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Manipulating Deformable Linear Objects: Force/torque Sensor-Based Adjustment-Motions For Vibration Elimination

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Abstract

The vibration induced in a deformable object upon automatic handling by robot manipulators can often be bothersome. This paper presents a force/torque sensor-based method for handling deformable linear objects (DLOs) in a manner suitable to eliminate acute vibration. An adjustment-motion that can be attached to the end of an arbitrary end-effector's trajectory is employed to eliminate vibration of deformable objects. Differently from model-based methods, the presented sensor-based method does not employ any information from previous motions. The adjustment-motion is generated automatically by analyzing data from a force/torque sensor mounted on the robot's wrist. Template matching technique is used to find out the matching point between the vibrational signal of the DLO and a template. Experiments are conducted to test the new method under various conditions. Results demonstrate the effectiveness of the sensor-based adjustment-motion.

1. Introduction

Automated handling and assembly of materials have been studied by many researchers in the areas of manufacturing, robotics, and artificial intelligence. Until now, most studies assume that the objects to be manipulated are rigid. However, deformable materials such as cables, wires, ropes, cloths, rubber tubes, sheet metals, paper sheets and leather products can be found almost everywhere in the real world of industry and human activity. In most cases, deformable materials and parts are still handled and assembled by humans. Practical methods for the automatic handling and manipulation of deformable objects are urgently needed.

Previous research work involving the modeling and controlling of DLOs such as beams, cables, wires, and tubes etc. has been found, for example in [1-10]. There are two basic methods for handling DLOs; one is the force-based method with physical model [2,7-9], the other is the vision-based modelless method [4,6]. Some researchers are trying to use hybrid methods (i.e. force and vision sensors or other sensors) to manipulate DLOs[1,5]. On the other hand, Zheng et al. [10] derived strategies to insert a flexible beam into a hole without sensors, while Hirai et al. [3] presented human skillful transplantation method. However, the above methods are specialized and confined to limited applications.

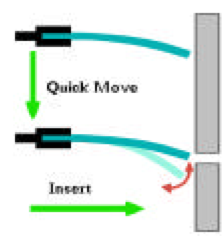

Figure 1. The vibration caused by a quick operation results in uncertainty and failure, e.g. when inserting a DLO into a hole.

When a robot executes a manipulation task, its motion can be divided into several motion primitives, each of which has a particular target state to be achieved in the task context. These primitives are called 'skills'. An adequately defined skill can have generality to be applied to various similar tasks. Until now, most of the research work on skill-based manipulation dealt with rigid objects [11,12].

Skill-based manipulation for handling deformable linear materials has been touched upon recently. For example, Henrich et. al [13] analyzed the contact states and point contacts of DLOs with regard to manipulation skills, Abegg et. al [14] studied the contact state transitions based on force and vision sensors, and Remde et.al [15] discussed the problem of picking-up DLOs by experimentation.

However, the effects of vibration are not taken into account in the skill-related work described above. The dynamic effects of deformable objects cannot be neglected, especially when the objects are moved quickly by a robot arm. As shown in Figure 1, the uncertainty resulting from oscillation may cause failure during the insert-into-hole operation. Therefore, the vibration caused by inertia should

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be depressed during the motion or eliminated as soon as possible after the motion.

Vibration reduction of flexible structures has been a research topic for many researchers, and Chen et al. have reviewed the previous works [16]. Chen et al. also present a passive approach based on open-loop concept for vibration-free handling of deformable beams; similar ideas can be found in [17,18], which deal only with rigid bodies. However, application of the method presented by [16] is limited due to its stable start condition and a relatively simple trajectory. Considering the complex manipulations involved in practical situations, such as avoiding obstacles, picking-up and insert-into-hole etc., stable start condition cannot be satisfied easily.

With respect to manipulation, only the vibration that may cause failure of the next operation must be eliminated. Therefore, we prefer to reduce the unwanted vibration to an acceptable level before the next operation. In a recent paper, we discussed a model-based method to reduce the vibration of DLOs using attachable adjustment-motions [19]. Although the model-based method can be computed off-line, effectiveness depends on how well the model matches the real DLOs, and how well the simulated robot operation matches the real robot operation.

To overcome these limitations of model-based methods, a sensor-based method is presented to eliminate acute vibration of DLOs. Vibration caused during the arbitrary previous trajectory can be reduced during an attached adjustment-motion. Unlike model-based methods, sensor-based methods do not involve the use of information from the previous motion. The adjustment-motion is generated automatically by analyzing data from a force/torque sensor mounted on the robot’s wrist.

The rest of this paper consists of seven parts. Section 2 and Section 3 describe the assumptions of residual vibration and the forced resonant vibration, respectively. The sensor-based adjustment-motion is specified in Section 4, while the sensor data processing is described in Section 5. Implementation of the method is stated in Section 6 and experimental results are shown in Section 7. Finally, conclusions and a description of future work are given.

2. Residual Vibration Assumptions

There is no external excited force during the residual vibration period, so the vibration of DLOs is a kind of *free vibration*, without excited force. A DLO may have many modes of vibration. Here, only the dominant vibration is concerned. To simplify the description, we use a one degree-of-freedom (DOF) system as an example. It is also assumed that the DLO behaves like a linear spring with constant stiffness. Thus, we have the following equations for free vibration [21]:

$$m\ddot{x} + c\dot{x} + kx = 0 \qquad (1)$$

where x is the endpoint displacement, m is the mass, c is the damping coefficient, and k is the stiffness of the spring. Since heavy damping is not of interest in this paper, the solution of equation (1) with light damping is as follows:

$$x = Ae^{-at}\sin(w\ t + h) \qquad (2)$$

where A and h depend upon initial conditions, $\alpha = c/2m$, and ω is the frequency of oscillation. Equation (2) describes the residual vibration of a one-DOF system, implying that the vibration of such a DLO behaves like a sine function.

The force or moment signals are also sine functions, according to the solution. A typical DLO force signal obtained using a force/torque sensor is shown in Figure 2. It behaves like a sine function too, though it may have more than one DOF. Therefore, a standard sine function will be employed in this paper as a template for comparison with signals from the sensor.

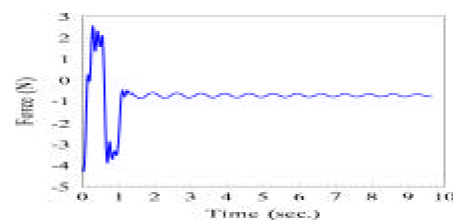

Figure 2. A typical low-pass filtered force signal of a DLO F_y during previous motion (0 to 1 sec.) and residual period (after 1 sec.)

3. Vibration During Handling

If the freely vibrating DLO is handled with a certain acceleration and speed, the vibration will either increase or decrease. Thus, during the acceleration and deceleration period, the DLO is in fact excited by external forces. In this situation, the vibration of the DLO can be treated as *forced vibration*.

The damped forced vibration equation is written as [21]:

$$m\ddot{x} + c\dot{x} + kx = F\sin(w_1 t) \qquad (3)$$

if the excited force is periodical.

It is well-known that if the excitation frequency of the system w_1 happens to coincide with the natural frequency of the system w ; i.e. when w_1/w=1, the dynamic magnification reaches very high values, although these are attenuated by the damping present. The frequency at which the peak dynamic magnification occurs is called the *resonant frequency*.

For a free vibration on the other hand, if an excited force is added at the opposite phase with the same resonant frequency, the vibrational amplitude may be reduced. This implies that the residual vibration can be decreased to a lower level if we carefully choose the acceleration, declaration and other related parameters of the handling operation, based on the resonant vibration theory.

To perform the adjustment-motion with resonant frequency, the natural frequency w (or vibrational period T) and the stiffness of the DLO will be measured experimentally with a force/torque sensor and used as known parameters when manipulating DLOs in this paper.

4. Adjustment-Motion Strategy

Adjustment-motion here refers to a kind of small-scale motion that can be performed at the end of any arbitrary trajectory to damp the vibration caused by this previous motion. Adjustment-motions can be sorted into two different groups according to the type of motion involved [19]. One is translation-adjustment-motion (TAMo) and another is rotation-adjustment-motion (RAMo). The adjustment-motions can also be classified as one-way and two-way adjustment-motions, as shown in Figure 3. Unlike model-based methods, in this paper the adjustment-motion will be generated automatically according to the results of signal data analysis. The type of adjustment-motion used is TAMo.

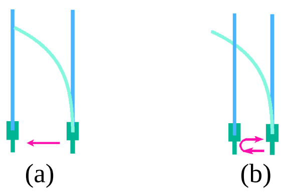

Figure 3. The end-effector conducts an adjustment-motion. (a) one-way TAMo, (b) two-way TAMo.

4.1 One-way TAMo

An one-way adjustment-motion consists of three parts, i.e. acceleration period, constant velocity period and deceleration period.

The strategy of the one-way adjustment-motion is: (1) starts at the time when displacement x reaches one of its maxima; (2) moves in the direction of the displacement; (3) covers a distance which equals the maximal displacement; (4) ends at the time when the displacement x reaches an adjacent minima.

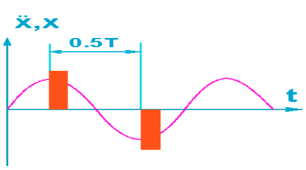

Figure 4. The one-way adjustment-motion strategy, where the sine-wave is the displacement of the DLO and the blocks are the acceleration and deceleration.

For industrial robots, the time of acceleration and deceleration can be quite small. The profile of acceleration is shown in Figure 4.

According to the strategy, the adjustment-motion period is one-half of the vibrational period *T*. These maxima occur when

$$|\sin(w\ t + h)| = 1 \quad (4)$$

i.e. when

$$w\ t = \frac{2n+1}{2}p - h \quad (n = 0, 1, 2, \cdots) \quad (5)$$

The equation (5) implies a theoretically infinite number of opportunities to implement the adjustment-motion, if damping is neglected.

The scope of the adjustment-motion is determined by the vibrational amplitude of the DLO, i.e. we have the following equation:

$$s_{amo} = f_{end} \quad (6)$$

where s_{amo} is the distance from the start to the end of an adjustment-motion, f_{end} is the vibrational amplitude of the DLO during the residual period, defined as half of the value of a peak minus an adjacent valley.

The vibrational amplitude is known indirectly based on the following linear stiffness assumption:

$$d = |f_{end}| / |M_{amp}| \quad (7)$$

where d is a constant that can be measured in advance and M_{amp} is the amplitude of moment. Here, we used moment instead of force to estimate vibrational amplitude of the DLO, because moment reflects more vibration information from the distal end of a DLO, where maximum vibrational displacements are located.

4.2 Two-way TAMo

A two-way adjustment-motion can be applied to the DLO, which returns to its original position after adjustment.

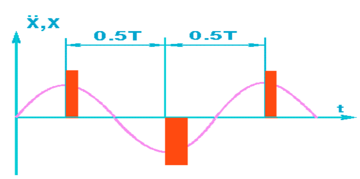

Figure 5. The two-way adjustment-motion strategy, where sine-line is the displacement of the DLO and blocks are the acceleration and deceleration.

A two-way adjustment-motion can be defined as two connected symmetrical parts as shown in Figure 5, and each part is an one-way adjustment-motion. A two-way adjustment-motion only covers half of the distance which an one-way adjustment-motion covers. Other details of a two-way adjustment-motion will not be described again.

One question arising here involves determining the ideal starting time for the adjustment motion. In the following section, template-matching method will be employed to solve this problem.

5. Sensor Data Processing

From Section 2, we learned that the vibrational displacement theoretically behaves like a sine function. We also have sample data obtained from the sensor. If we find the *matching point* where the sample data matches the sine function, we may use the sine function to predict all the maxima of the vibrational signal in advance. The adjustment-motion can then start at the calculated time corresponding to the predicted maxima.

Template-matching method [20] is used here to find the matching point between the signals obtained directly from the sensor and the sine function. We would now like to define a measure of how well a signal portion matches the template. Let

- $g(i)$ be the signal from the sensor data,
- $t(i)$ be the template, and let
- D be the domain of definition for the template.

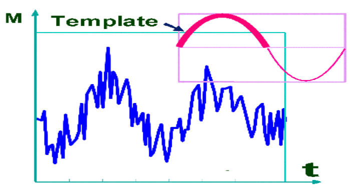

Figure 6. The template function: a half sine curve is used as the template and compared with the signal from sensor. The signal is drawn using raw data without smoothing.

We are looking for a region of the signal in which the signal function is similar to a previously specified template signal function. $R_{gt}(m)$, defined as the *cross-correlation* between the two functions g and t, is given by:

$$R_{gt}(m) = \sum_i g(i)t(i-m) \tag{8}$$

where $(i\text{-}m) \in D$.

The template and the signal are declared similar when the cross-correlation is large. The normalized cross-correlation $N_{gt}(m)$ is given by:

$$N_{gt}(m) = \frac{1}{\sqrt{\sum_i g^2(i)}} R_{gt}(m) \tag{9}$$

where i is within the domain of the translated template. Hence, the normalized cross-correlation has a maximum value when the match with the picture function is perfect (up to a scale factor).

Since the signal function from the sensor has three dimensions, the following equation is used to translate the three dimensional signal into an one dimensional signal:

$$N_{gt}(m) = \frac{1}{\sqrt{\sum_i (g_x^2(i) + g_y^2(i) + g_z^2(i))}} R_{gt}(m) \tag{10}$$

A half sine function with an unit amplitude is used as template (as shown in Figure 6) and compared with each part of the digital curve obtained according to equation (10) from the force/torque sensor. The point with the largest value of N_{gt} is the matching point. The time corresponding to the maximum of N_{gt} is one of these *critical times*, at which displacement is a maximum. Fortunately, according to equation (5), there are many opportunities where signal maxima are reached.

Since there is noise in the raw data obtained directly from the sensor, to smooth the raw data, the following function is used:

$$g(i) = \sum_{j=-n}^{n} g(i+j)\big/k, (n=(k-1)/2,\, k=1,3,5,7,\cdots) \tag{11}$$

The direction of the adjustment-motion is determined according to the equation:

$$\overline{M}_a = \overline{M}_{ax} + \overline{M}_{ay} + \overline{M}_{az} \tag{12}$$

where $\overline{M}_a$ is the vector of moment-amplitude, and $\overline{M}_{ax}, \overline{M}_{ay}$ and $\overline{M}_{az}$ are the moment-amplitudes in x, y and z axis, respectively. With respect to the noise, the dominant vibration can be determined if the sum of two moment-amplitudes is less than a certain proportion of the third one; for example, the vibration that occurs in the plane of *xoy* is determined as the dominant vibration, if

$$\overline{M}_{ax} + \overline{M}_{ay} < l\ \overline{M}_{az} \tag{13}$$

where $l \in [0,1]$.

6. Implementation

For the sensor-based adjustment-motion experiments, a Stäubli RX130 industrial robot was used. A standard 500mm stainless ruler with cross section of 0.5mm×18mm was used as the DLO in the experiment. One end of the ruler was grasped by pneumatic jaws as shown in Figure 7, and the experiments were conducted in the horizontal.

The force/torque sensor was mounted on the wrist of the robot. The sensor used in the experiments was an *AdaptForce* 50/100, weighing 0.35*kg*, with a relative accuracy of 2*%* of full scale and resolution (standard deviation of force sensor readings with filter 2) of F_x *and* F_y 0.027N, F_z 0.16N, and M_x, M_y, *and* M_z 0.0023*Nm*.

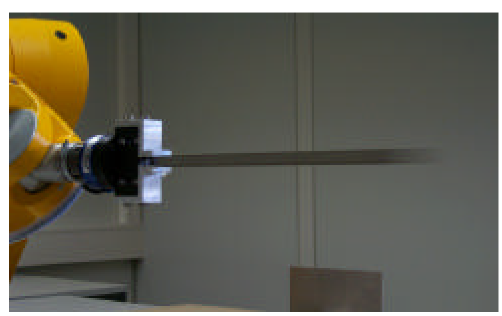

Figure 7. Experimental implementation, the DLO grasped by pneumatic jaws.

First, the vibrational period and the amplitude of the moments were measured using a previously developed program *period()*. At the same time, the maximum endpoint amplitude was recorded. Then, the calculated vibrational period and the defined stiffness coefficient d were used as known parameters in the experiments.

In order to contain at least one peak, the samples should cover at least one and a half vibrational periods of the DLO.

Here, all samples had a duration of 1.5 periods, with samples taken every 16ms. The coefficient l was set to be 0.618.

The overall adjustment-motion procedure consists of six main steps, which are executed sequentially until the vibrational amplitude is smaller than a predefined threshold:

(1) *The raw data is written into an array and then smoothed.*

(2) *The matching point is determined using template matching technique.*

(3) *The amplitudes of the moments from each direction (i.e. x, y and z) are compared, and the direction of the adjustment-motion is determined.*

(4) *The speed, acceleration and distance of the adjustment-motion are determined.*

(5) *The adjustment-motion is conducted.*

(6) *Finally, the effects of the adjustment-motion are evaluated.*

7. Experimental Results

The vibrational period of the DLO was experimentally determined to be T=0.667s (frequency 1.5Hz) and the constant d, which is defined in equation (7), was determined to be 200Nm/mm, while k for data smoothing was set to 7 in the experiments. In each case, the monitor speed of the robot was set to 50%. The program acceleration was set to 100% and the program speed altered automatically according to the scope of the adjustment-motion and the vibrational period of the DLO. The vibrational amplitudes and moments of the DLO were measured before and after the adjustment-motion. Experimental results are shown in Table 1, Figure 8 and Figure 9, respectively.

As can be seen from Table 1, with one-way adjustment-motion, the amplitude of vibration was reduced from 23cm to 2cm. Almost 91% of the vibrational amplitude was removed by the one-way adjustment-motion. In the case of the two-way adjustment-motion, the amplitude was reduced from 29cm to 1.5cm, a reduction of about 95%. It should be noted that the two-way adjustment-motion has a smaller moving scope, which is only one-half of the one-way adjustment-motion's.

The moments M_y, corresponding to the domain vibration that occurs in the horizontal plane, are shown in Figure 8 (one-way) and Figure 9 (two-way), respectively. A gap of about 0.3s between previous motion and sampling was used to avoid irregular data. Data can not be recorded during the data processing period (from about 1.2s to 1.5s). It can be seen that the amplitudes of the moments have been greatly decreased using one-way or two-way adjustment-motions. Moreover, the presented method worked very well, even though the signals were not perfect sine functions.

As described in the figures, one-way adjustment-motion can decrease the amplitude to 2cm level within only 2.8 seconds. In contrast, the vibration of an unadjusted DLO declines to the same level only after about 45 seconds, according to our tests. The two-way adjustment-motion decreased the amplitude to 1.5cm level within only 3 seconds, and unadjusted decline to the same level costs about 50 seconds. This illustrates the efficiency of the sensor-based adjustment-motion.

Additional experiments have been performed with the same DLO at different frequencies. The frequency was changed to 1.15Hz in one of these experiments by attaching an approximately 5g mass (two 50 Pfennig coins) to the free end of the DLO. In this case, the amplitude was decreased from 31cm to 3cm within 3.0 seconds, when a two-way adjustment-motion was applied.

Based on the results of the experiments, the presented method has proven to be effective in practice. Although not all of the vibration can be eliminated using the above method, because of the limited resolution of a robot system, it is reasonable to expect that if other vibration modes behave dominantly, the adjustment-motion can also be used to reduce them in the same manner.

Table 1. Vibrational amplitudes before and after adjustment-motion (average of 4 times of experiments).

type of TAMo	average amplitudes		amplitude reduction
	before	after	
one-way	23cm	2cm	91%
two-way	29cm	1.5cm	95%

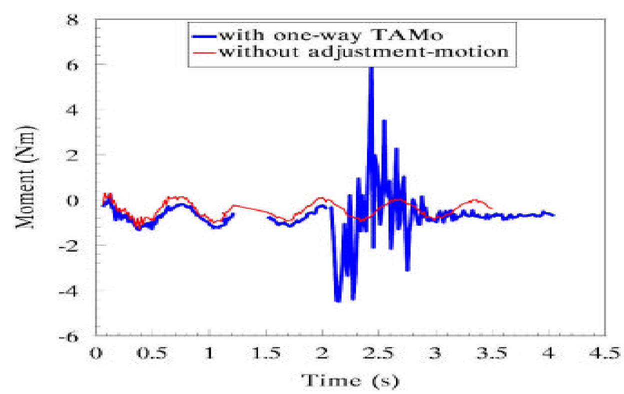

Figure 8. Measured moment M_y during the force/torque sensor-based adjustment-motion process

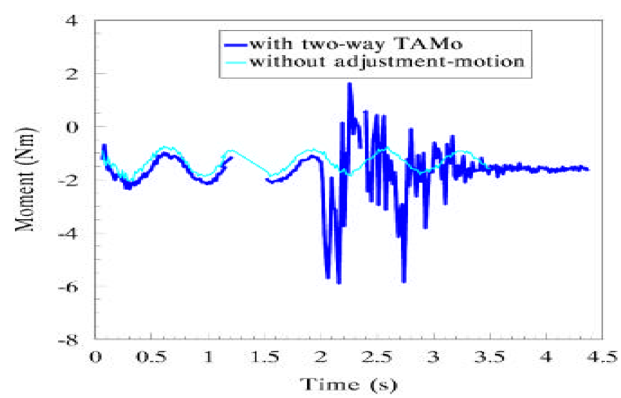

Figure 9. Measured moment M_y during the force/torque sensor-based adjustment-motion process

8. Conclusions

In the above sections, a force/torque sensor-based method for eliminating acute vibration during the handling of DLOs was presented and the experimental results were discussed. The attachable adjustment-motion can reduce the vibrational amplitude of DLOs effectively (cut more than 90% in each experiment).

Differently from model-based methods, the sensor-based method does not use any information from previous motions. The adjustment-motion is generated on-line and automatically by analyzing data from the sensor mounted on the robot's wrist. Template matching technique can be used successfully to determine the matching point between the signal of the DLO and the template. Results demonstrate the efficiency of the sensor-based adjustment-motion.

This sensor-based adjustment-motion can be easily used in practice, due to its simple but effective characteristics. However, it takes a great deal of time to obtain samples and process data. Therefore, in the future, new methods to reduce the sampling and processing time will be integrated into the sensor-based adjustment-motion.

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