Adaptive trajectory shaping for liquid container manipulation

Gi-Hong Kim[a], Sungsoo Rhim*[a], Seung-kook Yun[b], Sun-Ho Bum[a], Sungchul Kang[b],
Soon-Geul Lee[a]

[a]Kyung Hee University, Department of Mechanical Engineering, Yongin-si, Republic of Korea;
[b]Korea Institute of Science and Technology, Seoul, Republic of Korea

ABSTRACT

In the paper, a novel trajectory shaping scheme to improve the manipulation skill of the articulated manipulator for the liquid container transportation is proposed. The paper investigated the transient free surface behavior of liquid inside a cup during the horizontal transportation. Based on the observation of the free surface vibration of the liquid, the adaptive command shaping filter is proposed for the generation of the transportation trajectory to reduce the fluctuation magnitude without increasing the time required to travel the given transportation distance. Simulation results verify the effectiveness of the proposed scheme. An experimental testbed of an articulated manipulator with a simplified model of a liquid container is established. The proposed manipulation approach is implemented in the experimental setup and the experimental results also verify the effectiveness of the proposed scheme.

Keywords: Liquid container, manipulation, trajectory shaping, time-delay filter

1. INTRODUCTION

Articulated manipulators are used to manipulate various types of objects. Among them is the liquid container, for example a cup filled with water or coffee (or liquid-metal for industrial applications). The task of picking up and carrying an open container filled with liquid would be one of the most frequently requested errands that a robot needs to perform as a home-service robot in the near future. Up to now, however, the most of the manipulation objects considered in robotics applications are solid whether they are rigid or flexible. The manipulation of containers filled with liquid has not been studied intensively yet.[1]

The unique problem that the manipulation task will face when it deals with the liquid container is the fluctuation of the liquid. The manipulation of the container would inevitably result in the change in the acceleration of the liquid inside and the free surface of the liquid would fluctuate. To prevent the overflow during the transportation of an open container, obviously the maximum rise of the free surface of the liquid must be maintained less than the height of the container wall. The motion induced fluctuation can be compensated either with careful design of the trajectory or with feedback actuation of the container. In this paper, we focus on the feedforward control of the transportation system. In particular, a trajectory generation scheme of using time-delay command shaping filter technique to improve the manipulation skill for the transportation of the open container filled with liquid is studied.[2–5]

To fulfill the transportation task without sacrificing the transportation time, the feedforward controller needs to be carefully designed based on the dynamic characteristics of the liquid. The dynamic characteristics of the liquid in a container depend on the properties of the liquid and the properties of the container as well. For the thorough analysis of the liquid dynamics inside a container we would need to carry out in-depth analysis of the dynamics of the liquid container system. In the current paper, however, only a set of dynamic analysis results relevant to the control algorithm development for a typical in-house service task scenario are included.

In general applications, the properties of the liquid are either not known at all or partially known to the robot before hand. The adaptive nature of the adaptive time-delay command shaping filter approach proposed in the current paper is adequate to be applied in this uncertain situation.[6]

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*ssrhim@khu.ac.kr; phone 82 31 201-3248; fax 82 31 202-8106; robotics.khu.ac.kr

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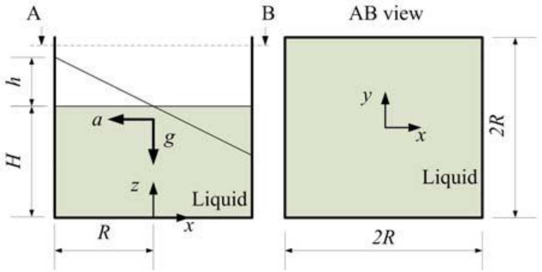


Fig. 1. Schematic illustration of cup and free surface of liquid in cup.

In the following sections, the dynamic behavior of the liquid contained in the container is numerically analyzed and the adaptive trajectory modification scheme is proposed. Also the simulation results obtained by implementing the proposed scheme are illustrated in the paper. Finally a set of experimental results where the scheme is implemented on a 6 DOF articulated manipulator with a simplified liquid cup model are included.

2. DYNAMIC ANALYSIS OF FLUID IN TRANSPORTATION

The dynamics of the liquid inside the container is modeled and analyzed numerically in the paper. A container partially filled with water is considered as the manipulation object. The shape of the container is chosen a $0.07m \times 0.07m \times 0.07m$ (W×D×H) cube. The cup and liquid model is schematically shown in Fig. 1, where a represents the acceleration applied to the cup, g for gravitational acceleration, $2R$ for the length of the side of the cup, H for the steady-state height of the free surface, h for the height of the free-surface contacting the wall of the cup measured from the steady-state height. H is chosen to be 3 cm.

The motion of the water present in the cup can be described by the following continuity equation and Navies-Stokes equation:[7]

$$\frac{\partial \rho}{\partial t} + \bigtriangledown \cdot (\rho \vec{v}) = 0 \tag{1}$$

$$\frac{\partial (\rho \vec{v})}{\partial t} + \bigtriangledown \cdot (\rho \vec{v} \vec{v}) = - \bigtriangledown P + \bigtriangledown \cdot (\tau_{ij}) - \rho g \hat{j} - \rho a \hat{i} \tag{2}$$

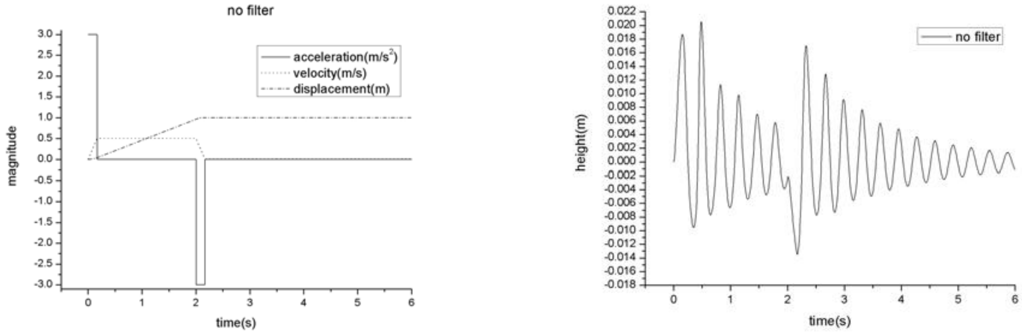
where ρa and τ_{ij} are the inertia force per unit volume associated with the acceleration and the shear stress tensor, respectively. τ_{ij} is expressed as

$$\tau_{ij} = \mu(\bigtriangledown \vec{v} + \bigtriangledown \vec{v}^T) \tag{3}$$

Since the cup is at rest initially the initial velocity of the liquid in the cup is set to be zero. At the wall, the no-slip condition is imposed and at the upper side of the cup a fixed zero pressure boundary condition is employed. Contact angle between the water and the wall of the cup is assumed to be always 90 degree.

The commercial software **CFD-ACE2006** is employed to solve the governing equations, wher VOF (Volume-Of-Fluid) method is employed to identify the position of the free surface.[8] Computational grid system for three-dimensional cup model is established with 20,213 structured grids. Time step used for the transient calculation is 0.0025 seconds. Figure 2 shows the response of h when the container is transported horizontally in x direction following the trapezoidal velocity trajectory given in Fig. 2(a). The trajectory has finite acceleration and deceleration. As can be seen in Fig. 2(b), the fluctuation of liquid during the transportation of the cup has conspicuous tendency of exponential damping during the residual period as well as the consistent period of the oscillation. This tendency in the response encourages us to apply a time-delay command shaping technique which has been successfully applied to various flexible motion systems.[2,3,6]

In the following section, the adaptive command shaping filter is introduced, which will be applied to reshape the transportation trajectory to reduce the fluctuation of the liquid and eventually to reduce the chance of overflow.



(a) reference trajectory applied to cup (b) height variation of free surface

Fig. 2. Calculated variation of free surface height of liquid inside cup.

3. ADAPTIVE TIME-DELAY COMMAND SHAPING FILTER

A command shaping filter reshapes the desired input to a flexible system such that the resonances of the elastic system modes are not excited.[2] It takes the form of a finite impulse response (FIR) filter, with filter parameters determined by the resonant frequencies and the damping ratios of the undesired elastic modes of the flexible system. The control system in this paper uses a three-term time-delay shaping filter. For single elastic mode cancelation, the three-term filter is given by the following equation:[3]

$$c(t) = \frac{1}{M}\{\delta(t) - 2\cos(\omega_d T_d)e^{-\zeta\omega_n T_d}\delta(t - T_d) + e^{-2\zeta\omega_n T_d}\delta(t - 2T_d)\} \tag{4}$$

where T_d is the time delay, δ is the unit impulse function centered at $t = 0$, ω_n is the first natural frequency of the flexible system, ζ is the corresponding damping ratio, ω_d is the corresponding damped natural frequency, and $M = 1 - 2\cos(\omega_d T_d) + e^{-2\zeta\omega_n T_d}$. It cancels the poles of the flexible system with filter zeros.[3]

In the face of system parameter uncertainties, one approach to retaining effectiveness is to produce more robust fixed filters. Unfortunately, the robustness of the shaper comes at the expense of the response time. Moreover this approach still requires a fair amount of a priori knowledge about the range of the system parameter variation for proper design.[3] Another approach is to adapt the filter parameters either directly or indirectly. The indirect adaptive command shaping methods pursue the system identification first either in the frequency domain.[6] Direct adaptation algorithms can also be used, where system parameters are never explicitly utilized.

The direct adaptive command shaping filter has many merits compared to the indirect approaches.[6] The direct adaptive time-delay command shaping filter algorithm has been proved robust to the noise in the signal. It also can be shown that the direct adaptation algorithm has a very strong convergence property in the frequency domain. The block-diagram of the direct adaptive command shaping applied in the liquid transportation system control is shown in Fig. 3 where the filter $C(z, n)$ takes the form of (5).

$$C(z, n) = c_1(n) + c_2(n)z^{-\Delta} + c_3(n)z^{-2\Delta} \tag{5}$$

The filter coefficients in (5) are initially chosen arbitrarily and they are to be learned by the adaptation algorithm. The time delay Δ can be chosen arbitrarily. The adaptation algorithm finds the optimal filter coefficients for the given time delay value that would minimize the vibration in the system response . Among many types of adaptive algorithms based on the least squares cost function, we use the RLS method that is modified for the ACS filter to satisfy the unit DC gain constraint after filtering.[6]

4. SIMULATION

To demonstrate the effectiveness of the adaptive command shaping filter in reducing the fluctuation amplitude of the liquid in the container which is being transported, a control system model is constructed as shown in

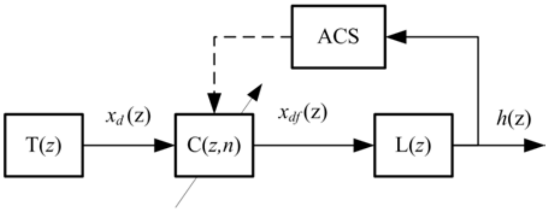
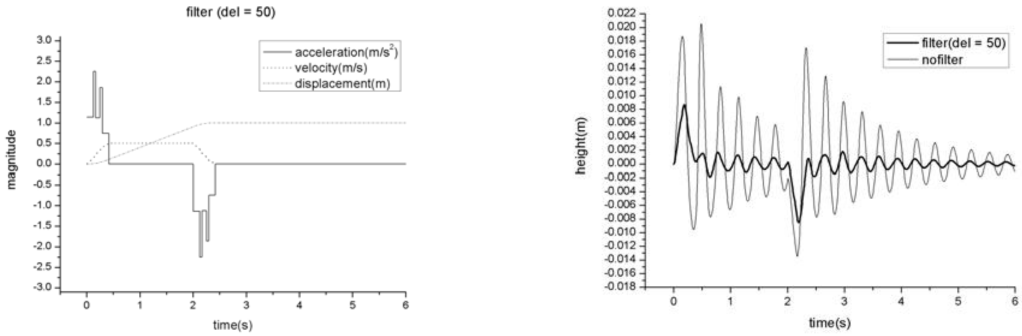


Fig. 3. Block-diagram of control system used in simulation.



(a) reference trajectory applied to cup (b) height variation of free surface (2nd cycle)

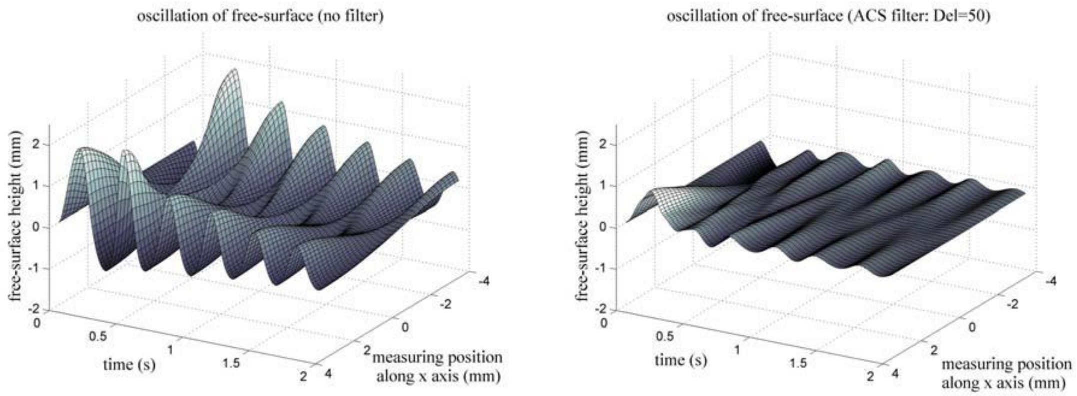
Fig. 4. Calculated height variation of free surface of liquid inside cup with an adaptive command shaping filter ($\Delta = 50$).

Fig. 3. In the figure, $T(z)$ represents the discrete trajectory generation process, $x_d(z)$ is the desired trajectory that the container will follow, $C(z,n)$ is the adaptive command shaping filter which reshapes the trajectory of the container in order not to excite the fluctuation of the liquid. $L(z)$ represents the dynamics of the liquid container system, $h(z)$ is the height of the free surface at the given time. $h(z)$ is caculated by **CFD-ACE2006**. Initially $C(z,n)$ is designed without knowing the dynamic characteristics of the liquid container system and it is updated based on the calculated h value as the simulation proceeds. As explained in the previous section, for a given time-delay Δ a set of effective coefficients c_i's in (5) is learned by the adaptive command shaping (ACS)algorithm. The simulation results for $\Delta = 50$ are shown in Fig. 4. Filter coefficients in $C(z,n)$ are learned during the first round-trip motion between the initial point ($x = 0$) and the target point 0.5m away. After the first round trip, a learned $C(z,n)$ is applied to reshape the trajectory of the cup motion and the simulation results show that the maximum height of the free surface during the motion is reduced down to almost one third of the original motion. Figure 5 compares liquid responses with and without ACS.

5. EXPERIMENTS

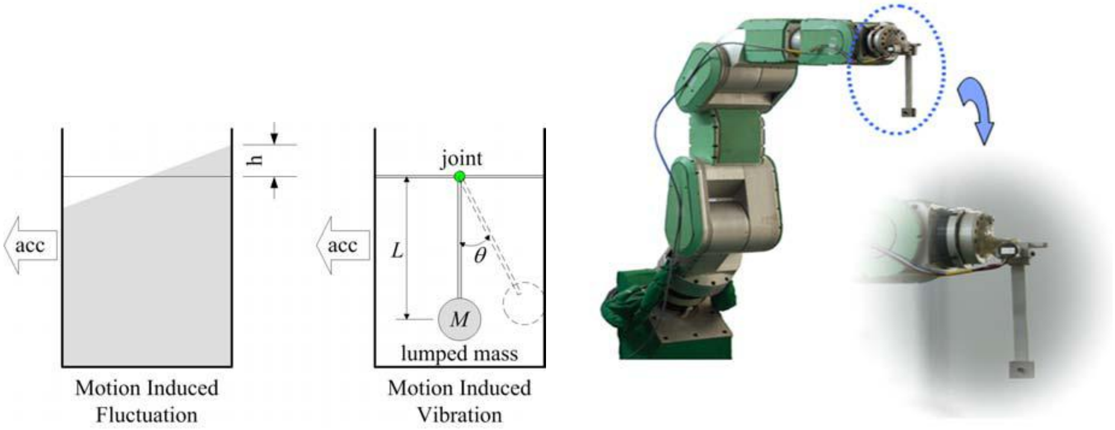
Based on the observation of the computation results of the liquid dynamic response, we introduce a simplified analogous model as a testbed using a pendulum and revolute joint as shown in Fig. 6 (a). The natural frequency and damping effect of the pendulum motion are designed to match the dynamic response of the liquid. Then the fluctuation of the free surface of the liquid can be represented as the angular displacement of the pendulum. A pendulum model is attached at the end of a 6 DOF articulated manipulator as shown in Fig. 6 (b).The manipulator is used to transport the simplified liquid container model.

The block-diagram in Fig. 7 shows the configuration of the system used in experiments. $x_d(z)$ is the desired cup position, $x_{df}(z)$ is the filtered desired cup position, $k^{-1}(x)$ is the inverse kinematics that is to generate reference joint angles, $D(z)$ is a conventional PD (proportional derivative) joint controller, $G(z)$ is the joint dynamics, $k(x)$ is the forward kinematics, and $L(z)$ is the simplified liquid cup model dynamics. The joint controller uses measured joint angle $q(z)$ to force the manipulator tip to follow the given trajectory $x_{df}(z)$. The measured pendulum angle $\theta(z)$ is fed into the adaptive command shaping algorithm and used to update the adaptive command shaping filter $C(z,n)$.



(a) no ACS filter (1st cycle) (b) with ACS ($\Delta = 50$, 2nd cycle)

Fig. 5. Transition of free-surface height calculated along x axis during the motion.



(a) (b)

Fig. 6. (a) Simplification of liquid dynamics (b) 6 DOF arm with a simplified liquid model attached at the tip.

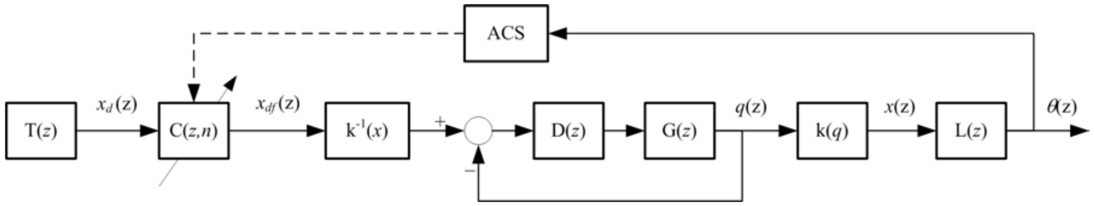
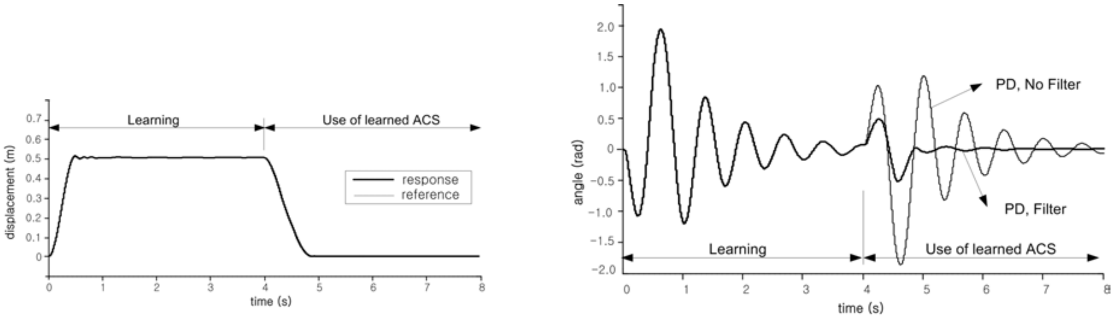


Fig. 7. Block-diagram of experimental control system.

The experiment procedure is similar to the simulation. Initially the command shaping filter is set without knowing the system parameters and during the first forward motion between two points 0.5 m apart the adaptive command shaping algorithm learns the effective filter coefficients based on the measured $\theta(n)$. Then, just before the initiation of the backward motion toward the starting point, the learned command shaping filter is updated and used to reshape the motion of the manipulator tip. In Fig. 8(a) shows the tip reference trajectory and the measured tip motion together. Figure 8(b) shows the measured responses of the pendulum during the forward and backward motion. The maximum fluctuation magnitude of the pendulum has been significantly reduced down to almost one third of the original maximum value where no filter was used.



(a) reference tip trajectory and measured tip position (b) measured response of the pendulum

Fig. 8. Experimental results with simplified liquid model and an adaptive command shaping filter.

6. CONCLUSIONS

In the paper, a novel scheme to improve the manipulation skill of an articulated robot for the liquid container transportation is proposed. The scheme is a feedforward control technique of applying adaptive command shaping filter to reshape the liquid container motion. To analyze the adequacy of the adaptive shaping filter application, the paper investigated the transient response of the free surface the water inside a cup moving horizontally following a given trajectory. The numerical analysis shows that the oscillatory behavior of the water in container has strong periodicity as well as the exponential damping characteristic. Based on the observation, the adaptive command shaping filter is applied to reshape the transportation trajectory to reduce the fluctuation magnitude without increasing the time required to travel the given transportation distance. Simulation results verifies the effectiveness of the proposed scheme. An experimental setup with an articulated manipulator and a simplified model of a liquid container is established. The proposed approach is implemented in the experimental setup and the experimental results verifies the effectiveness of the scheme.

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