Experimental Study on Manual Operation Method of a Multiple-DOF Space Robotic Arm Considering Vibration Suppression

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Abstract: Space robotic arm, such as robot manipulator systems on International Space Station (ISS), are usually operated manually by astronauts and ground operators. Such manipulator systems are subject to vibrations due to its flexibility, which cause degradation of the operation accuracy. We use Input Shaping method in order to suppress the vibration. However, when a posture of the arm changes dynamically, we need to improve the scheme of vibration suppression control. We propose the practical manual operation method without additional sensors and actuators. In proposed method, sensing the vibration during robotic arm operation, the parameters for vibration suppression are updated as required. Though a strain gauge is used for sensing the vibration, only actuator's current of each joint is practicable. In this paper, we conduct manual operation experiment, and examine the validity of the proposed manipulation method considering vibration suppression.

1. Introduction

The manipulation methods for space robotic arm are classified into two operation modes. One is automatic operation mode, and the other is manual operation mode. In the case of the automatic operation mode, the robotic arm moves automatically according to the preset command profile. This mode is suitable for a routine work, a point-to-point motion, and so on. For example, this mode is applied to the transport operation. In the case of the manual operation mode, the robotic arm moves manually by operator’s command. Existing space robotic arm, such as SSRMS, SRMS and JEMRMS, are usually operated manually by astronauts and ground operators. Manual operation means manipulation method by using joystick controller. Because of vibration caused by its flexibility, accuracy of manipulation comes to be degraded. We use Input Shaping method in order to suppress the vibration. The Input Shaping method, in principle, works by creating a command signal that cancels the vibration produced on the system to which it is applied. The method adopted for the present research is based on linear system theory. Input Shaping method decreases vibration in flexible systems by filtering the reference command with sequence of impulses known as the input shaper. When Input Shaping method will be applied to manual operation, it is necessary to improve implementation, because the command profile changes in real time according to the operator’s purpose. Moreover, we need to improve the vibration suppression control method, considering the parameter alteration due to posture of the arm or setting error of experimental system, in order to achieve more reliable space robotic manipulation method.
In this paper, we propose the vibration suppression method based on Input Shaping using parameter estimation method, and consider implementation to the actual system. And then we conduct numerical simulation and ground experiments using the 6-DOF flexible robotic manipulator under 2-dimensional microgravity environment. Based on both analytical and experimental results, we examine the proposed method in detail, and discuss the reliable space robotic manipulation method.

2. Ground Experimental System

We have constructed two-dimensional microgravity environment experimental system. 6-DOF planar robotic arm is floated by air on glass flat floor. Fig.1 shows overview of robotic arm system. Fig.2 shows robotic arm console, and Fig.3 shows system block diagram. Robotic arm can be manipulated by two control modes; single joint (SJ) control mode and resolved motion rate control (RMRC) mode.

This robotic arm has one flexible link, which is a 600mm long boom made of aluminum plate (4mm in thickness). The first natural vibration mode, caused by the flexible link, is about 0.312Hz (3.2sec in period).

The angles and currents of each joint can be acquired as telemetry, and the position of end-effector can be measured by the camera above the experimental system. Shown in Fig.3, a strain gauge is attached to the flexible link in order to monitor vibration. The vibration can be also monitor by currents of each joint. Shown in Fig.2, operator can manipulate the robotic arm manually by using joystick and monitor the camera image above the experimental system.

3. Robotic Arm Manipulation Considering Vibration Suppression

The Input Shaping method, in principle, works by creating a command signal that cancels the vibration produced on the system to which it is applied. The method adopted for the present research is based on linear system theory.

Suppose we have an underdamped second-order linear system. The system’s response to an impulsive input at \( t = t_i \) can be expressed as an equation (1).

\[
h_i(t) = A_i e^{-\zeta \omega_i (t-t_i)} \sin \left( \omega_i \sqrt{1 - \zeta^2} \cdot (t - t_i) \right)
\]

where, \( \omega_i \) and \( \zeta \) are the natural frequency and damping ratio of the system, respectively. \( A_i \) is the impulse amplitude that occur at time \( t = t_i \). If the system is linear, its total response to a series of impulses can be expressed as a sum of the responses to each impulse. That is,

\[
h(t) = \sum_{i=0}^{N} h_i(t) = \sum_{i=0}^{N} A_i e^{-\zeta \omega_i (t-t_i)} \sin \left( \omega_i \sqrt{1 - \zeta^2} \cdot (t - t_i) \right) = A \sin(\omega \phi - \phi) \]

(2)
A train of properly arranged impulses can suppress residual vibration by forcing the amplitude to equal zero.

To construct an impulse sequence that will act as a vibration reducing input shaper, we start by imposing two constraints:

\[ t_0 = 0, \sum_{i=0}^{N} A_i = 1 \]  

(3)

In the case of \( N = 2 \), we can obtain the following profile about time and amplitude.

\[
\begin{bmatrix}
 t_1 \\
 t_2 \\
 A_1 \\
 A_2 \\
 \end{bmatrix} = \begin{bmatrix}
 0 \\
 1 \\
 \frac{\pi}{\omega_b \sqrt{1 - \zeta^2}} \\
 \frac{-\zeta \pi}{\omega_b \sqrt{1 - \zeta^2}} \\
 \frac{-\pi}{\omega_b \sqrt{1 + \zeta^2}} \\
 \frac{1}{\omega_b \sqrt{1 + \zeta^2}} \\
 \end{bmatrix}
\]  

(4)

The impulse spacing depends on the values of \( \omega_b \) and \( \zeta \), but the impulse amplitude are only \( \zeta \) dependent. In this paper, we suppose the value of \( \zeta \), damping ratio, equal zero in experiment. Fig. 4 shows schematic image of modified command profile by input shaper.

The effect of vibration suppression by using Input Shaping is dependent on the difference between actual natural vibration period and the period used for Input Shaping. If the robotic arm has flexibility, natural frequency will change due to the posture.

Fig. 6 shows the two postures of the flexible robotic arm. The natural frequency of posture (a) is 0.1282Hz and posture (b) is 0.22Hz as about 70% of (a). Fig. 7 shows sensitivity curve in the case of ZV shaper. The effect of vibration suppression is dependent on the difference. The difference cannot be ignored.

In order to compensate the error about parameter, two characteristic approaches have been studied. One is improvement about robustness, and the other is improvement about control scheme considering

4. Parameter Tuning of Input Shaping

4-1 Necessity of Parameter Tuning

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In order to compensate the error about parameter, two characteristic approaches have been studied. One is improvement about robustness, and the other is improvement about control scheme considering
real-time adaptation. One type of robust input shaper can be obtained by requiring the derivative with respect to the frequency of the residual vibration be equal to zero. That is, the sensitivity curve must have zero slope at the modeling frequency. This input shaper is called as a zero vibration and derivative (ZVD) shaper, which has three input impulses. If the numbers of input impulses are increased, the robustness to errors can be increased. But the price of the increased robustness is an increase in rise time. Especially, low frequency vibration mode, whose vibration period is long, is dominant in space robot system. Applying the robust input shaper to space robotic arm, the working efficiency will be degraded. Therefore, in this study, we choose the latter approach, which is improvement about control scheme considering real-time adaptation. We consider the method of parameter tuning in implementation, and verify analytically and experimentally.

4-2 Parameter Tuning by Using Learned Type of Estimation

Presetting initial parameter using already-known vibration properties and on-line monitoring data, the maximum amplitude of the residual vibration can be acquired. According to the following estimation scheme, actual vibration frequency can be estimated. Updating the parameter, which is based on the history of responses, a suitable parameter can be estimated. In this method, the vibration frequency and the maximum amplitude of residual vibration are used as a sample.

4-2-1 Estimation of Natural Vibration Frequency

When the linear system are applied Input Shaping, the relation between vibration frequency and maximum amplitude of residual vibration is shown as Fig.7.

Suppose two maximum amplitudes of residual vibration are monitored at two different case of estimated frequency, the actual vibration frequency \( f_{act} \) can be estimated according to the following two patterns. \( f_k \) means the k-th estimated frequency, and \( M_k \) means the maximum amplitude of residual vibration in the application of Input Shaping using k-th estimated frequency \( f_k \).

(i) Suppose the actual vibration frequency \( f_{act} \) exists k-th and (k-1)-th estimated frequencies.
\[
\begin{align*}
 f_{k+1} &= \frac{M_{k-1}}{M_{k-1} + M_k} (f_k - f_{k-1}) + f_{k-1} \\
 &= \frac{M_{k-1} f_k + M_k f_{k-1}}{M_{k-1} + M_k}
\end{align*}
\]  
Shown in Fig.8, \( f_{k+1} \) can be estimated as follows.

\[
\text{Fig.8 Estimation of natural frequency; pattern (i)}
\]

(ii) Suppose the actual vibration frequency \( f_{act} \) doesn’t exist k-th and (k-1)-th estimated frequencies.
\[
\begin{align*}
 f_{k+1} &= \frac{M_k}{M_{k-1} - M_k} (f_k - f_{k-1}) + f_k \\
 &= \frac{M_{k-1}}{M_{k-1} - M_k} (f_k - f_{k-1}) + f_{k-1}
\end{align*}
\]  
Shown in Fig.9, \( f_{k+1} \) can be estimated as follows.

\[
\text{Fig.9 Estimation of natural frequency; pattern (ii)}
\]
4-2-2 Numerical Simulation

We conduct numerical simulation, in order to verify proposed estimation scheme in section 4-2-1. Fig.10 shows 1dof vibration system model.

\[ x_0 \] and \( x \) mean displacement of the base and the mass. Velocity input is provided for the base, and the residual vibration of the mass is examined. The actual vibration frequency of this system is supposed to be 0.5859[Hz]. Initial estimated frequencies are 0.5[Hz] and 0.1[Hz].

Fig.11 and Table 1 show the results of simulation. Shown in Table 1, the maximum amplitude of the residual vibration can be suppressed to 1% of unshaped profile after 6th estimation. After 4th estimation, the residual vibration can be suppressed less than 5% and proposed estimation scheme is said to be validated.

4-3 Parameter tuning by using FFT analysis

In order to verify proposed estimation method, we compare that and the method using FFT analysis. In this method, monitoring change of actual vibration frequency using FFT analysis, preset frequency is updated on-line. Fig.12 shows the schematic image of this method.

This method is expected to be effective in vibration suppression, because change of property is monitored actually. But it is necessary for conducting FFT analysis to collect 128 samples at the lowest; therefore it is inefficient of time.

5. Ground experiment

In order to verify the proposed method experimentally, we have conducted ground experiment using 2-dimensional microgravity experimental system shown in Fig.1. 6-DOF flexible robotic arm is manipulated by manually on single joint control mode. Fig.13 shows two characteristic postures. The vibration frequency is 0.312[Hz] at posture (i) and 0.390[Hz] at posture (ii). When the robotic arm is on posture (ii), Input Shaping is applied using the suitable parameter to posture (i), and the effect of modeling error is examined. We verify the proposed estimation method and discuss the effect of parameter tuning.
Table 2 Vibration suppression rate
(Experimental results)

<table>
<thead>
<tr>
<th>Case</th>
<th>Posture</th>
<th>Profile</th>
<th>Amplitude [mm]</th>
<th>Rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>posture(i)</td>
<td>Unshaped</td>
<td>124.36</td>
<td>100.0</td>
</tr>
<tr>
<td>B</td>
<td>posture(ii)</td>
<td>ZV fixed(i)</td>
<td>15.19</td>
<td>12.2</td>
</tr>
<tr>
<td>C</td>
<td>posture(ii)</td>
<td>Unshaped</td>
<td>132.3</td>
<td>100.0</td>
</tr>
<tr>
<td>D</td>
<td>posture(ii)</td>
<td>ZV fixed(i)</td>
<td>51.9</td>
<td>39.2</td>
</tr>
<tr>
<td>E</td>
<td>posture(ii)</td>
<td>ZV_tuning(Learning)</td>
<td>32.3</td>
<td>24.4</td>
</tr>
<tr>
<td>F</td>
<td>posture(ii)</td>
<td>ZV_tuning(FFT)</td>
<td>35.67</td>
<td>26.9</td>
</tr>
</tbody>
</table>

Table 2 shows experimental results in vibration suppression. In case A, the posture of the robotic arm is (i), and Input Shaping is not applied (Unshaped profile). In case B, the posture of the robotic arm is (i), and Input Shaping is applied using a suitable parameter for posture (i). In case C, the posture of the robotic arm is (ii), and Input Shaping is not applied. In case D, the posture of the robotic arm is (ii), and Input Shaping is applied using an unsuitable parameter for posture (i). The estimated frequency in case D is fixed. In case E, the posture is (ii), and Input Shaping is applied using the learned type of parameter tuning. The vibration frequency is updated on-line according to the proposed estimation method. In case F, the posture is (ii), and Input Shaping is applied using parameter tuning by FFT analysis.

Shown in Table 2, if the posture of the robotic arm is fixed, the residual vibration can be suppressed to 10% of unshaped profile using a suitable parameter. When the posture is changed, the effect of vibration suppression is degraded using a fixed parameter. Therefore conducting on-line parameter tuning according proposed estimation method, the effect of vibration suppression can be improved. The proposed estimation method produces almost same results as the method using FFT analysis. Therefore we could experimentally demonstrate the validity and the feasibility of the proposed method.

6. Conclusion

In this paper, the operation methods for 6-DOF flexible robotic arm are discussed analytically and experimentally, especially considering manual operation. In order to suppress vibration, we propose the implementation method based on Input Shaping and verify the effectiveness analytically and experimentally. And then, in order to adapt to change of system property, the estimation method of vibration frequency is proposed, which is the learned type of parameter tuning. Updating the parameter, which is based on the history of responses, a suitable parameter can be estimated. Finally, conducting 2-dimensional micro gravity experiments, we verified the proposed method.

Reference