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Manipulating Deformable Linear Objects: Sensor-Based Fast Manipulation during Vibration

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Abstract

It is difficult for robots to handle a vibrating deformable object. Even for human beings it is a high-risk operation to, for example, insert a vibrating linear object into a small hole. However, fast manipulation using a robot arm is not just a dream; it may be achieved if some important features of the vibration are detected on-line. In this paper, we present an approach for fast manipulation using a force/torque sensor mounted on the robot's wrist. Template matching method is employed to recognize the vibrational phase of the deformable objects. Therefore, a fast manipulation can be performed with a high success rate, even if there is acute vibration. Experiments inserting a deformable object into a hole are conducted to test the presented method. Results demonstrate that the presented sensor-based on-line fast manipulation is feasible.

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 assumed 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 life. 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. In this paper, we concentrate on deformable linear objects (DLOs), such as ropes, hoses, electric wires or leaf springs, which can be found in many industrial products.

Recent reviews of methods for the manipulation of deformable objects by robots are provided by Henrich and Wörn [1] and Nakazawa [2]. Attempts involving manipulation of DLOs can also be found, for example, in [3-7]. In these papers, either the physical model is used to compute the shape of DLOs, or different kinds of sensors are used to guide and/or compensate for the uncertainties of DLOs. However, these methods are specialized and confined to limited applications.

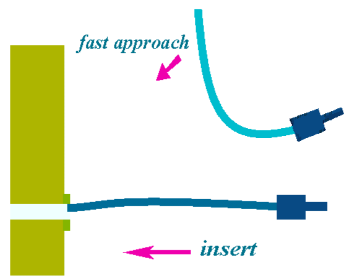

Figure 1. The fast manipulation of a deformable linear object. The DLO is inserted into hole while vibrating acutely.

It was found that an adequately defined skill-based manipulation can have generality to be applied to various similar tasks [8-10]. Skill-based manipulation for handling deformable linear materials has been touched upon recently. For example, Henrich et al. [11] analyzed the contact states and point contacts of DLOs with regard to manipulation skills, Abegg et al. [12] studied the contact state transitions based on force and vision sensors and Remde et al. [13] examined via experimentation the problem of picking up DLOs. However, the deformation of the DLO is only considered in a quasi-static way; time-varying dynamic effects (vibration) are not taken into account in the skill-related work described above. The uncertainty in the DLO changes with time and slows down the next operation, especially when the object is moved quickly by a robot arm.

To speed up the manipulation, one alternative method is to reduce the vibration to an acceptable level. In fact, vibration reduction of flexible structures has been a research topic for some researchers; for example, Chen et al. reviewed the previous works and presented a two-step method to avoid acute vibration [14]. Yue and Henrich presented attachable adjustment-motions [15] and sensor-based motion skills [16] to reduce the vibration of DLOs after an arbitrary operation.

Another method is to manipulate in spite of acute vibration of the object, just as a human would. It is true that manipulating in a dynamic way is a high-risk operation, never-

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theless, attempts at dynamic manipulation have already been performed. For example, Akella et al. [17] explored a method for dynamic manipulation of a planar rigid body on a conveyor belt using a robot with just one joint. With regard to manipulating DLOs, Casting manipulators [18], which include a flexible string in the link mechanism to enlarge the work space, are also an attempt to manipulate in a dynamic way. Lamiraux and Kavraki [19] addressed the problem of path planning for a thin elastic metal plate under fairly general manipulation constraints. Wakamatsu et al. [20] mentioned dynamic manipulation of DLOs and presented a dynamic model to derive the shape of the dynamically deforming object. However, sensors are not integrated in the above attempts. In fact, it is quite difficult to manipulate DLOs in an on-line way without any information from sensors.

In this paper, we present a sensor-based skill for manipulating DLOs in a dynamic manner. The state of the DLO is sensed by a force/torque sensor. Template matching method is used to find the phase of the time-varying displacement of the DLO. The fast manipulation can then be achieved with a high success rate, since the position of the DLO can be predicted on-line. A similar data processing method was used in [16], but aims at vibration reduction.

The rest of this paper consists of five parts. The assumptions used while analyzing the vibration of DLOs after an arbitrary motion are given in Section 2. Section 3 describes the template matching method used to determine the phase of the vibrational signal. Implementation of the experiments is given in Section 4. Experimental results verifying the effectiveness of the proposed on-line fast manipulation method are shown in Section 5. Finally, conclusions and future work are outlined.

2. Vibration Assumptions

Although a physical model with high accuracy is not needed in this paper, we still need to know some basic characteristics of the residual vibration of the DLO in order to recognize the phase of the vibration displacement.

Suppose the robot is moving a DLO from an arbitrary start position to the desired goal position, which is just in front of the hole. The next task is to insert the DLO into the hole. However, acute vibration has been stimulated in the previous operation. The insert operation will probably fail because of the high uncertainty caused by vibration. It would be a great help if we know how the DLO behaves during this period.

Since there is no external excited force during this residual vibration period, the vibration of DLOs is a kind of *free vibration* without excited force. The real DLO may have many vibrational modes. To simplify the problem, 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. The solution of equation (1) is as follows when the damping is light:

$$x = Ae^{-\alpha t}\sin(\omega\, t + \eta) \qquad (2)$$

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

To estimate the shape of a DLO, force/torque sensors and vision sensors can be used. Since a vision sensor needs much more effort to compute simple object features robustly, only a force/torque sensor, which is mounted on the robot's wrist, is used in our experiments. The force or moment signals are also Sine waves, 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 wave too, though the DLO may in fact have more than one flexible DOF. Therefore, it is reasonable to employ standard Sine functions as templates to recognize the phase of vibrational signals from sensors.

To recognize the phase of the vibrational signals, the dominant natural frequency of the DLO should be known in advance. In this paper, the dominant natural frequency ω (or vibrational period T) is measured off-line with a force/torque sensor and used on-line as a known parameter when manipulating. To measure the dominant natural frequency, a software package *period* was developed in V+. It receives sample data from a force/torque sensor, and finds the peaks and valleys of the sample data by dividing the sample data into many small windows. The vibrational period or dominant natural frequency can be obtained after averaging the time intervals between these adjacent peaks or valleys respectively.

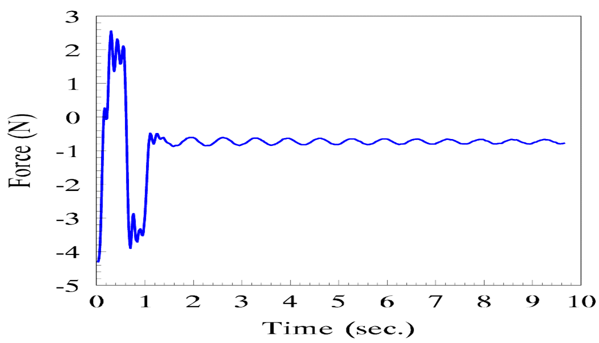

Figure 2. A typical low-pass filtered force signal of a DLO F_y during previous motion (0 to 1 sec.) and residual period (after 1 sec.)

3. Sensor Data Processing

In Section 2 it was noted that the DLO's vibrational displacement theoretically behaves like a damped Sine wave.

Now, suppose that we have already obtained the sample data from the sensor. If the *matching point* can be found, where the phase of the sample data matches the Sine wave's (i.e. the peaks and valleys of the sample data will match the template's perfectly), we may use the Sine wave to predict the vibrational signal in advance, as shown in Figure 3. The next operation (e.g. an insert operation) can then start at the time corresponding to one of the predicted points of the signal.

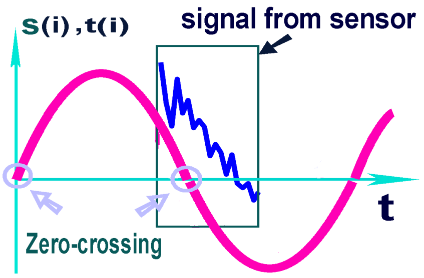

Figure 3. To recognize the phase of the vibrational signal, a piece of the periodic signal from the sensor is compared with the template of Sine segments using the mean squared error (MSE) method.

The sensor can provide 6D data, i.e. 3D for forces and 3D for moments. Here, only moments are used to sense the vibration of DLO. Compared with a force signal, the moment can reflect more vibrational information from the distal end of the DLO. The position of the DLO's endpoint is vital for the fast manipulation. The vector of the moment can be determined according to:

$$\mathbf{M} = (M_x \; M_y \; M_z)\begin{pmatrix} i \\ j \\ k \end{pmatrix} \tag{3}$$

where **M** is the vector of moment, M_x, M_y and M_z are the moments in x, y and z axis, and $\boldsymbol{i}$, $\boldsymbol{j}$ and $\boldsymbol{k}$ are the unit vectors in x, y and z axis respectively. The absolute value of the moment signal can be obtained as:

$$\|M\| = \sqrt{M_x^2 + M_y^2 + M_z^2} \tag{4}$$

Thus, the 3D data from the sensor is projected to 1D data and compared with 1D template in the following operation. It should be mentioned here that only the shape of the signal is considered. The moment can be translated to meet different demands as long as the value between the minimum and the maximum remains unchanged.

If the signal from the sensor does not cover even one period, it is impossible to determine the offset values of the signal. Moreover, the value of the signal may not just fluctuate around zero due to gravity. Thus, the data has to be translated to find the matching point. The sensor signal *s(i)* is translated to the domain of [0,1] as:

$$s(i) = \frac{s(i) - s_{\min}}{s_{\max} - s_{\min}} \tag{5}$$

where

$$s_{\min} = \min(s(i))_{i \in D_s} \tag{6}$$

and

$$s_{\min} = \max(s(i))_{i \in D_s} \tag{7}$$

where D_s is the domain of the signal segment for comparison. The compared portion of the template $t(i)$ can also be translated to the domain of [0,1] in the same way.

A measure of how well a piece of signal matches the portion of template is defined based on the *minimum squared error* (MSE) [22] between the signal and template, and is given by:

$$M_{se}(m) = \sum_{i-m \in D_s} (s(i-m) - t(i))^2 \tag{8}$$

Notice that D_s is the domain of signal data. It is the sensor data that is translated to the position *(m)* and compared with the corresponding portion of the template in this case. The definition in (8) is also the standard Euclidean distance between two vectors. Hence, the MSE has a minimum value when the match with the signal function is perfect (up to a scale factor). The point with the smallest value of M_{se} is the matching point.

Knowing the matching point, it is not difficult to predict the time corresponding to an arbitrary point on the Sine curve. However, the time corresponding to the zero-crossing is preferable, since it is easier to conduct the insert-into-hole operation when the free end of the DLO reaches its zero-crossing. By the way, predicting the real position of the endpoint of the DLO corresponding to an arbitrary time is also possible if a stiffness coefficient can be defined and measured off-line [16]. This is useful only when the next operation is expected to be performed at the time corresponding to a non zero-crossing.

4. Implementation

In the sensor-based fast manipulation experiments, a Stäubli RX130 industrial robot was used. A 500mm stainless steel ruler with cross section of 0.5mm×18mm was used as the DLO in the experiments. One end of the ruler was grasped by pneumatic jaws as shown in Figure 4. All of the experiments were conducted in the horizontal plane.

A force/torque sensor JR3 KMSi 90M31-63 was mounted on the robot's wrist. The sensor weighs 0.35kg and its relative accuracy is 2% of full scale, resolution (standard deviation of force sensor readings with filter 2) is F_x and F_y : 0.027N, F_z : 0.16N, and M_x, M_y, and M_z : 0.0023Nm.

A box with a rectangular hole was used in the experiment. The hole was 29mm high and 25mm wide. The hole depth was about 5mm; this is also the thickness of the carton material. The distance from the hole to the end of the DLO was about 5mm. To carry out a successful insert operation, the DLO should pass this 5mm distance at first, which of course costs a bit of time. Therefore, the fast manipulation should start a little bit earlier than the predicted start time t_{fm} of the fast manipulation because of the existing distance and acceleration properties of the robot arm. The new start time is compensated for as:

$$t'_{fm} = t_{fm} + t_{cp} \quad (9)$$

where t_{cp} is the compensation time depending on the distance from the end of DLO to the hole and the robot's acceleration abilities. This compensation time is constant no matter which zero-crossing the fast manipulation starts from, if the related parameters (distances, accelerations and speeds) are fixed.

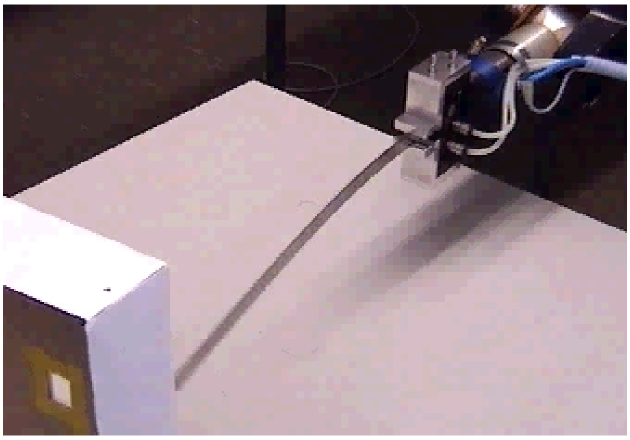

Figure 4. Experimental set-up. The DLO is grasped by pneumatic jaws and is to be inserted into a hole while vibrating acutely.

In the following experiments, samples are taken every 16ms. The overall fast manipulation procedure consists of four main steps, which are executed sequentially:

(1). Read the force/torque signals;
(2). Determine the matching point;
(3). Determine the critical time from which the fast manipulation should start;
(4). Conduct the fast manipulation.

5. Experimental Results

To verify the presented method, experiments were conducted in the horizontal plane. In this case, the DLO's dominant vibration occurs in the horizontal plane, as shown in Figure 4. The samples covered more than one-half of the vibrational period of the DLO. Considering the distance and acceleration ability, the compensation time t_{cp} was set to be 128ms (this value is fixed if the distance, acceleration and speed are unchanged in the experiments). The vibrational period of the DLO was determined off-line to be T=0.667s (frequency 1.5Hz).

Since the vibrational amplitude is about 20cm, the average speed of the endpoint of the DLO reaches about 60cm/s. This means it costs only 50ms for the endpoint to pass the hole if it travels at the average speed. Actually, the speed around the zero-crossing is the largest. The real time to pass the hole is of course less than 50ms. The fast manipulation of the DLO must be agile enough to make use of the small window of opportunity of (less than) 50ms. Several experiments that started from different zero-crossing were conducted. Results are shown in Figure 5, Figure 6 and Figure 7, respectively.

A series of pictures of the fast-insertion manipulation can be found in Figure 5. These pictures show that the fast manipulation started from the time corresponding to the first zero-crossing. Here the first zero-crossing refers to the first zero-crossing of the signal from the sensor (or the Sine wave template) immediately after the matching point was determined. The robot arm conducted the fast manipulation while the DLO was vibrating from right to left, as shown in the series of pictures. Notice that the free end of the DLO contacted the left side of the hole and bowed due to inertia.

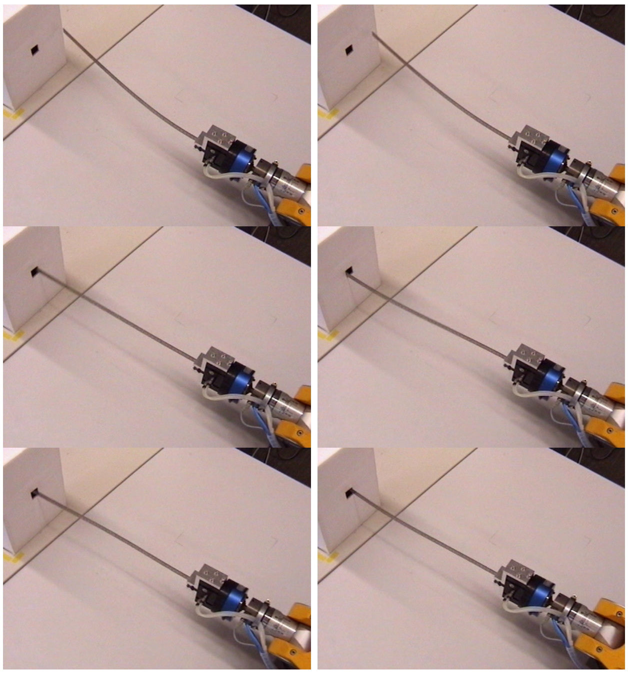

Figure 5. Fast manipulation. The DLO is being inserted into a hole while vibrating acutely*. The fast manipulation started from the time corresponding to the first zero-crossing while the DLO was vibrating from right to left. The fast manipulation was performed within about one second between the sampling period and insertion into the hole.

To describe the fast insertion manipulation in detail, the moments and forces correspond to the sampling and manipulation are shown in Figure 6 and Figure 7. As shown in the upper part of Figure 6, sampling data covers more than half

* Video clips for this dynamic manipulation can be found at Http://resy.informatik.uni-kl.de/

of a vibrational period. The blank part is the data processing period, as it is difficult to record data while processing. To show the results of the presented method clearly, the fast insert manipulation starts from the time corresponding to the third zero-crossing of the vibrational signals, as in Figure 6. The delay between sampling and the fast-insertion manipulation is about 2 seconds. Because the fast manipulation made use of the third zero-crossing opportunity, this implies, as shown in Figure 6, that at least two zero-crossings were missed in this experiment. However, the total time can be easily reduced to a bit more than 1 second when starting the fast-insertion manipulation from the time corresponding to the first zero-crossing, as shown in Figure 7.

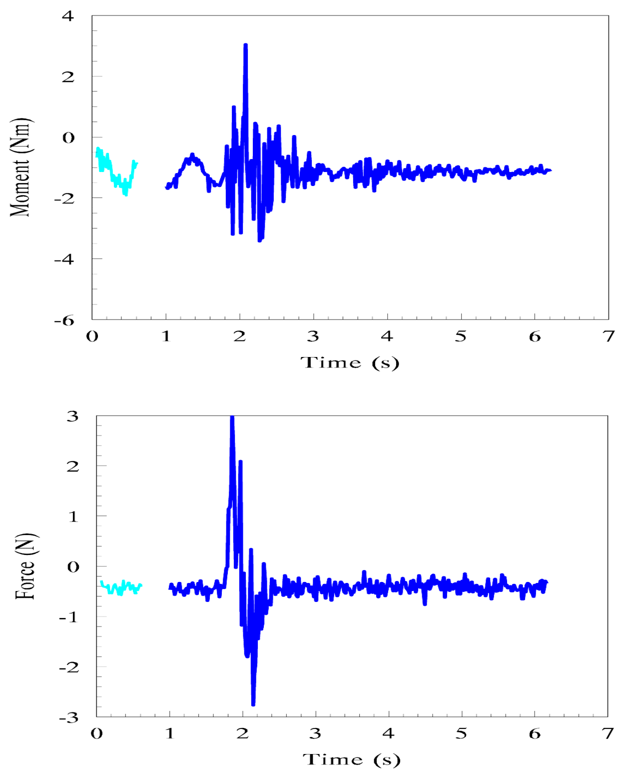

Figure 6. The moment M_y and the force F_z of the DLO during sampling and fast-insertion manipulation. The fast manipulation started from the time corresponding to the third zero-crossing. The sampling data covers more than half a vibrational period (from 0 sec to about 0.6 sec).

Since the presented method does not depend on the absolute value of signals from the sensor, it can work quite well no matter whether there is offset of absolute value (caused by gravity or other reasons) or not. Although the average values of the moments are quite different, as shown in Figure 6 and Figure 7, both of the experiments were successful. During the experimental investigation, we also found that fast manipulation is still a high-risk operation, with about 10% unsuccessful cases. At least two reasons for the unsuccessful cases were noted. One is that the real DLO has many vibrational modes, and the vibration signal is sometimes more complicated than the template. Another reason arises in the robot system; we noticed that the robot is sometimes unable to repeat the same task exactly, probably due to a communication delay. Nevertheless, our attempts to manipulate DLOs in a dynamic way for higher efficiency were feasible. Moreover, this fast manipulation skill can be attached to any kind of previous motion.

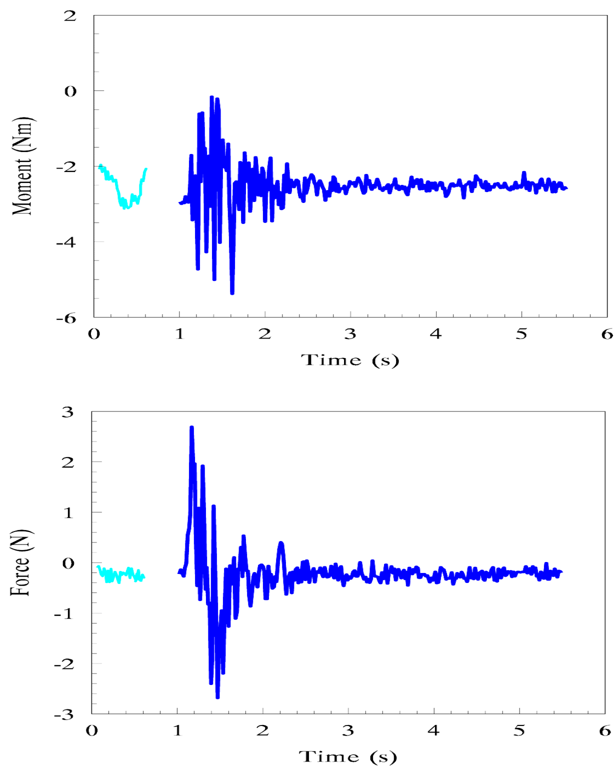

Figure 7. The moment M_y and the force F_z of the DLO during sampling and fast-insertion manipulation. The fast manipulation started from the time corresponding to the first zero-crossing. The sampling data covers more than half a vibrational period (from 0 sec to about 0.6 sec).

6. Conclusions

In this paper, a force/torque sensor-based method for fast manipulation of an acutely vibrating DLO was presented and experiments with different situations were conducted and discussed.

In the presented method, the phase of the vibrational signal of the DLO was recognized on-line using a template matching technique. The MSE method was used to find the matching point between the signal and template. Experimental results demonstrate the feasibility of the sensor-based fast manipulation method for handling DLOs in a dynamic way. The fast insert-into-hole operation can be performed within about one second from sampling to the end of the fast manipulation.

In the future, the present method should be revised to deal with more complicated vibrations of the DLO. Algorithms should be developed to manipulate DLOs using visual sensors in a dynamic way without knowledge about the vibrational frequencies.

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