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String Tying Operation by Industrial Manipulator Based on Shape Abstracted Data

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***Abstract*— Recently, the demand to manipulate deformable objects such as a string and cloth by robots is growing. The reason is that it has the possibility of making our lives more convenient in many domains such as housework, manufacturing and medical field. However, manipulation of deformable objects is more difficult than that of rigid objects, because deformable objects have variety of shape and variety of appearance. Therefore, our research group has been focusing on the string shape operation by a robot. This paper describes planning method of string tying operation based on knot theory and algorithms to generate the motion of a manipulator. Face List is proposed as shape abstraction data of string projection. Face List is data in which a plurality of faces included in the string projection are listed in a list form. Finally, the result of string tying experiment is reported.**

***Index Terms*— Deformable Object, Industrial Manipulation, Face List**

I. INTRODUCTION

There are many deformable objects such as a string and cloth around our living space. Recently, the demand to manipulate deformable objects, especially deformable liner objects, by robots is growing. The reason is that it has the possibility of making our lives more convenient. There are also many application domains such as housework, manufacturing and medical field. When the housework robots work around our living space in the future, there will be many deformable objects. Actions to tie and untie a string are very common and important for housework robots. In factories, a lot of manipulators have been introduced to automate manufacturing processes. But many of processes which use deformable objects such as wiring process of flexible cables are not be automated. In recent years, various types of surgical robots have been developed. If they can conduct surgical task such as suturing, fatigue and human error of doctors can be reduced.

However, manipulation of deformable objects by robots is difficult and still unsolved problems. It is due to variation of shape and appearance of rope. When a robot manipulate a string, its control system must obtain shape and position information of the string at first. In addition, it is very important to recognize topological state of the string to realize tying and tying operations. Next, the robot grasps a part of the string and moves to appropriate point. In this regard, control system have to calculate the effects of some phenomena such as deformation, slack, torsion and self-collision.

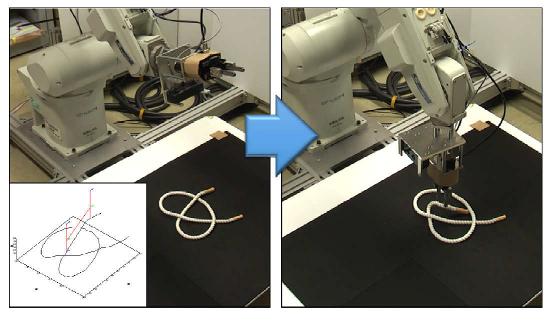

Fig. 1. String tying operation by a robot manipulator

This paper describes a planning method of string tying operation based on knot theory and algorithms to generate the motion of a manipulator. In this planning method, P-data, Reidemeister moves and Cross are introduced. The former is representation method of topological state of a string. The latter is basic shape operation of a string defined in knot theory originally. P-data is generated from point chain model, which is a data structure to describes 3D shape and position of a string proposed in our previous study [1]. However, we consider the planning of the tie knotting operation using P-data and conclude that the information is insufficient with only P-data. We propose Face List as shape abstraction data of string projection. Face List is data in which a plurality of faces included in the string projection are listed in a list form. The novel contribution of our method is selection of optimal shape operation based on cost function. Topological state transition caused by both of Reidemeister moves and Cross is represented as a tree diagram of P-data and Face List. Our cost function provides scores with each shape operation in the tree diagram. Then, the path which has the minimum total score is selected as optimal shape operation. The concept of proposed algorithms for robot motion generation is a deterministic approach to automatic motion generation for string tying operation. Therefore, proposed algorithms do not need human interventions and a lot of teacher data because they do not include teaching-playback and learning. Finally, the result of string tying experiment using a manipulator to evaluate proposed algorithm is reported.

II. RELATED WORKS

A. Applying Knot Theory to operation planning

Knowledge in Knot theory such as description of topological state of string and Reidemeister moves is introduced in almost research of deformable liner objects. Ladd et al. [2] investigated planning method for knot untangling using Knot theory. However, their method was only demonstrated in computer simulation. Takamatsu et al. [3] proposed a representation method for knot-tying tasks using P-data. They indicated that P-data is useful to represent topological state of a string and easy to handle by computers. Nevertheless, we cannot achieve the automation of knot-tying tasks with only methods proposed in their paper. Additionally, the mechanisms to generate robot motion are not described. On the other hands, we established a method to calculate state transition of P-data and implemented it to the program with graph search algorithm in this paper. Therefore, automatic string untying operations by a robot manipulator was achieved. Wakamatsu et al. [4] proposed a planning method based on topology transition of string and a principle to classify the action of manipulator depending on shape of part of rope. But the shape operations and its robot motion were manually selected in their experiments because the difficulty of shape operation in actual situations is not considered in proposed method. In our planning method, the optimal shape operation is automatically selected by scoring each operation based on cost function. Reidemeister moves and Cross, which are units of shape operation defined in Knot Theory, are divided into several groups, heuristic cost and robot motion are set up.

B. Robot motion generation

Robot motion generation in string shape operation is a challenging problem. It is due to diversity of shape and behavior of strings. Yamakawa et al. [5] investigated dynamic knotting of a rope using a high-speed manipulator. Their strategy is string shape control by high-speed performance of the robot, with that rope became straight form by centrifugal force. They realized making a simple knot in rope knotting experiments. However, the robot motion was not generated automatically in that article. Trinh Van Vinh et al. [6] proposed motion generation method by analysing human-performed knotting actions. They also conducted string knotting experiment. It can be said that this method depends on human interaction such as teaching-playback. Lui et al. [7] investigated applying machine learning to robot motion generation of string untangling. They defined an evaluation function of robot motion and introduced learning method proposed by Jiang et al. [8]. In addition, the result of robotic experiments using several types of string and knot is described. Learning can be an effective approach to string shape operation. Nevertheless, it is also a probabilistic process and needs a lot of teacher data. In our study, proposed algorithms to generate robot motion is deterministic and do not include human interventions such as teaching-playback and probabilistic process such as learning.

III. OVERVIEW OF STRING TYING OPERATION

In this research, for the purpose of realizing the tying knot operation by the robot, the process is divided into four major stages. The four stages are shape recognition, planning of shape manipulation, motion generation of a robot, and execution of shape manipulation. Then these processes are sequentially repeated until the string matches the target shape. In the shape recognition, the shape of the string is acquired using distance camera. The purpose of the planning phase of shape manipulation is to determine the optimal shape manipulation to apply to the string. We apply knowledge of knot theory and robot system calculate change of knot state applied to shape manipulation and derive a series of shape manipulation which changes string from current shape to target shape. Further, the optimal shape manipulation is determined by scoring the difficulty in executing the shape manipulation by the robot. At the next motion generation stage of the robot, an action of the robot for realizing the shape manipulation decided at the previous stage is generated. The hand trajectory, the grasping position of the rope, the releasing position of it and so on are determined based on the shape data of the string acquired at the shape recognition stage. In the final stage of shape operation execution, the generated motion of robot is executed and actual shape manipulation is performed.

IV. PRIMITIVE MOTION

A. Expression of strings by projection

Although the actual string exists in the three-dimensional space, it is projected an appropriate two-dimensional plane in order to obtain diagram of string as shown in Fig.2. In the string projection diagram the end of the string is called an endpoint, the intersection is the intersection or node, the line connecting the endpoint or intersection is called a segment. Here, as shown in Fig.2, one of the two endpoints is set as a initial endpoint and the other endpoint is terminal endpoint. Then, when tracing a string from the initial endpoint to the terminal endpoint, the i-th encountered segment is called the i-th segment.

B. Ridemaster movement I

Reidemaster movement I (RMI) in string tying operation is an operation of creating a simple loop, so the number of intersections increases by one. There are two possibilities that an operation to create a clockwise direction loop and other

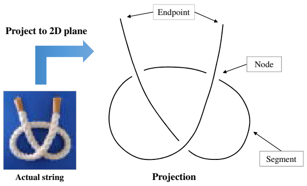

Fig. 2. A projection of string

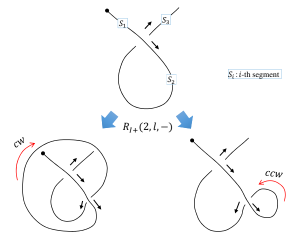

Fig. 3. Shape operation by RM_I in outer face

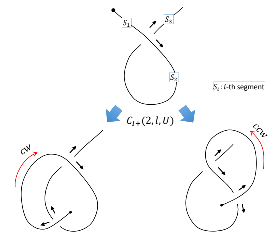

Fig. 4. Shape operation by Cross in outer face

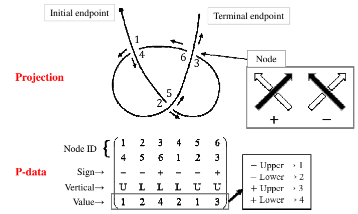

Fig. 5. A projection of string and its P-data

operation to create counter-clockwise direction loop, because there are two types of "+" and "-" at the intersection. Even for operations that create intersections of the same type, it can be divided into cases where a loop is created on the right side of the segment and cases where it is made on the left side. The number of the segment to be manipulated is n, the left-right direction of the segment making the loop is d (d = r: right side, d = l: left side), and the type of intersection to be made is s, RM_I is described as $R_{I+}(n, d, s)$. However, as shown in Fig.3, let us consider a case where RM_I is performed on a segment in contact with the outer face. In Fig.3, although the same R_{I+} (2, l, -) operation is performed, two different types of shapes are obtained, and the shape operation on the right side of Fig.3 is creating a simple loop, whereas on the left side is creating a structure surrounded by a loop made by RM_I. In detail observation, it can be seen that these two types of shapes can be distinguished depending on whether the segment making the loop is clockwise or counter-clockwise. Therefore, by introducing a new parameter t (t = cw: clockwise, t = ccw: counter-clockwise) representing whether the segment is clockwise or counter-clockwise, RM_I can be expressed as R_{I+} (n, d, s, t). Therefore, the shape manipulation on the left side in the Fig.3 is symbolised as R_{I+} (2, l, -, cw) and the shape manipulation on the right side is R_{I+} (2, l, -, ccw). RM_I can be classified into four types when not in contact with the outer face.

C. Cross

The cross in tying knot is an operation in which the endpoint crosses the segment. And there are two types of endpoints in the crossing segment, that are the initial endpoint and the terminal endpoint. A considered parameter of shape manipulation by cross is the number of the segment that the endpoint crosses. We have to consider whether the endpoint crosses a segment from the right side to left side or converse. Also, we have to consider whether endpoint goes above or below the segment. n means the ordinal number of segment which the endpoint crosses. The parameter d (d = r: right to left, d = l: left to right) represents the direction across which the endpoint traverses, up and down v (v = U: upper, v = L : Lower side). Then C_{I+} (n, d, v) is the crossing point of the initial endpoint and C_{T+} (n, d, v) is the crossing point of the terminal endpoint. In Fig.4, although the shape manipulation of the same C_I (2, 1, U) is performed, there are possibilities that two different shapes can be obtained. It can be seen that it can be distinguished by whether the segment orbits in the clockwise direction or the counter-clockwise direction on the outer periphery like the RM_I. Therefore, by introducing a new parameter t (t = cw: clockwise, t = ccw: counter-clockwise) indicating whether the segment moves clockwise or counter-clockwise, the crossing of the initial endpoint on the outer face is C_{I+} (n, d, v , T). The cross of the terminal endpoint is described as C_{T+} (n, d, v, t). Therefore, the shape operation on the left side in the figure is C_{I+} (2, 1, U, cw) and the shape operation on the right side is C_{I+} (2, 1, U, ccw). Cross on the inner face can be classified into four types.

V. Shape Abstraction Data

In the previous study, we proposed a planning method of shape manipulation using abstracted data describing the phase of the string called P-data, and performed stringing operation with a manipulator. This method is originally proposed by Takamatsu[3][9]. In this research, we propose a Face List which is new shape abstraction data in order to realize the tying knot operation. Whereas P-data consists of intersection information of projected string diagram, the Face List is considers the relation of face and surrounded segment. Face List has ability to complement the information of both segments and face, that are not included in P-data.

A. P-data

As described above, P-data is abstraction data describing the phase state (topology) of a string represented by a projection map in the form of a matrix. Figure 5 shows the string projection and its P-data. The first and second rows of P-data are numbers of intersection points. The third

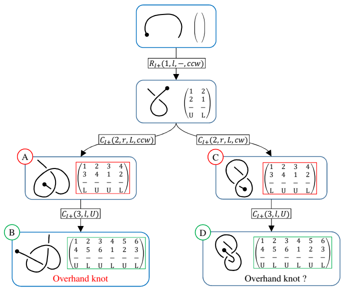

Fig. 6. Representation of string shape transition using P-data

row is the type of intersection called Sign (Sign). As shown in Fig.5, the direction in which the underlying segment crosses the segment passing over is represented by "+". The contraverse is represented by "-". The character on the fourth row represents the vertical (Vertical) of the string, and takes the value of either U (Upper) or L (Lower). In the fifth row, a value (Value) is determined by the sequence of the sign and the upper and lower (1: - / U, 2: - / L, 3: + / U, 4: + / L). When the number of intersection points is 0, P-data of the string becomes an empty matrix.

B. Problems of P-data in string tying operation

We consider the planning of the tie knotting operation using P-data and conclude that the information is insufficient only with P-data. For example, as shown in Fig. 6, there is a case of generating a overhand knot from a released string. Applying C_{I+} (2, 1, L, ccw) to R_{I+} (1, l, -, ccw) to generate knot "A" is the correct route, but C_{I+}(2, 1, L, cw) is applied, the knot "C" is generated which have same P-data with "A". Furthermore, knots "B" and "D" have the same P-data. The fact that we cannot distinguish knot "A" and knot "C" with only P-data is confirmed though above thought experiment. Also, "B" and "D" cannot be distinguished. This means that a robot cannot generate correct knotting plan with only P-data. The shape abstraction data proposed in this research can distinguish the difference between knots "A" and "C" or "B" and "D" by incorporating information on a face and surrounded segments and when Face List and P-data are used as a set, a robot can generate correct motion plan of shape operation.

C. Face List

In this research, we propose Face List as shape abstraction data of string projection. A face is a region surrounded by a closed curve with several segments as shown in Fig.7, and the Face List is data in which a plurality of faces included in the string projection are listed in a list form. P-data consists of information of intersections, on the other hands, the Face List consists of information of segments.

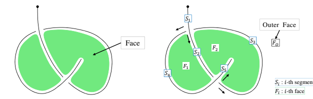

Fig. 7. Faces in a projection of string

D. Definition of face and expression of Face List

Here, the definitions and descriptions of faces is explained. By setting the initial endpoint and the terminal endpoint in the string projection diagram, directionality occurs in the segment. Here the direction from initial endpoint to terminal endpoint is defined as forward direction, the converse is define as the reverse direction. The face is described by both of the number and direction of the segment. And the situation that the face F_1 is surrounded by a counter-clockwise closed curve formed by S_2 in the reverse direction and S_4 in the forward direction shown in Fig.7 is described as F_1 (2^b, 4^f). The direction segment number sequence starts from the smallest number, and the closed curves are listed in the order of constituting it in the counter-clockwise direction. F_2 is surrounded by a counter-clockwise closed curve consisting of S_2 in the forward direction and S_3 in the forward direction and further includes the endpoint in the face. Because the segment S_5 owning the endpoint is located between S_2 and S_3, it is described as F_2 (2^f, 5, 3^f). Although F_1 and F_2 are internal regions bounded by closed curves, the unbounded face surrounding the periphery of the projection diagram is called the outer face. Therefore, F_1 and F_2 are also called inner faces. The outer face F_O shown in Fig.7 is bounded to the inner face by a clockwise closed curve composed of S_4 in the reverse direction and S_4 in the reverse direction, and includes the initial endpoint inside. Because the segment S_1 owning the initial endpoint is located between S_3 and S_4, it is described as F_O (1, 3^b, 4^b).

The number in the inner side is sorted in ascending order with respect to the segment number. The outer face is described in the end of the list, and in the case of the string projection shown in Fig.7, the outer face F_O is expressed as the third face F_3.

E. Advantages of the Face List

Figure 8 shows shape operation plan from untied string to locking knot. Also P-data and Face List are described for each shape of string on the way of tying motion plan. When only P-data is used, knots "A" with "C" and "B" with "D" cannot be distinguished because P-data of them are the same, but by using Face Lists it is possible to distinguish them. This means that the robot can distinguish the difference between knots "A" and "C" and correctly control the shape operation until knot "B" is generated.

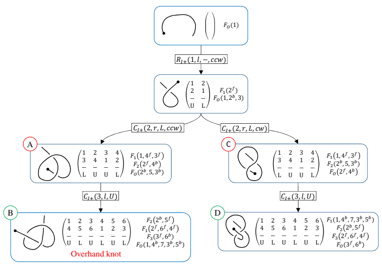

Fig. 8. Representation of string shape transition using P-data and Face List

VI. Determination of Optimal Shape Manipulation

By using the above description method and P-data by the primitive motion and deformation rule of the Face List, it is possible to derive a sequence of primitive motion that changes the current string shape to the target shape. In theory of mathematics, it is possible to generate a target shape by applying any of these sequences. However, in an actual environment using a manipulator, the availability of manipulation depends on the type of primitive motion performed, the shape of the string, physical characteristics, and so on. The probability of success is considered to fluctuate. Then, difficulty of the shape operation is defined as cost. In addition, cost calculation is utilized the tree search algorithm. Then the sequence of shape operations with the smallest total cost is selected as the optimal operation, in order to increase the possibility of successful shape manipulation by the manipulator.

Table I shows the cost of primitive motion of shape operation. First of all, Reidemeister movement I is explained. RM_{I+} (in) is an operation to create a simple loop, while RM_{I+} (out) is an operation to create an intersection encompassing the entire string by the loop created when creating a loop on the outer face, R_{I+} $(n, r, *, ccw)$ and R_{I+} $(n, l, *, cw)$ are applicable. The success rate is considered high because RM_{I+} (in) has less interfere with segments and robot hands, so we set the lowest cost. In the operation of RM_{I+} (out), it is necessary to arrange the loop created so as to surround the entire string, and it is considered that the success rate of the operation is extremely low because it accompanies a large deformation of the string. Therefore, the cost is set highest.

Next we describe the cost on cross. CR_+ (U, in) and CR_+ (L, in) means cross operation where an endpoint which belongs to inner face. On the other hands, CR_+ (U, out) and CR_+ (L, out) means cross operation where an endpoint which belongs to outer face. Here, U and L in argument means upper side and lower side on intersection. CR_+ (U, in) means the operation to move the endpoint in inner face. The operation has less interference of strings and between hand and string. Therefore it is expected that success rate is high, and we set cost of CR_+(U, in) low. CR_+ (L, in) means the operation to move the endpoint in inner face. The operation has interference of strings when the endpoint crosses below the segment. Therefore it is expected that success rate is lower than CR_+(U, in), and we set cost of CR_+(L, in) higher than CR_+(U, in). CR_+ (U, out) means the operation to move the endpoint in outer face. The operation has less interference of strings and between hand and string. However, it accompanies a large deformation of string. Therefore, it is expected that success rate is lower than CR_+(U, in), and we set cost of CR_+(U, out) higher than CR_+(U, in). CR_+ (L, out) means the operation to move the endpoint in outer face. The operation has interference of strings when the endpoint crosses below the segment. Also it accompanies a large deformation of string. Therefore it is expected that success rate is low, and we set cost of CR_+(L, out) high.

The optimal sequence of primitive motion is selected according to a total cost above mentioned. The first primitive motion is decided as the optimal shape operation among the optimal sequence of primitive motion. Then the operation by the manipulator is executed. As an example, Fig.9 shows a state transition of a knot that generates an overhand knot in a tree diagram. In this case, the sequence of primitive motions of R_{I+} $(1, l, -, ccw)$ $\rightarrow$ C_{T+} $(2, r, U, ccw)$ $\rightarrow$ C_{T+} $(3, l, L)$ indicates the lowest total cost, which equals 17. Then, the first shape operation R_{I+} $(1, l, -, ccw)$ is selected as the optimal shape operation.

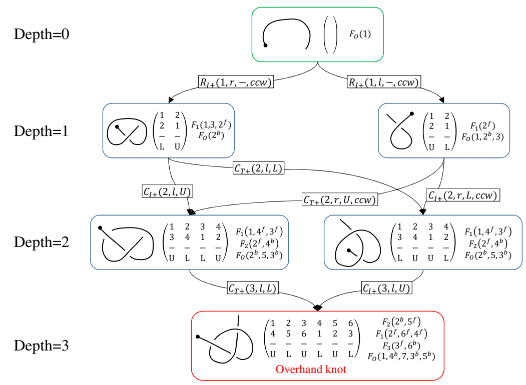

Fig. 9. A tree diagram which represents knot state transition

TABLE I

THE COST OF PRIMITIVE MOTION IN STRING TYING OPERATIONS

Primitive Motion	Cost
RM_{I+}(in)	1
RM_{I+}(out)	25
CR_+(U,in)	6
CR_+(L,in)	8
CR_+(U,out)	8
CR_+(L,out)	15

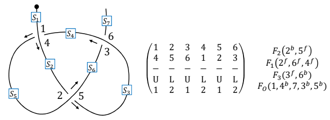

Fig. 10. The target shape (Overhand knot) of string tying experiments

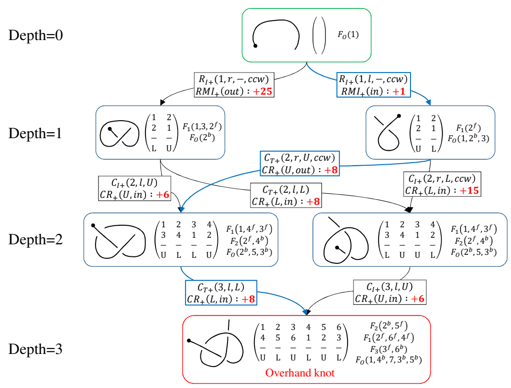

Fig. 11. Tree diagram which represents knot state transition to overhand knot with costs

VII. EXPERIMENT

In this experiment, the overhand knot shown in Fig.10 is selected as the target shape. The P-data and Face List of the overhand knot are as shown in the Fig.10. The industrial manipulator RV6SL made by Mitsubishi Electric Corporation is used for experiment, and the gripper and the distance camera Creative Senz 3D are attached to the manipulator's hand. The operation is conducted three times, and each time the operation is completed, the shape is recognized using a distance camera. The shape recognition algorithm is detailed in [1].

A. Result

It is an experiment to generate an overhand knot from a string in untying state. The actual string shape change, the point chain model, and the generated robot motion in the successful example of this experiment are shown in Fig.12. In Fig.12, the point at the tip of the point chain model is the initial endpoint, the arrow of the dotted line shows the hand trajectory, and the horizontal arrow shows the direction of the hand. The optimal sequence of shape manipulations is as shown in Fig.11. In the first step, operation of RM_{I+} (in) was conducted and a loop was formed. After that, the operation of CR_{+} (U, out) was conducted in the second step. In third step, the operation of CR_{+} (L,in) was conducted. Finally, three shape operations were performed.

This experimental result is based on automatic calculation by a program that implements the proposed method. And there is no human interaction during the experiment. Therefore it is confirmed that proposed Face List is useful to generated motion plan to tie a string.

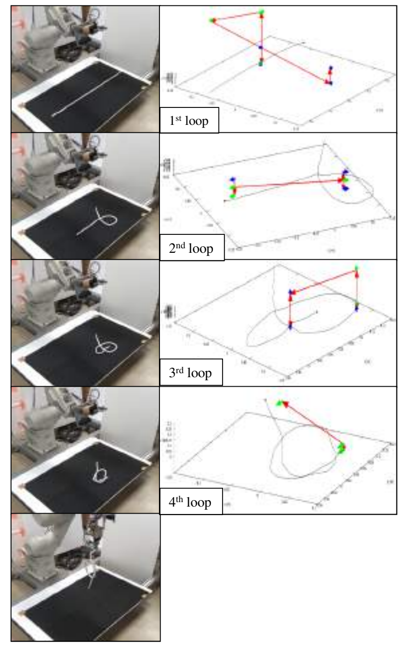

Fig. 12. The experiment result

VIII. CONCLUSION

In this paper, we propose an operation planning method using P-data and Face Lists in string tying operation. In addition, the effectiveness was confirmed by string tying experiment using industrial manipulator.

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