Dynamically manipulating flexible objects using robots is difficult. Some studies have been conducted that only considered one type of object with known properties or that needed an identification test for string properties in advance. We propose a method to realize the dynamic manipulation of a string with unknown characteristics. We use a mass-spring-damper model for the string and repeat three steps: motion generation, real manipulation, and parameter estimation. The proposed method estimates the string properties to realize the motion objective via the real manipulation of the string. An identification test in advance was not necessary. In this study, we focus on swing manipulation. This can increase the motion energy of a string without a high-power actuator. After making a large swing, the robot can throw strings to a more distant target, such as a hammer throw. This motion is useful for explanation robots, rescue robots, and so on. We modified the proposed method to generate a swing manipulation. Then, we investigate whether swing manipulation can be performed by the proposed method and demonstrate its effectiveness via experiments with various strings with unknown characteristics.

Keywords: dynamic manipulation, unknown characteristics, periodic manipulation, string, swing

1. Introduction

Some robots are primarily used for assembly tasks in factories. However, their use in homes, offices, and shared spaces has recently increased. These environments feature a variety of flexible objects, such as clothing, futons, curtains, paper, and cables. Therefore, manipulating flexible objects is critical in the field of robotics. Flexible objects can easily deform under low force. The deformation takes different forms and varies with the nature and circumstances of the flexible object. Thus, it is challenging to predict and recognize the deformations for motion planning.

A linear object such as a string is a deformable object. Many studies have been conducted on static manipulation of linear objects. Katano et al. proposed decomposing a knotting sequence into steps that combine stable states, capable of handling ambiguous string states of the same category, with subsequent string operations; they realized five types of knotting using a dual-arm robot [1]. Rambow et al. used a variable admittance controller, adjusted via tactile information during teaching, to complete insertion tasks for soft linear objects by correcting the teaching trajectory via tactile information during the task [2]. Many other studies have been conducted using robot arms [3–5]. These studies did not consider the influence of string dynamic parameters. In other words, these manipulations have realized static manipulation without considering the dynamics.

However, several studies have dealt with dynamic manipulation. In particular, throwing or casting manipulation using ropes or strings has been discussed. Suzuki et al. developed a special casting manipulator consisting of a one-degree-of-freedom (DOF) link and cable. Winding and casting manipulations were analyzed by modeling the cable as a multilink [6, 7]. Sawada et al. considered a mass-spring model, which contains bending properties that vary depending on the string elongation and realize casting manipulation by a one DOF link [8]. Miyakawa et al. proposed a model-based analysis of yo-yo throwing motion with a one DOF arm [9]. Though these studies considered dynamic parameters, the manipulators were only one DOF, which cannot generate various manipulations due to insufficient DOF.

A few studies tackled dynamic manipulation using a multi-DOF robot arm. Yamakawa et al. formulated an equation of motion of a string and demonstrated that when one end of a string is grasped and moved, the string motion follows the trajectory of the robot arm [10–12]. However, its manipulation assumes that the robot hand speed is high and constant. Manipulations that satisfy this assumption are very limited. It cannot be said that their method can be applied to various manipulations.

In addition, almost all studies deal with only one type of string, not various types of strings. In addition, the dynamic parameter of the string was given or measured by other specific methods in advance. However, this is not a realistic approach. For instance, they do not consider...
2. Realizing the Swing Manipulation of an Unknown String

2.1. Proposal for the Swing Manipulation

We propose a method for swing manipulation, as shown in Fig. 1. It is realized with a 3-DOF robot arm in a two-dimensional space.

First, the desired amplitude of the string tip was provided. The initial parameters of the string model were set randomly. In motion generation, the robot arm movement is based on the angular velocity of the joint. This movement was generated randomly, and the initial arm position was randomly determined within the movable range. The movement of the string was simulated from the grasping point movements of the robot arm using a mass-spring-damper model. When the simulated amplitude was satisfied within a certain error margin of the desired amplitude, motion generation was regarded as a success.

Second, the generated motion was conducted using a robot arm. Manipulation was recorded using a camera. The string shape was extracted by image processing, and dilation and erosion were applied concretely for noise reduction after binarization.

In the first manipulation, the string model parameters and actual string properties did not match. Therefore, we estimated the string parameters. By providing parameters randomly, we simulated the string motion based on the actual arm movement. The matching rates of the simulated and actual string movements were analyzed. The parameter combination with the highest matching rate was retained. From the second manipulation onward, motion generation and actual manipulation were performed using the estimated string parameters.

By repeating these processes, the actual and simulated string movements gradually approached each other. Manipulation was then generated to reflect the string properties and realize swing manipulation. If the manipulation was not achieved after repeating this procedure several times, the manipulation was regarded as a failure.

2.2. String Model

The proposed method requires repeating the string movement simulation for motion generation and parameter estimation. A string model is necessary for this simulation. The mass-spring-damper model was selected because of its low computational load. Our method does not aim to express the various string movements completely, but only a specific string movement approximately for swing manipulation.

We assume that the string is homogeneous. Twisting is not considered because if the string movement and observation plane are limited to 2D, the effect of twisting is also contained in 2D. To represent the properties of elongation and bending, the string model is composed of mass points, springs, dampers, hinge springs, and hinge dampers, as shown in Fig. 2. The mass point numbers were set to $i = 1, \ldots, n$, starting from the grasping point. The equation of motion for mass point $i$ (position vector $\mathbf{r}_i$) is expressed as follows:

$$m\ddot{\mathbf{r}}_i = \mathbf{F}_m + \sum_{j \neq i} \mathbf{F}_{nj} - \sum_{j \neq i} \mathbf{F}_{ijn} + \mathbf{F}_{bi} - \mathbf{F}_{r_i}$$

$$+ \mathbf{F}_{ri1} + \mathbf{F}_{ri1} - \mathbf{F}_{hi} + \mathbf{F}_{hi1} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots$$

(1)
\[
\vec{F}_p = \begin{cases} 
F_{ph} + F_{phe} & \text{if } i = 1 \\
0 & \text{otherwise}
\end{cases} \quad (2)
\]

The forces and their coefficients are listed in Table 1. The spring and damper are required to express the axial elongation. These forces are calculated based on the distance and relative velocity between the neighboring mass points. A hinge spring and hinge damper are required to express the bending property. These moments are calculated based on the angle and its relative angular velocity between the three mass points and the vertical distance affects the string easily, we introduced a resistance. Air resistance and relative velocity between the neighboring mass points.

Both sides of Eq. (1) are divided by the mass \( m \) of the mass points, and unit mass conversion (i.e., designation of a value in \( k \) to the spring constant) is performed for each parameter. Thus, we do not need to consider the mass; there are eight string parameters \( k_1, c_h, k_1, c_1, C_{c1}, C_{c2}, k_{ph}, \) and \( c_{ph} \).

When the string is manipulated by a robot arm, time-series data about the orientation and position of the robot finger (the first mass point coordinates \( \vec{r}_1 \)) are provided.

The position vector \( \vec{r}_l \) for each string mass point is obtained by numerical calculation (Euler’s method) of the equation of motion.

### 3. Robot Arm Motion Generation

We generated the velocity curve of the robot arm for the swing motion of the string. This motion is periodic. Hence, after making a one-period motion, it is repeated, that is, connected to generate a swing motion.

At first, the initial angles for each joint of the robot arm were randomly selected from the movable range and specified as the initial positions (Fig. 3). Subsequently, a joint velocity curve was generated using a Bezier curve. The time \( T \) of one period is determined randomly within a certain range, and the time from 0 to \( T \) is divided into six equal parts \((t_0-t_5)\). The acceleration \( \alpha_0 \) at time \( t_0 \) is randomly determined from the range of the limit accelerations of the robot arm. We consider that the robot moves at a uniform speed in each time interval \( \Delta t \). The joint velocity for the control points is determined by

\[
V_n = V_{n-1} + \alpha_0 (t_k - t_{k-1}) \quad (k = 1, \ldots, 4) \quad (3)
\]

\[
V_0 = V_5 = 0. \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4)
\]

Using the control points \( V_0-V_5 \), a Bezier curve \( v(t) \) was
Realization of Swing Manipulation by 3-DOF Robot Arm for Unknown String via Parameter Estimation and Motion Generation

4. Parameter Estimation

The actual string movement in the swing manipulation was captured by a camera and used for parameter estimation. The image of the string was extracted based on the grasping point of the robot arm. The value of each string model parameter was randomly selected. Motion simulation of the string was performed using robot arm motion. The matching rate $E$ was calculated by comparing the point positions in the string model obtained from the simulation and the image series of the actual string motion. This was repeated while the parameters were changed. After a fixed number of repetitions, the eight parameters with the highest matching rates were output as the estimated parameters.

4.1. Random Parameter Selection

When randomly selecting each parameter in the string model, its value was determined using the exponential form to vary the parameter widely. For fast convergence, we narrowed the parameter estimation range in a stepwise manner using the following equations. For manipulation times $M$, the number of parameter changes shall be $m$ and a certain parameter shall be $p_a$.

$$P_a = P_{\min} + \frac{P_{\max} - P_{\min}}{M} \cdot \text{RAND}(1, 1)$$

$$z_m = z_{\text{best}} + \frac{z_0}{M} \cdot \text{RAND}(1, 1)$$

The maximum and minimum parameter values $P_{\max}$ and $P_{\min}$, respectively, were determined in advance. The initial value $z_0$ when determining $z_m$ was chosen. $\text{RAND}(1, 1)$ expresses random numbers from $-1$ to 1. Also, $\beta$ is a value slightly below 1 and is used to narrow the search range every time the parameters are updated. Finally, $z_{\text{best}}$ is the final estimated parameter value (exponent) in the previous manipulation.

4.2. Calculating the Matching Rate

The matching rate $E$ is obtained by comparing the actual string movement and string movement simulated by the selected parameter sets, as shown in Fig. 4. The binarized images of the actual string movement were dilated multiple times, and weighted scores were assigned in accordance with the dilation application times. Thus, an area closer to the center corresponds to a higher score ($p_{\max}, \ldots, 2, 1, 0$). The mass point positions in the string model correspond to the score $p_i$ based on the expanded area to which they belong.

At this point, the scores are weighted depending on the mass point number ($i = 1, \ldots, n$), because the mass points near the grasping area are likely to move slightly; they do not contribute to the parameter estimation. The movement increases near the end of the string. Hence, the weighting $w_i$ increases toward the end of the string. After weighting each image $E_i$, the sum for all images ($f = 1, \ldots, f_{\text{max}}$)

$$E = \sum_{f=1}^{f_{\text{max}}} E_i$$

Fig. 3. Generation of periodic motion.
becomes the matching rate $E$ using the following equation, where the weighting increment is $\Delta w$.

$$E = \frac{1}{f_{\max}} \sum_{f=1}^{f_{\max}} E_f, \quad E_f = \frac{\sum_{i=1}^{n} p_i \cdot w_i}{p_{\max} \cdot \sum_{i=1}^{n} w_i}$$

$$w_i = 1 + (i - 1)\Delta w$$

5. Manipulation of a String

5.1. Wire-Driven Robot Arm

Dynamic manipulation of a string requires a robot arm to move at a high speed. We built a 3-DOF wire-driven robot arm for this study, as shown in Fig. 5. The robot arm has no motors at its joints and only rotary encoders that detect the joint angle. Because the joints are driven by wires from the motors beneath the arm base, the robot arm is maintained at a low weight. The overall height of the arm was 585 mm, and the maximum composite speed of the arm finger was 21.8 m/s. Speed control (PID) was performed for each motor at the arm joint. When manipulating the string, the arm was moved via commands every 5 ms. The joint angle was sampled at the same time interval. We demonstrated a comparison of the target and actual trajectories of the finger when the robot arm made a circular motion with a 5 cm radius at the center of (0.41, 0.06) m in 1 s. The results showed that although some overshoot was observed, a virtually circular movement was exhibited, which was sufficient for string operation.

5.2. Obtaining String Movement with a Camera

We used a camera to judge the success of swing manipulation and capture the actual string shape for parameter estimation. The camera used for the experiment was an IDS camera UI-3580CP-C-HQ (512 × 480 pixels), which recorded string movement images at 50 fps. A (round, yellow) marker was attached to the robotic arm hand to capture the string movement from the perspective of the robot finger. Its location was detected from the images and used as a reference. An area of 240 × 250 pixels around the marker was cut from the images to investigate the string movement. After binarization and noise removal, the string area was slightly enlarged by dilation to easily detect the string.

6. Experimental Results of Swing Manipulation

We examined the swing manipulation of the desired amplitude achieved using the proposed method. The range of the one-period robot movement time was $T = 0.2$–0.8 s. The initial values used for the first motion generation were the minimum values listed in Table 2. The

![Fig. 5. 3DOF wire-driven robot arm.](image)

Table 2. Range for parameter estimation.

<table>
<thead>
<tr>
<th>Parameter coefficient</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring $k_s$ [N/m/kg]</td>
<td>$9.0 \times 10^3$</td>
<td>$9.0 \times 10^5$</td>
</tr>
<tr>
<td>Damping $c_s$ [Ns/m/kg]</td>
<td>0.13</td>
<td>1.3 $\times 10^5$</td>
</tr>
<tr>
<td>Hinge spring $k_h$ [Nm/rad/kg]</td>
<td>$8.0 \times 10^{-3}$</td>
<td>$4.0 \times 10^2$</td>
</tr>
<tr>
<td>Hinge damping $c_h$ [Nms/rad/kg]</td>
<td>$3.0 \times 10^{-7}$</td>
<td>0.67</td>
</tr>
<tr>
<td>Air resistance (proportional) $C_{c1}$ [Nms/rad/kg]</td>
<td>1.0 $\times 10^{-4}$</td>
<td>10</td>
</tr>
<tr>
<td>Air resistance (squared proportional) $C_{c2}$ [Nms/rad/kg]</td>
<td>1.0 $\times 10^{-4}$</td>
<td>10</td>
</tr>
<tr>
<td>Hinge spring at grasp point $k_{ph}$ [Nm/rad/kg]</td>
<td>$5.0 \times 10^{-3}$</td>
<td>5.0</td>
</tr>
<tr>
<td>Hinge damping at grasp point $c_{ph}$ [Nms/rad/kg]</td>
<td>1.1 $\times 10^{-6}$</td>
<td>0.37</td>
</tr>
</tbody>
</table>
number of mass points in the model was 10. Furthermore, the convergence factor was \( \beta = 0.995 \), initial search range \( \chi_{w0} = 0.6 \), and weighting increment used for the matching rate \( \Delta w = 0.25 \). The success condition was defined as a 20% error range of the desired amplitude.

6.1. Swing Manipulation with Different Length Strings

First, we examined whether the proposed method could be applied to swing manipulation with different string lengths. String lengths of 200 mm, 300 mm, and 400 mm were prepared for the experiments. Fig. 6 shows the result for a string length of 200 mm. The desired amplitude was 100 mm. In the first manipulation, the actual and simulated amplitudes did not match. After parameter estimation, the matching rate \( E \) increased. This means that the simulated string movement with the estimated parameter matches the actual movement more than that with the initial parameter. The generated manipulation with the estimated string parameter approximated the actual string amplitude to the simulated one.

Figures 7 and 8 show other manipulations with string lengths of 300 mm and 400 mm. The desired swing amplitude was also achieved in these cases.

In the experiment with a string length of 400 mm, manipulation failed in the case of a model with 10 mass points. A long string deforms more easily than a shorter one, and the string movement becomes more complicated so that real string movement cannot be expressed by the string model. When the number of mass points was changed to 13, the swing manipulation realized the desired amplitude.

As a result, the proposed method can be applied to the three kinds of string lengths. The estimated parameter reflects the string property for swing motion generation.

6.2. Swing Manipulation of Strings with Different Properties

We investigated the effectiveness of the proposed method for unknown strings with different properties. We prepared four types of strings for the experiment (strings A–D). The order of string hardness was string D, C, A, and then B. All string lengths were 300 mm. The desired amplitude was 200 mm. Swing manipulation with different strings was successful, as shown in Fig. 9. However, in the case of string D, swing manipulation could not be generated after parameter estimation, because the range of the motion time \( T \) was too short for the natural frequency of the swinging of the more flexible string. The motion time range of \( T = 0.6–1.2 \) s made the swinging manipulation with string D a success. The estimated parameter values are shown in Fig. 10. The axial spring coefficient, \( k_s \), along with string D, was estimated to be the lowest value for all strings. This implies that string D is the most flexible. Focusing on the estimated value of string B, both the air resistance squared proportional coefficient \( C_{c2} \) and the hinge spring coefficient \( k_h \) (Fig. 10(c)) are the highest values among all the strings. This indicates
that string B was the hardest. This result matches the real string properties. In contrast, the estimated parameters of strings C and A were not distinct. The parameters are redundant and are not always uniquely estimated.

6.3. Toward Smooth Swing Manipulation

Previous manipulation aimed to realize the desired amplitude of the string tips. Even if the motion objective was achieved, the amplitude did not continuously increase in some cases. This is not effective because the kinetic energy is not continuously amplified in every period. Therefore, we attempted a swing manipulation that continuously increased the swing amplitude. We defined a smooth swing as the manipulation. In random motion generation, we set the motion so that the swing angle increases every period. This manipulation can utilize the previous period motion, that is, store the motion energy every swing even if the arm motion is small. This can lead to throwing manipulation. We used strings A and D for the experiment. The experimental results are shown in Figs. 11–16. A smooth swing was realized using both strings. After parameter estimation, the actual and simulated swings of the string match more than those with the initial parameter. The robot tip trajectory in the final manipulation was smaller than that in the first manipulation. This is effective, and the robot can perform other motions after using this swing motion. We can see that the trajectory with string D is slightly complicated owing to the nonlinearity of the string property.

7. Conclusion

In this paper, we describe the swing manipulation of an unknown string with various dynamic manipulations by a robot. By repeating parameter estimation, motion generation, and actual manipulation, swing manipulation can be realized without requiring advanced knowledge of string characteristics. In motion generation, the one-period motion, which is generated randomly, is connected periodically and seamlessly. We realized the swing manipulation with three types of string lengths and four types of different string properties. The applicable range of our
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Fig. 11. Generated and actual manipulation for smoother swing motion with string A.

Fig. 12. Swing angle of smoother swing motion with string A.

Fig. 13. Robot’s tip trajectory of smoother swing motion with string A.

Fig. 14. Generated and actual manipulation for smoother swing motion with string D.

Fig. 15. Swing angle of smoother swing motion with string D.

Fig. 16. Robot’s tip trajectory of smoother swing motion with string D.

proposed method cannot be shown exactly because of the variety of strings, but these results indicate the possibility that the proposed method is effective for strings with unknown characteristics. Smoother swing motion was also achieved by considering a smooth increase in amplitude. In the future, we would like to attempt a manipulation that combines periodic and momentary manipulations, such as a hammer throw or casting manipulation.

References:

Tabata, K. et al.
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