Handling and Describing String-Tying Operations based on Metrics using Segments between Crossing Sections

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***Abstract*— Many robotics researchers are currently addressing the challenge of string-tying operations. Actual knot-tying tasks require metrics, such as the positions, sizes, and shapes of the knots, as well as the segment lengths of the knots. In this paper, we propose unified expressions for string-tying operations based on metrics and a method of realizing knot-tying tasks considering these metrics. Unified expressions, which are needed for the actual knot-tying task, are described using crossing sections and the segments between them. The realization method is the movement perturbation method, which first realizes a topological knot-tying task as a special solution to the task while considering the metrics; it determines where perturbations can be applied by means of sensitivity analysis, and extends the special solution using the movement perturbations. These allow us to realize knot-tying tasks by considering the metrics and relying on the results of topologically realized previous studies. Through experiments, we show the efficacy and limitations of our method.**

Index Terms—Intelligent robots, Robot Motion

I. Introduction

In real life, string-tying operations often involve instances requiring consideration of both the topology of the knots or the crossing sections and the adjustment of the string lengths or the knot positions. Relevant prior studies include research into string tying by robots. These studies sought to determine the crossing relationships of knots without considering the metrics (topology in cases where the endpoints are connected) [1-10, 16]. Inaba et al. were the first to achieve a string-tying operation using a jig that was manipulated by a single arm that was visually guided [1]. Matsuno et al. achieved successful string tying by using two arms [2]. Morita et al. performed a string-tying operation using Reidemeister moves [3]. Wakamatsu et al. performed a string-tying operation based on the modeling of flexible Reidemeister moves [4]. Kavaraki et al. performed planned movements for string-tying operations using a geometric model of a string [5]. Yamakawa et al. performed dynamic string tying operations at high speed [6]. Hopcroft et al. proposed a programming language for knot tying [7]. Spillmann et al. devised an accurate collision handling method for elastic rods in simulation [8]. Schulman et al. introduced the concept of *trajectory transfer* and dealt with the issue of the geometry of the relevant objects varying from one trial to another in teaching by demonstration [9]. Lee et al. dealt with the overhand-knot–tying of ropes of different lengths using force [16]. Their target [9], [16] differed from ours. The understanding of knot-tying manipulation itself or a

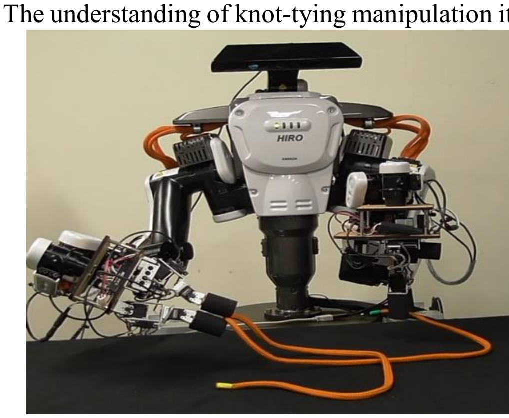

Fig. 1. Knot-tying by our dual arm robot system

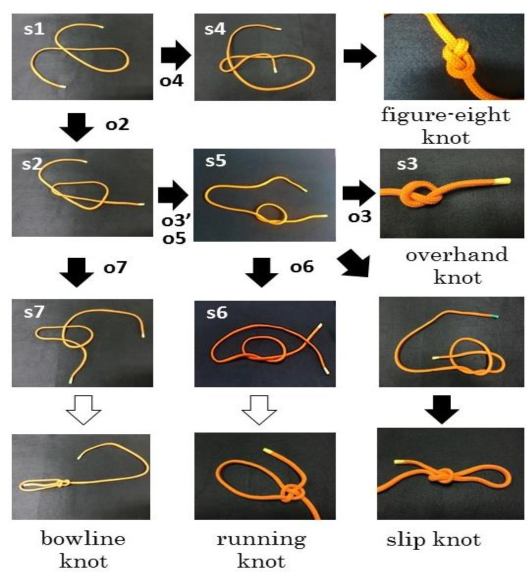

Fig. 2. Procedure for five types of knot [14]

knowledge of a specific domain, in this case, knot-tying, was not their goal. In more complicated manipulation tasks, a knowledge of knot tying and knot theory is also integrated into the program that deals with knot-tying tasks. A "learning by demonstration" approach is ideally complementary to our approach to ultimately understand the manipulation and its implementation. Saha et al. developed pioneering motion planner constructs for a topologically biased probabilistic

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roadmap in the DLO's configuration space [10]. Such pioneering studies of topological knot tying were conducted in the past. To the best of the authors' knowledge, there is no existing solution to knot tying while considering metrics, such as the positions, sizes, and shapes of the knots. In this study, we not only examine manipulations that consider the topology or crossing sections of knots but also explore how to perform string-tying operations that enable the adjustment of string lengths and the positions, sizes, and shapes of the knots. The modeling and basic operational movements for the strings proposed in this paper can help realize unified expressions for string-tying operations based on metrics.

We developed a method for designing a knot-tying program while considering metrics based on a topological knot-tying program. We assumed the use of a topological knot-tying program that had previously been analyzed and designed the related procedures. We used our program [14] (Appendix I) to realize five types of topological knot tying on a table by using a dual-arm robot (Fig. 1). Fig. 2 shows the branch and final forms of the five types of knots previously addressed [14]. The labels in the figure correspond to the states and operations. A black arrow depicts an application of one operation while a white arrow depicts the application of a sequence of operations.

This paper presents a method for tying a string while considering metrics by describing segments based on the crossing sections and designing movement perturbations. The presented method is demonstrated to find the applicable part of the movement perturbation in the program [14] and to make string tying considering metrics possible if any such metrics exist. Indexing of the crossing points during the string-tying procedures is also devised. Since a string segment is grasped and moved by the robot arm step-by-step, the system can easily discern the type of intersection: either undercrossing or overcrossing. Once the sequence and types of the crossing points are decided, the length of the segments and the center of the loop can be computed.

II. String Tying Considering Metrics

In this paper, "string tying considering metrics" means that the string-tying objective is to form knots that are completely identical, including aspects such as the positions and segment lengths of the crossing sections (metrics that will be addressed in future work will include the curvature).

A. State Representations of Segments between Crossing Sections of String

1) Expression by Segments

The State of the string (knot representation) S is defined as $S = \{(L,\ C_1, \dots,\ C_{num}, R), (Len(L,\ C_1), \dots, Len(\ C_{num}, R))\}$ such that

S: State of the string (knot representation),

C_i: i-th crossing; J_i (over crossing) or j_i (under crossing), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) position, where 1D, 2D, and 3D positions have different representations (Fig.3 and Fig. 4).

L: one endpoint, named L; 1D, 2D and 3D position

R: another endpoint, named R; 1D, 2D, and 3D position

$Len(C_i, C_{i+1})$: length of segment between crossing C_i and C_{i+1}.

TABLE I. Variations in Segment Lengths of String with Knots

L-J1	J1-j2	j2-J3	J3-j4	j4-J5	J5-j6	j6-R
69	15	19	85	63	20	18
85	14	15	95	61	20	15
179	*	*	*	*	*	125

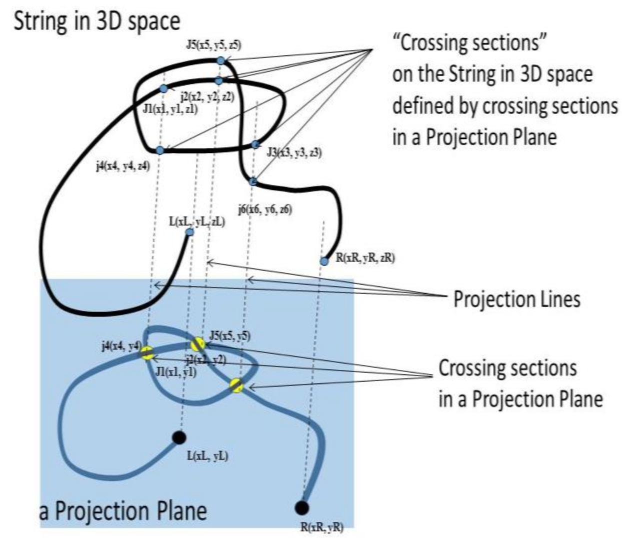

Fig. 3. Definitions of crossing sections and segments of strings (3D space).

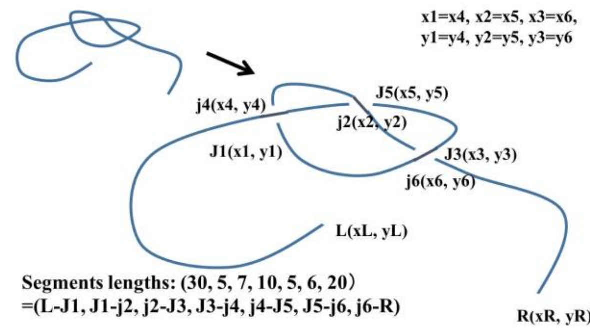

Fig. 4. Crossing sections and segments of string (for one string)

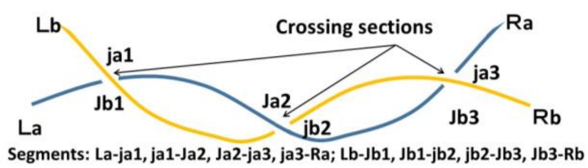

Fig. 5. Crossing sections and segments of strings (for two strings)

For the knot configuration of a string, a diagram can be drawn by projecting the string onto a 2D plane. The state of the string can be expressed based on the crossing sections and their upper-lower relationships (Fig. 3). The section of a string between two crossing sections is called a segment. The condition of a string can be quantitatively expressed by the length, position, and shape of such segments, and the string lengths and knot positions during the string-tying operation can be adjusted by using such expressions. "Crossing sections" (the points denoted by the small circles in Fig. 3) on the string in 3D space, which may not actually be crossing in 3D space, are defined as crossing sections in a projection plane. When a

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string is manipulated on a 2D plane, such as a table top, the projected string on the projected plane coincides with the actual string. Fig. 4 illustrates an example in the upper-left area with the positions of the string crossing sections highlighted. The crossing section positions are represented by a lower-case "j" when going below and by an upper-case "J" when going above, starting from one end (L) to the other end (R). An example sequence would be L, J1, j2, J3, j4, J5, j6, and R. The crossing section positions are expressed by the length of the string (1D coordinate) with the origin set to 0 at the left end position L, and the coordinates on the projected plane (2D coordinates), and the coordinates of the actual space (3D coordinates). This example has seven segments. If the length of segment L-J1 is 30, the lengths of the other segments would be 30, 5, 7, 10, 5, 6, and 20, respectively. Fig. 4 indicates the crossing section positions with 2D coordinates on a projected plane, such as (xL, yL) at L. When there are two strings, a suffix (e.g., a or b) is added to the otherwise similar descriptions. For example, Fig. 5, which shows a step during the process of tying a square knot, shows positions La, ja1, Ja2, ja3, Ra, Lb, Jb1, jb2, Jb3, and Rb. String-tying operations can be described in this manner, as well as in cases involving two strings.

2) Transient Conditions and Expressions for Configuring Knots

a) Description of Knot-Forming Process

Table I presents an example description of the formation process for an overhand knot using the segments described in this paper. Only the last segment of the string tying is presented to demonstrate the change in the length of the segment; however, segments can potentially be generated or eliminated in association with the crossing sections during an actual string-tying operation. The lengths and positions of the segments vary during an operation. The way in which the final lengths and positions vary is described here. In the table, the asterisks (*) represent those cases for an overhand knot where defining the lengths of individual segments is difficult because the knots are small and tight. In such cases, only the distances from both ends of the string are important. The values for all the segments must be controlled when the size and shape of the knot are controlled such as for a bowknot.

b) Control of Segment Lengths and Positions

Monotonic lengthening or shortening of a segment from the initial length is referred to as a monotonic adjustment movement. Achieving monotonic adjustment movements limits the positions at which transfer can occur, starting from the location of the first crossing section. This means that upper and lower limits can be considered for such transfers.

Although the monotonic lengthening or shortening of a segment is very easy to deal with and is optimal, it is not easy to achieve in an actual task. It can be achieved only approximately. Here, a more realistic category of control of segment lengths and positions is required. Quasi-monotonic knot tying occurs when an endpoint or grasp point is drawn in only one direction along the string. This quasi-monotonic knot tying corresponds to actual knot tying without untying a tangled knot or relaxing a knot. We assumed the performance of quasi-monotonic knot tying unless specified otherwise.

B. Formulation of String Tying

This section presents the formulation of string tying considering metrics using the state representations for segments between crossing sections, as described in the previous section.

1) Expression of Problems

For the preparation of formalizing the problem,
State Space $< S, O, \phi, S_I, S_F >$ is defined, such that
S: States of a string
O: Operations
ψ : $S \times O \rightarrow S$, a Map from S and O to S
S_I: initial state, $S_I \subset S$
S_F: $final$ state, $S_F \subset S$
The Operations O are defined by
$O = \{O_i | O_i = (M_{i,1}, \dots, M_{i,k_i}, \dots, M_{i,K_i})\}$ *i=1,…, N, k_i=1, …, K_i*
M_{i,k_i}: k_i-th sub-operation for tips' movements in Operation O_i
$T_i = (p_{i,1}, \dots, p_{i,k_i}, \dots, p_{i,K_i})$: tips' positions in Operation O_i
p_{i,k_i}: k_i-th position of tips of both arms in Operation O_i

First, the tying of a knot is reassessed while considering the metrics. In other words, the sizes, positions, and shapes (balance of respective sections) of the knots should be expressed.

Next, the process for solving the above problem is described using crossing sections and the segments between them. Movements for configuring the intended knot are performed to generate (or eliminate) and adjust crossing sections and segments, to achieve the same crossing sections and segments as those of the intended knot.

2) Generation of Movements

Here, we assume that the above problem has been solved to describe how the movements can actually be achieved. Topological knots have already been achieved in a variety of ways by robots, as noted earlier. The methods and programs used to do so represent particular solutions to the problem when metrics are considered. Movement perturbation methods for achieving objectives while considering metrics are described here using such solutions.

We assume that a formulation was performed using expressions based on the segments between crossing sections for the problem described above, and that the movements for tying a string were performed by a program for tying knots topologically that tied knots with particular metrics. The key feature of such a movement perturbation method would be whether the final results considering the target metrics can be achieved by a certain movement perturbation based on the topological program. It is therefore necessary to determine the relationship between the perturbation of the movements and the metrics of the final knot. The perturbation of a crossing section position with this method is based on the assumption that a certain relationship can be determined between the crossing section position and the perturbation of such movement. If the crossing section positions can be expressed by a deterministic expression, such as J1 = (x1, y1, z1), j2 = (x2, y2, z2) etc., then segment lengths are expressed

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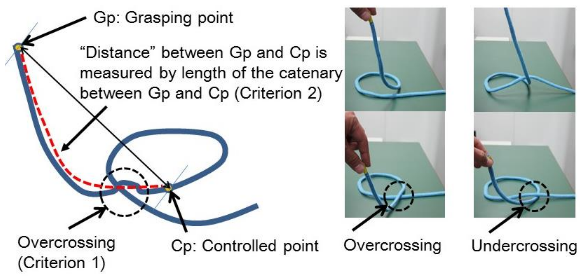

Fig. 6. Criterion 1 and Criterion 2

as Seg1 = l1, Seg2 = l2 etc. If the crossing section positions can be expressed by a probabilistic expression such as J1 = (X1, Y1, Z1), j2 = (X2, Y2, Z2)…, where Xi, Yi, Zi are random variables, then the same is true for the segment lengths, which become randomly variable such as Seg1 = L1, Seg2 = L2 etc. For instance, for a given motion perturbation A1, the conditional probability distributions P(X1, Y1, Z1|A1) and P(L1|A1) are determined under the above assumption.

For considering movements with metrics, the movements of a single operation can be categorized into three types: main movements (primary procedures), broad adjustment movements (broader view with feedforward in advance), and local adjustment movements (local view with feedback at the end).

The main movements are used to actually form the necessary crossing sections as well as the final knot. Broad adjustment movements are related to the setting of the initial conditions. If the task can be divided into several parts, the setting of each initial condition for each part corresponds to the broad adjustment movements. This is achieved with feedforward; for example, broad adjustment movements are performed to determine where the initial position for a crossing section should be set or what the initial length of a segment should be. Local adjustment movements are used for converging the length of the formed segment to the desired value. They are intended for fine adjustments of the sub-goal conditions during the process, including adjustments of the final knot. In particular, by assuming quasi-monotonic knot-tying, broad adjustment movements determine most of the results of the sub-goal conditions, while local adjustment movements slightly modify the results of the sub-goal conditions.

a) Overall flow of Movement Perturbation Method

The overall flow of the movement perturbation method can be described using the notation of Section II-B-1 as follows:

1. Prepare the main movements $\boldsymbol{O_{main}}$

$O_{main} = (O_1, \dots, O_i, \dots, O_N),\ O_i \in O, i = 1, \cdots, N\}$ *such that*

$O_i = (M_{i,1}, \dots, M_{i,k_i}, \dots, M_{i,K_i}), k_i = 1, \dots, K_i$

$T_{main} = (p_0, p_1, \dots, p_j, \dots, p_{N_A}),\ p_j \in R^3,\ j = 0,1, \dots, N_A$

$N_A = 1 + \sum_{i=1}^{N} K_i$, where T_{main} contains the tip positions in Operation O_{main}, which are the operations in the main movement of the task. Without loss of generality, O_i in O_{main} and p_j in T_{main} are renumbered in the order of the above notation to simplify explanation.

2. Implement broad adjustment movements (the perturbed position $p_{pertrubed}$ and vector $\Delta_{perturbed}$ are selected).

- Perform sensitivity analysis of T_{main}

Choose a state S_i, the corresponding Operation O_i, and position p_j in which movement perturbation is applied. Perform the movement perturbation ($p_j \rightarrow p_j + \Delta$). Here, Δ is the perturbation vector that has the following property:

$\Delta = (\Delta_x, \Delta_y, \Delta_z),\ \Delta_x, \Delta_y, \Delta_z \in R, |\Delta| = \sqrt{{\Delta_x}^2 + {\Delta_y}^2 + {\Delta_z}^2}$

Perform $O' = (O_1, \dots, O_i', \dots, O_N)$, which includes $p_j' = p_j + \Delta$, and record the value of the evaluation function $F(T')$.

- Investigate the sensitivity of the final results and determine the perturbation (the perturbed position $p_{pertrubed}$ and the perturbed vector $\Delta_{perturbed}$) to optimize $F(T')$.

3. Implement local adjustment movements.

This method attains the perturbation of a crossing section position through perturbation of the tying movements (minor changes in movements). When a section in a series of movements is perturbed, there are still sections that are unaffected by the positions of the crossing sections. This means that the sensitivity of the crossing section positions and segment lengths resulting from movement perturbations is negligible. The range of control is defined as the portion of sections that would be affected by the perturbation of a movement. The evaluation function of the one dimensional position after the perturbed string tying operations with T' on the string, $\mathrm{F}(\mathrm{T}')$, is defined by measuring the difference of the positions $\mathrm{s}(\mathrm{T}')$ and $\mathrm{s}(\mathrm{T_{main}})$, such as $\mathrm{F}(\mathrm{T}') = \mathrm{sgn}(\mathrm{s}(\mathrm{T}') - \mathrm{s}(\mathrm{T_{main}})) * |\mathrm{s}(\mathrm{T}') - \mathrm{s}(\mathrm{T_{main}})|,\ \mathrm{s}(\mathrm{T}') \in \mathrm{S}[0, \mathrm{L}]$,where L is Length of string and sgn is the sign function.

Sensitivity analysis is necessary for not only the perturbation of given movements or crossing section positions but also their "conditions" (changes). In short, sensitivity analysis here refers to sensitivity analysis in operational research (OR) and consists of a systematic study of the sensitivity of solutions (outputs) to small changes in the data (inputs) [15]. In general, movement perturbations are either strongly sensitive to adjustments of directly controlled parts (e.g., segment length) or robust and do not affect the final results; their sensitivity needs to be determined to achieve the objective.

a) Spatially Localized Movement Perturbation Method

Next, we describe a spatially localized movement perturbation method, which is a variation of our movement perturbation method and in which the perturbations are applied to positions that do not globally affect the main motion other than the main objective of the perturbation. In the case of string tying on a 2D plane (table top), the direction is normal to the plane. While the movement parallel to the plane does not change, the movement perturbation normal to the plane applies spatially localized perturbation of the main motion and achieves the objective knot tying. The criteria for evaluating candidate movement perturbations are as follows:

1. Choose the state in which there is no undercrossing point on the manipulating segment between the grasping point and the

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controlled point that is moved by the perturbation (Fig. 6).

2. Choose the state in which the distance between the grasping point after the movement perturbation and the controlled point before the perturbation on a string is equal to a function of the length of the string segment between the grasping point and the controlled point. The function should be defined or chosen in order to approximate the actual string. If the string is sufficiently soft, the function is that of a catenary. For this study, we assumed this because the simple measurement of an actual string validates the equation of a catenary.

The function of a catenary is

$y = a\cosh(b/2a)$, (Eq. 1)

where cosh is a hyperbolic cosine function, a is the scaling factor of the catenary, and b is the distance between the tips of the catenary. The arc length of the catenary is $\mathrm{L_c} = 2\mathrm{a}\sinh(\mathrm{b}/2\mathrm{a})$. We assume that $\mathrm{L_{before}}$ is the length of the string segment between the coordinates of the current grasping point and the current controlled point before perturbation and $\mathrm{L_{after}}$ is the length of the string segment between the coordinates of the current grasping point after the movement perturbation and the controlled point before perturbation.

Criterion 2 is, in this case,

$L_c/2 = L_{before}$.

If the movement perturbation is applied to the state, the controlled point can be moved by infinitesimal movement perturbation, such that

$L_c/2 > L_{after}$.

If $L_c/2 \leq L_{after}$, the controlled point may not be moved by the movement perturbation.

3. Choose the state in which there is a perturbation that minimizes the length between the new locus after the perturbation and the old locus before the perturbation.

These criteria allow us to realize spatial localization of the effect of the movement perturbation (Criterion 1 and Criterion 2) and to minimize the side effects of the movement perturbation (Criterion 3). The first criterion is for generating no side-effects of movement perturbation for the global state of the string. The second one is for choosing an appropriate perturbation and limiting its effects to the spatially local area that corresponds to the segment between the grasping point and the controlled point (Fig. 6). The length is approximated by the catenary. The third is for minimizing any inappropriate side effects to the global state of the string. Fig. 7a and 7b show the loci of the tip of the right and left arm in 3D space and a projected one on the 2D plane, respectively. The numbers (right arm: numbers from R1 to R19, left arm: numbers from L1 to L15) indicate the time sequence of the motions. In Fig. 8, the five main scenes (corresponding to the five stable states in this task) of the string on the table top are shown with the loci. These loci of the tip positions of the arms were generated by using a program [14] and recorded. Thinned string images for five main images were also recorded and used. The grasped points are determined semi-automatically by detection procedures (endpoint detection and loop-detection) of our vision system (see Appendix for details), where the operator inputs the endpoint that is chosen to detect and measure (e.g., one of two

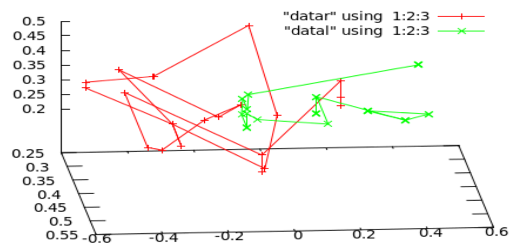

Fig. 7a. Loci of Tips of Right Arm (datar) and Left Arm (datal) in 3D space

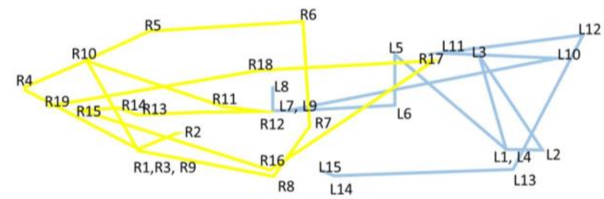

Fig. 7b. Loci of Tips of Right and Left Arms Projected onto 2D plane on the Table (Right Arm: R1 to R19, Left Arm: L1 to L15)

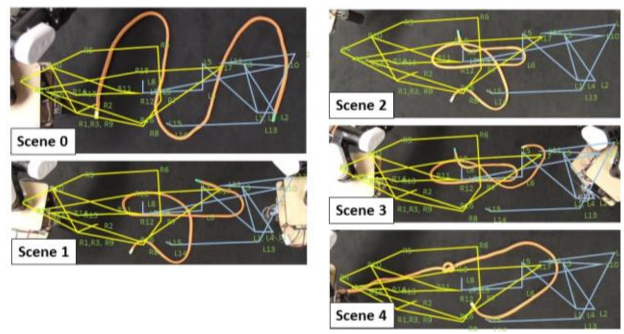

Fig. 8. Five main scenes with the loci

endpoints can be chosen by specifying "up, down, right, or left" in the image. If a relatively high upper endpoint is chosen, “up” should be input). The necessary information to determine the grasp point, i.e., the length from the endpoint to each grasped point in each stable state, was specified in the program in advance. The actual loci were 3D, but 2D projected loci are shown in this figure to make it clearer and more legible. In this example, there are nine candidate states in which Criterion 2 holds, which correspond to the red parts of Fig. 9. The state existing at R18 is that in which Criterion 1 does not hold. According to the results of a sensitivity analysis, the final results were not affected by perturbation of the states at L2, L3, L5, R4, and R8. Perturbation in the state between L6 and L7 caused a failure in the topological knot tying. The states existing at L11 and L12 are not used for broad adjustment movements because the next “stable state” is the final state, which is not handled as another initial state of the next part of the operation. The remaining candidate is the state between R5 and R6. R6 was one of the extreme points in this state and the small perturbation leads to the final result. Therefore, we chose to apply a movement perturbation to R6 because there was no undercrossing point on the manipulating segment between the grasping point and the controlled point in this state (Criterion 1) and because $\mathrm{L_{before}}$ was equal to $\mathrm{L_c}/2$ and the perturbation candidate easily satisfied Criterion 2 and 3 by a small movement perturbation.

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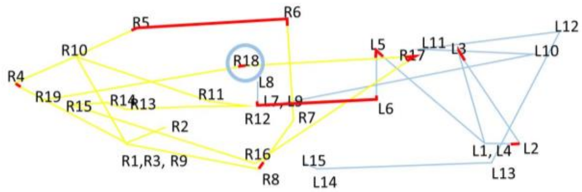

Figure 9. Candidate States on Loci
(Red Lines: Criterion 2 is held. Blue circle: Criterion 1 is not held.)

In this example, it was assumed that the string is sufficiently soft, as follows: $\mathrm{B} = \mathrm{b}/2 = 48.0\ \mathrm{cm}, \mathrm{D} = \mathrm{y}(\mathrm{b}/2) - \mathrm{y}(0) = \mathrm{a}\cosh(\mathrm{b}/2\mathrm{a}) - \mathrm{a} = 46.0\ \mathrm{cm}, \mathrm{a} = 33.1$. The length of the half catenary that corresponds to the segment between the grasping point and the controlled point was calculated by $\mathrm{a}\sinh(\mathrm{b}/2\mathrm{a}) = 66.7\ \mathrm{cm}$. The actual length in this case was 67.0 cm when B = 48.0 cm and D = 46.0 cm. These values corresponded to the values of the state existing at R6 in which actual movement perturbation is applied to shows that the approximation of the catenary was good and that the assumption was valid.

3) *Expression of Final Targets*

The final targets depend on the specifications of an operation, but the following expressions are needed when metrics are considered. The position of a knot is described by the length of a segment. The size of a knot is described by the positions and lengths of the respective segments. The shape of a knot is described by the positions, lengths, and shapes of the respective segments.

4) *Specifications for Operations Related to Knots*

There are several ways to provide knot-tying specifications.
Position of knot: from end E_a to $L_a \pm \varepsilon$ (one-side designation) or from end E_a to $L_a \pm \varepsilon$ and from end E_b to $L_b \pm \varepsilon$
(dual-side designation when the knot itself has a size)
Size of knot: length of knot L (total length of string) $- L_a - L_b$; segments and crossing sections
Shape of knot: shape of segment (row of discrete or continuous points)

III. Examples of Basic Movements Actually Achieved for String-tying Operations

A. *Overview*

Here, we designed and actually found the stable states of the string that could be handled as "the identical states," from which the necessary information for the next operation could be extracted and the current state could transition to the next state using the information. Different knot-tying tasks could be completed by repeatedly using this process. These procedures were designed for a dual-arm robot, and five different knot-tying tasks were achieved by using them, thereby demonstrating the efficacy of this approach.

The robot system used in this study was as follows:
Dual-arm robot: A HiroNX of Kawada Robotics Corporation was used. Each arm has six degrees of freedom.
Hand: Three-fingered hands were developed in the authors' laboratory at the University of Electro-Communications [12–14]. Each finger has 3 degrees of freedom. In this study, two opposing fingers were used in the knot-tying experiments on a desk. **Camera**: A Kinect camera manufactured by Microsoft Corporation was used to capture visual information. The RGB Camera of the Kinect was used to detect the string, based on its color, while the depth camera was used to obtain the coordinates of the robot's objective point from the image coordinates of the point.

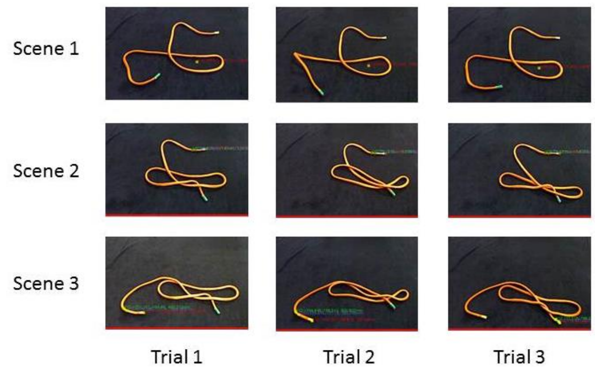

Figure 10. Variation in segment lengths of string during tying movements

TABLE II. Variation in Segment Lengths of String during Tying

segments	L-J1	J1-j2	j2-R				
Scene 1	70	119	102				
segments	L-J1	J1-j2	j2-J3	J3-j4	j4-J5	J5-j6	j6-R
Scene 2	69	15	19	85	63	20	18
Scene 3	85	14	15	95	61	20	15
Results	179	*	*	*	*	*	125

TABLE III. Variations in Segment Lengths of String during Tying (Increase)

segments	L-J1	J1-j2	j2-R				
Scene 1	74	122	105				
segments	L-J1	J1-j2	j2-J3	J3-j4	j4-J5	J5-j6	j6-R
Scene 2	79	8	27	85	65	32	10
Scene 3	185	*	*	*	5	5	125
Results	188	*	*	*	*	*	116

TABLE IV. Variations in Segment Lengths of String during Tying (decrease)

segments	L-J1	J1-j2	j2-R				
Scene 1	84	113	105				
segments	L-J1	J1-j2	j2-J3	J3-j4	j4-J5	J5-j6	j6-R
Scene 2	84	5	15	81	86	22	12
Scene 3	100	5	7	80	88	11	13
Results	174	*	*	*	*	*	130

B. *Broader Adjustment Movements by Robots*

The conditions of the tying process, such as those shown in Scene 1–3 in Fig. 10, can be regarded as being the initial conditions for the movements described here. Broad adjustment movements are used to establish the initial conditions. The manner in which broad adjustment movements adjust the knot positions can be evaluated by measuring how the final results change depending on the initial conditions. Here, a case is presented in which the movement of a section was perturbed (in this case, the size of a loop), and the changes in the final position were recorded. The results indicated that the position of a knot can be changed in a particular direction by extending the loop. There were also cases in which the lack of a "margin" (that is,

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applicable candidates for the movement perturbations) in the program for generating such movements led to the failure to secure the lengths at the ends necessary for grasping, such that the string was not grabbed during the process. Here, a "margin" refers to the ability of a program to execute movements for generating knots in a topological manner without being affected when some of the movements to be performed by the program are changed.

Fig. 10 depicts the knot-tying process in progress. Tables II–IV describe changes in the results due to perturbations of the tying movements. The values measured from the images were entered as the lengths of segments. These values were converted into the lengths of the actual strings: from left to right, the final results were 78 cm, 81 cm, and 75 cm, respectively. (The lengths to the knots in the strings were actually measured to obtain the final results.) These corresponded to perturbations while a loop was being formed during a tying movement increasing or decreasing the positions of the endpoints by 2 cm. The position of the knot decreased by 3 cm and increased by 3 cm from the left end because of this change. Five trials were performed. The standard deviations were 0.545 cm, 0.860 cm, and 1.020 cm, respectively. This result indicates the possibility of controlling and increasing the position of a knot through broad adjustment movements, but also the difficulty of controlling and decreasing the position of the knot in this example.

In such instances, the challenge is determining whether the relationship between the perturbation of such movements and the final results is reproducible and reusable. In this instance, the final position of the knot was moved in one direction by a perturbation, but if the very same perturbation can move the final position in the opposite direction, this method naturally cannot be depended upon to adjust the final position. This experiment on broad adjustment movements shows that the perturbation increasing the positions of the endpoints is reusable even though the perturbation decreasing the positions at the endpoints is not reusable.

C. *Discussion on the Different Strings*

The following strings were examined.

SA) the string used the experiment in Section III
SB) a string (acrylic spindle cord) with a small diameter, made of the same material as SA
SC) a string (acrylic spindle cord) made of the same material as SA in which its threads are differently twisted
SD) a string made of different material

While strings SB and SC satisfy the "soft" assumption, string SD does not. That is, string SD does not satisfy the Eq. 1. The result of experimenting with string SB was successful. Sometimes the small diameter made it difficult to reliably grasp the string. The result of experimenting with string SC was almost successful. Because the softness of the string is different from that of string SA, the endpoint droops, which made it difficult to penetrate the loop. If the length between the endpoint and the grasp point on the string is shorter, it does not droop as much; therefore, this process can be performed successfully. However, re-grasping the endpoint on the table in a subsequent process becomes relatively difficult. It is necessary to strengthen this aspect such that this task can be stably achieved. If the "soft" assumption holds, this method can be applied to different strings with little or no tuning to the grasping point.

The characteristics of problems with this method are described below. If a program for topological knot tying is already available, then the programming effort can be significantly reduced. However, the extent to which metrics can be incorporated is limited depending on the specifications of such programs. This paper discusses how to investigate the limits through sensitivity analysis of the movement perturbations.

For topological knot tying, the successful formation of knots is the only variance that can present problems. Additional efforts are required when metrics are considered because their variance must also be evaluated and kept within tolerance.

IV. Conclusion

This paper has described a method for tying a string while considering metrics by describing segments based on the crossing sections and designing movement perturbations. This was found to be difficult to achieve by merely extending string-tying methods that merely consider the topology, but extra-sensitive analysis led to the potential extendibility of the given topological program. Uncertainties with regard to segments between crossing sections were found to be associated with different parts of the string contacting. The presented method was demonstrated to find the applicable part of the movement perturbation and to make string-tying considering metrics possible if any such applicable part of the movement perturbations exist. A method for extending a string-tying program that only considers the topology to one that also considers metrics was described along with the potential for reuse and limitations.

In our experiments, the efficacy of broad adjustment movements was addressed. Both broad adjustment and local adjustment movements of a string will be dealt with in future research.

In some cases, twisting can play an important role in string tying, which may be relevant to future developments on this topic. Within the framework of this paper, this can be considered by allowing segments to have twisted shapes.

Appendix I
Summary and Loci of Tips of Arms of [14]

A new method for a knot-tying task with a dual-arm robot system was previously proposed [14]. The task is divided into a series of "steps" taking account of the timing of obtaining visual information. The start state of each step is observed and confirmed visually. Subsequently, an adequate operation from the start state to the end state (i.e., the start state of the next step) is conducted according to the visual information. Five different types of knot-tying tasks were realized with the robot system (Fig. 2). The operations and the related motions were designed by a human by means of trial and error. These tasks have steps that are in common with each other, and these steps were successfully reused. The experimental result showed that complicated knot-tying tasks could be realized as a sequence of these kinds of steps.

The loci of the tips of the arms are mostly determined in advance. The endpoint of a string is extracted from the view captured with the 3D vision system, which is slightly different from each point in Scenes 1, 2, and 3 (Fig. 8). The actual trajectories are different from the pre-determined trajectories in this sense. While the picking-up motion is slightly different, the placing motion is the same. The latter motion is perturbed by our method. Although the endpoints can be set rather freely in Scene 0, the configurations of the string in Scenes 1, 2 and 3 exhibit almost the same pattern because the string is straightened once and then reset by both arms after Scene 0.

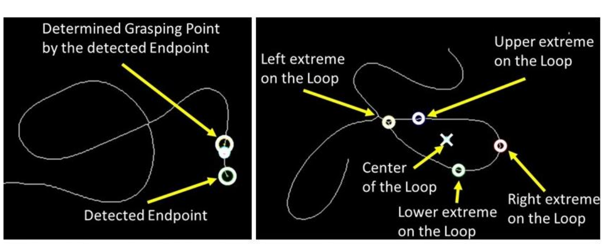
APPENDIX II
EXTRACTION OF NECESSARY INFORMATION WITH VISION SYSTEM [14]

In this task, color images were used to extract the states of a string and the information necessary for the operations. We assumed that the background color is black and that a string is of a single color (in this example, orange) because this combination makes the string easy to detect. Because sophistication of the string detection was not our main theme, a relatively simple image processing technique was applied. The basic procedure was as follows: (1) RGB–HSV conversion, (2)HSV image thresholding, (3) Shrinking and expansion processing of the image to remove noise, (4) Thinning, and (5)Removal of short lines. The OpenCV library was used to perform steps (1), (2), and (3). In addition, steps (4) and (5) enable us to acquire the thinned string image. Using the thinned string image, endpoint detection and loop detection are achieved to obtain the information necessary for the operations.

The string model has two visual features: endpoints and loops, if any. The two endpoints and the loop are recognized by a 3D vision system. The grasping point is determined by the length from the endpoint or is determined by choosing one of four points on the loop (upper, lower, right, and left). The endpoint was used to specify the grasping point as “grasp the

Endpoint detection: Fig. 11(a) shows an example of the results of endpoint detection. A search is made for an endpoint in a thinned string image (the circle neighboring the endpoint in this figure). From the endpoint, the thinned string is followed by the specified length (the solid circle point in the figure). Based on this, the grasp position (circle neighboring the solid circle point in this figure) and the direction of the string from the grasp position to the endpoint were extracted from the image.

Loop detection: Fig. 11(b) shows an example of the results of loop detection. The upper bound of the length of a short line to be removed should be specified, because a part of the line with an endpoint is also removed without it. In this figure, the thinned string is drawn where part of the line with the endpoint remains, in order to improve the clarity. Five feature points were detected: four extreme points (circles in the figure) in the x-direction (top and bottom) and the y-direction (left and right) on the loop and a middle point between the corresponding extreme points (X in the figure). The extracted information consists of the upper and lower extreme points on the loop, the left and right extreme points on the loop, and the center of the loop that is the midpoint between the endpoints in the x direction and the y direction.



a) Endpoint detection b) Loop detection

Fig. 11 Feature Detection

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