Input Shaping Filter Methods for the Control of Structurally Flexible, Long-Reach Manipulators*

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Abstract *

Within the Environmental Restoration and Waste Management Program of the U.S. Department of Energy, the remediation of single-shell radioactive waste storage tanks is one of the areas that challenges state-of-the-art equipment and methods. Concepts that utilize long-reach manipulators are being seriously considered for this task. Due to high payload capacity and high length-to-cross-section ratio requirements, these long-reach manipulator systems are expected to exhibit significant structural flexibility. To avoid structural vibrations during operation, various types of shaping filter methods have been investigated. A robust notch filtering method and an impulse shaping method were used as simulation benchmarks. In addition to that, two very different approaches have been developed and compared. One new approach, referred to as a "feedforward simulation filter," uses imbedded simulation with complete knowledge of the system dynamics. The other approach, "fuzzy shaping method," employs a fuzzy logic method to modify the joint trajectory from the desired end-position trajectory without precise knowledge of the system dynamics.

1. Introduction

Within the Department of Energy's (DOE's) Office of Technology Development, Robotics Technology Development Program, Environmental Restoration and Waste Management (ER&WM) Program, waste storage tank remediation is one of the most urgent tasks. Concepts which utilize long-reach manipulators are being seriously considered for this task. The development of a tank waste retrieval manipulator system (TWRMS) may be one of the DOE's most significant robotics projects.

The TWRMS will consist of three elements: a long-reach manipulator (LRM) including a vertical deployment mast, a short-reach, dexterous manipulator, and various end-effector tools. From preliminary studies [1][2], it is anticipated that the LRM will have very low structural natural frequencies, and its structural flexibility will significantly affect the positioning accuracy of the end of the manipulator. Control of the end position of the LRM considering its flexibility will be very important to the performance of various cleaning processes with the dexterous manipulator.

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

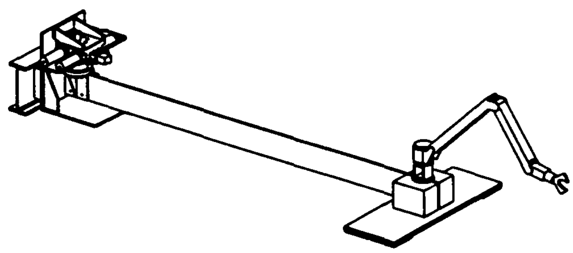

Fig. 1. Flexible-beam testbed built by Battelle Pacific Northwest Laboratories.

The most prominent filtering methods available can be grouped as impulse shaping filters [4][5], robust notch filters [6], and inverse dynamic methods [7][8]. There are many other potentially effective control schemes such as acceleration feedback [9], passive damping treatment [10], and end-position feedback [11]. Various approaches are well summarized by Book [3].

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 wide filtering band, it is robust to the change of the system dynamics [6]. However, it also introduces a significant time delay like that of an impulse shaping filter.

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In this research, the above shaping filter methods were implemented for simulation and evaluated, and two very different approaches have been demonstrated. Because both shaping filter methods need at least partial information of the flexible dynamic system, e.g., a dominant vibration frequency or the dominant frequency and damping ratio, the limiting cases of complete knowledge and no knowledge of the structural dynamics are of significant interest. Therefore, two approaches which represent these extremes have been proposed and investigated. One new method called "feedforward simulation filtering" incorporates the advantages of several other methods: end position feedback, robust notch filtering, and feedforward torque. It requires a complete knowledge of the dynamics of the system like that required by the inverse dynamic method, and shows excellent tracking performance. The other approach, called the "fuzzy shaping method," does not require precise knowledge of the flexible dynamics. The joint trajectory was modified from the end-position trajectory by fuzzy rules to include the effect of flexibility and to avoid commanding the flexible beam to move like a rigid beam. To date, all results have been generated in the simulation environment associated with a real-time control software system called MICA (Modular Integrated Control Architecture) [12] and these methods will be implemented on the PNL testbed as soon as modification of the testbed to add a base actuator and associated control hardware is completed.

2. Control System

The control software was designed within the framework of MICA which provides modularity, a graphic user interface, and expandability. MICA is a software package developed at Oak Ridge National Laboratory (ORNL) as a framework for robotic manipulator control. MICA yields operational codes that are portable among different manipulators and operating environments. It allows precise operation of multiple processors that have to be coordinated to control manipulators. Within the MICA framework, specific aspects of LRM control can be considered during 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 Fig. 2. The SUN workstation is used for the graphical user interface and supervises the control system. The control 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. Data exchange between the SUN workstation and the system rack is by Ethernet.

3. Modeling

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

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

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

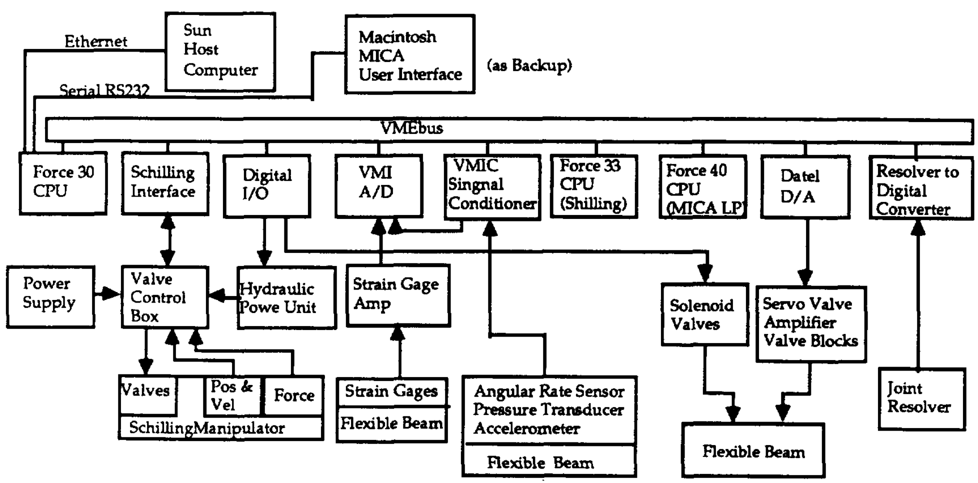

Fig. 2. VME system controller for the flexible-beam testbed.

The inertia matrix $[M]$ is expressed with mode shape functions, a hub rotational inertia, and an end mass and rotational inertia. The damping matrix $[D]$ represents the viscous joint friction, and the input matrix $[B]$ is for the joint torque. The stiffness matrix $[K]$ represents structural flexibility.

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 impulses were digitally convolved with the desired command trajectory.

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

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 Fig. 5. However, it introduces a time delay that is as long as the duration of the impulse sequence. While it is not easy to determine the exact damping ratio, the performance depends on the accuracy of the estimated frequency and the damping ratio.

4.2 Robust notch filter

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

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

where ω_z = resonant frequency of the system;

ω_p = low-pass filter natural frequency,

$\omega_p = \alpha\omega_z \quad (\alpha = 1 \sim 2)$;

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

The robust notch filter introduces zeros at the damped resonant frequency of ω_z and adds critically damped poles at the frequency of ω_p. The parameter α was set, by trial, to 1.5 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 filter. Fig. 6 shows smooth responses without overshoot. However, it also has the same tracking delay problem for slow systems as the impulse shaping filter.

4.3 Feedforward simulation filter

Since the shaping filter induces a time delay of half the system's natural frequency or multiples of that frequency, it is not practical for very slow 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 gives perfect tracking at the end point. However, the inverse dynamic method usually gives noncausal 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 parameter variation and 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].

Fig. 3 describes a feedforward simulation filtering method that integrates most of the advantages of the above methods. 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 end-position feedback is conditionally stable and sensitive to the modeling errors,

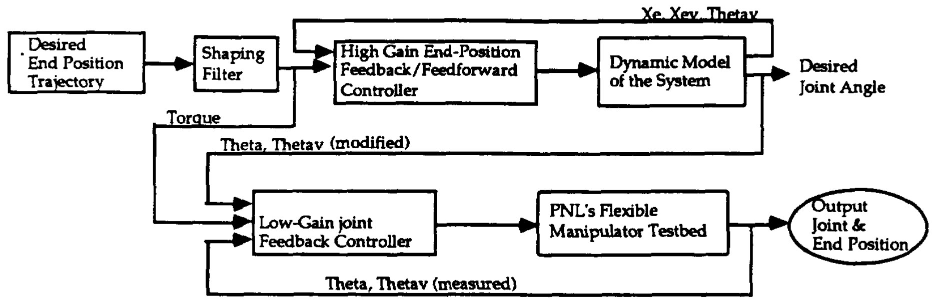

Fig. 3. The feedforward simulation filtering method.

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 Fig. 7.

4.4 Fuzzy shaping method

The above mentioned shaping techniques are based on the knowledge of the system's dynamics. If we have only imprecise knowledge on the system, which is expressed in linguistic terms, fuzzy logic can provide an efficient tool for treating imprecise knowledge [13]. As shown in the inverse dynamic method [7], the flexible beam should be allowed to deflect to follow a certain trajectory at the end-point. When the beam is accelerated or decelerated, the joint trajectory includes the deflection effect in addition to the rigid body motion that is assumed to be equivalent to the end-point motion. The modification of the joint trajectory has been tried by fuzzy rules using the acceleration profile to allow the deflected motion during acceleration and deceleration. Fig. 4 describes joint trajectory generation scheme of the fuzzy shaping method. The modified joint trajectory is obtained by adding the fuzzy system's output to the original joint trajectory. The fuzzy rules used are shown in Table 1. For instance, one of the rules takes the following form:

IF desired acceleration of end position is Negative Big, THEN change of joint angle should be Negative Big.

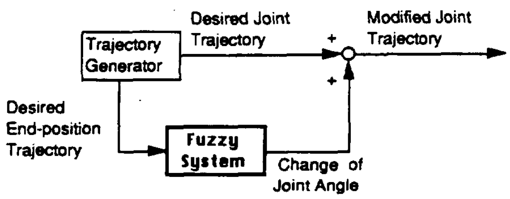

Fig. 4. Fuzzy shaping method.

The fuzzy singleton method, the max-product method, and the center of gravity method were used for fuzzification method, inference method, and defuzzification method, respectively. A triangular shape was chosen for the membership function of each fuzzy variable. Even though the rules were set up very roughly, Fig. 8 shows that the modified joint trajectory significantly improved the performance compared to the case of no modification (joint PD control only).

Table 1. Fuzzy rule

a_d	NB	NM	NS	ZE	PS	PM	PB
$\delta\theta_d$	NB	NM	NS	ZE	PS	PM	PB

a_d : Desired acceleration of the end point
$\delta\theta_d$: Change of joint angle
NB : Negative Big — PB : Positive Big
NM : NegativeMedium — PM : Positive Medium
NS : Negative Small — PS : Positive Small
ZE : Zero

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 vibration, and gives reasonably good performance. The robust notch filter is insensitive to the variation of the plant dynamics at the cost of slow responsiveness by having multiple zeros. 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. In many previous approaches [14][15], fuzzy logic has been tested as a basic controller that can substitute for the joint PD controller. The result of the fuzzy shaping method shows possibility of using fuzzy logic as a shaping filter for unknown systems or time varying systems. More improvement can be expected if more knowledge on the system's dynamic characteristics is added to the fuzzy rules.

ORNL is pursuing extension of the above filtering methods to actual three-dimensional, multi-link LRMs. The use of a real-time Fast Fourier Transform (FFT) to adapt the shaping filter is being tested for situations when variations in the manipulator configuration or payload result in significant changes in the fundamental natural frequency of the system's structure.

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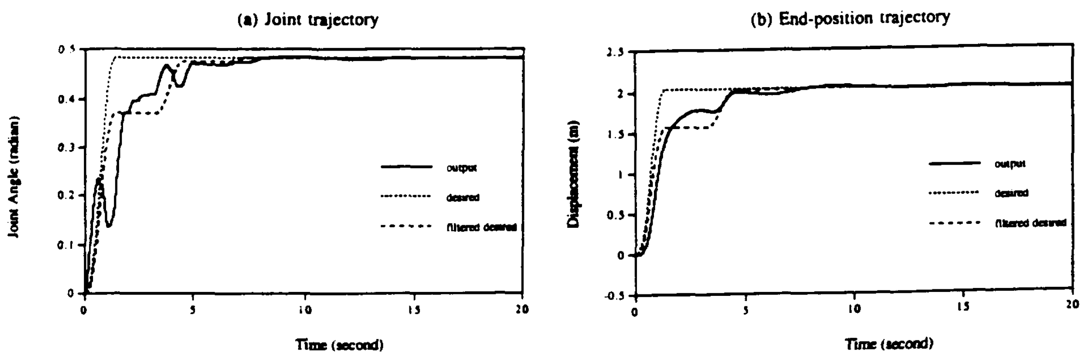

Fig. 5. Responses of the impulse shaping filter with the joint proportional-derivative controller.

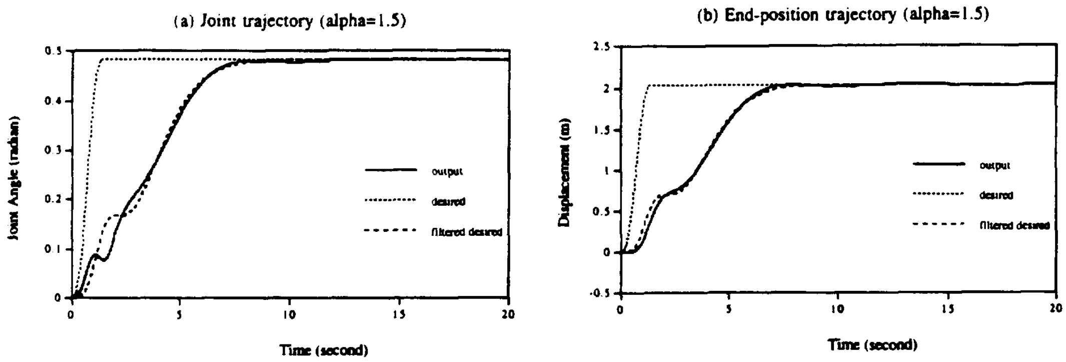

Fig. 6. Responses of the robust notch filter with the joint proportional-derivative controller.

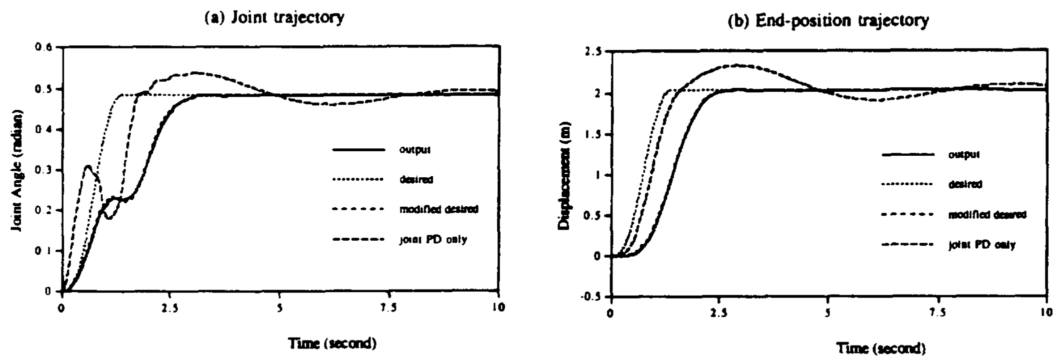

Fig. 7. Responses of the feedforward simulation filtering method with the joint proportional-derivative controller.

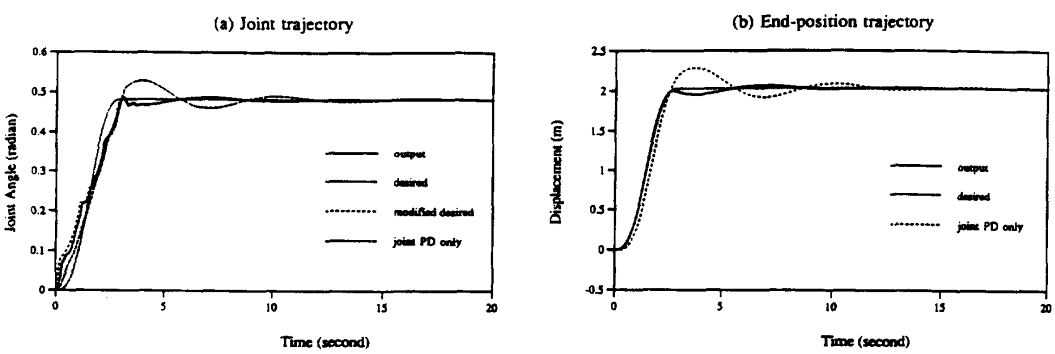

Fig. 8. Responses of the fuzzy shaping method with the joint proportional-derivative controller.