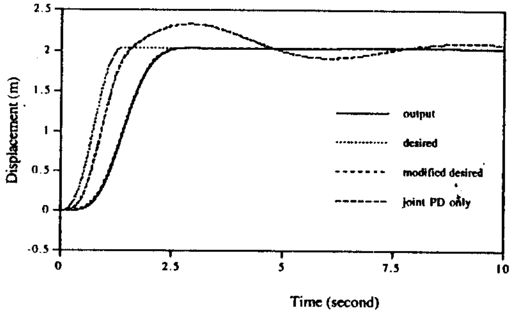


(b) End-position trajectory (alpha=1.5)

Figure 5. Responses of the robust notch filter with the joint proportional-derivative controller.



(a) Joint trajectory



(b) End-position trajectory

Figure 6. Responses of feedforward simulation filtering method with the joint proportional-derivative controller.