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Knotting a Flexible Rope using a High-speed Multifingered Hand System based on Synthesis of Knotting Manipulation Skills

Yuji Yamakawa ¹, Akio Namiki ²,

Masatoshi Ishikawa ¹ and Makoto Shimojo ³

¹ Graduate School of Information Science and Technology, Univ. of Tokyo
Japan

² Graduate School of Engineering, Chiba University
Japan

³ Graduate School of Electro-Communications, Univ. of Electro-Communications
Japan

1. Introduction

Until now, the dexterous manipulation of a rigid body has been achieved. In our laboratory, the dynamic manipulations such as batting (Senoo et al., 2004), dribbling (Shiokata et al., 2005), regrasping (Furukawa et al., 2006), pen spinning (Ishihara et al., 2006), and throwing (Senoo et al., 2008) (<http://www.k2.t.u-tokyo.ac.jp/fusion/>) have been performed by using the high-speed robot system and the high-speed sensory feedback. In the future, the high-speed and dexterous manipulation of a flexible body should be carried out in order to improve the manipulation ability. Therefore, we aim at the high-speed and dexterous manipulation of a flexible body.

Manipulation of flexible linear objects is a significantly important problem in the robotics research, and the number of studies looking at this problem has been increasing recently.

We have developed strategies for the skills required by a multifingered hand in a knotting task (Yamakawa et al., 2007, Yamakawa et al., 2008). To improve the robustness of these strategies, we proposed high-speed visual and tactile sensory feedback control. We demonstrated successful completion of a so-called overhand knot by sequential application of the individual skills involved.

However, it has not been explained that many knots can be produced using only these proposed skills. Therefore, in this research we examine this point based on an original knot theory. The goal of this research is to analyze the knotting process and to define the relationship between the knotting process and the individual skills that can be performed by a robot hand (Yamakawa et al., 2008).

Finally, two kinds of knot (overhand knot and half hitch) were achieved using a high-speed multifingered hand with high-speed tactile sensors and a high-speed vision.

In this paper, “task” is defined as one manipulation carried out by the robot, and “skill” is defined as a minimum required element to achieve the task and a meaningful element that

Fig. 1. Purpose of This Research

changes the rope state. Therefore, one “task” is achieved by the combination of a certain number of “skills”. In order to further develop the manipulation theory, it is extremely important not only to achieve many tasks, but also to integrate the skills that are needed for task realization (Fig. 1(a)).

2. Related Work

Some researchers have focused on manipulation of flexible linear objects. For instance, Inoue & Inaba proposed a method of knotting a rope using visual feedback (Inoue & Inaba, 1984). Matsuno et al. used an imaging system to recognize the shape of a rope and demonstrated knotting using dual manipulators (Matsuno et al., 2001). Saha & Isto suggested a topological motion planner for manipulating flexible linear objects (Saha & Isto, 2006). Morita et al. suggested a knot planning technique by using a system called Knot Planning from

Observation (KPO) (Morita et al., 2003). Wakamatsu et al. formulated a description of knots and a process of knot manipulation (Wakamatsu et al., 2006).

Fig. 2. Human Knotting

In this research, we focus on the relationship between the structure of a knot and the individual robot hand skills required to implement the knot, and we propose a new method of producing a knot with a robot hand. In addition, we also propose a new description that takes the grasp configuration of the intersections of a knot into account.

Knotting manipulation of a flexible rope has been demonstrated in numerous studies. These studies generally considered the geometry of the knot and proposed a knotting process; however, they did not match the actual type of manipulation performed by the robot hand. For example, even if the geometric relation of a rope is the same, the knotting process substantially changes depending on the grasp configuration (for example, loop production). Thus, to consider the actual manipulation by a robot hand, it is necessary to determine the relationship between the knotting process and the individual manipulation skills of the robot hand. In addition, a description of the knotting process that is appropriate to the robot hand should be considered.

The aim of this research is to identify the knot manipulation skills required by a general robot arm and robot hand to achieve a knotting process, as shown in Fig. 1(b).

3. Extraction of Knotting Skills

It is extremely important to identify the skills that are appropriate to the knotting task. There are two main reasons why the manipulation of a flexible linear object is difficult:

- 1) Rope deformation during manipulation, and
- 2) Difficulty of predicting the rope deformation.

To overcome these difficulties, the following strategies are considered:

- 1) Using sensory feedback control by real-time measurement of the rope deformation,

- 2) Identifying a manipulation skill that cancels rope deformation, and
- 3) Identifying a manipulation skill that exploits the rope deformation.

Fig. 3. Description of Intersection (Wakamatsu et al., 2006)

Based on these strategies, in order to identify manipulation skills required for knotting, we analyzed a one-handed knotting process performed by a human hand, as shown in Fig. 2. Fig. 2(a) is the initial state, Fig. 2(b) shows loop production using rope deformation by arm motion, Fig. 2(c) shows rope permutation by finger motion, and Fig. 2(d) shows rope pulling by arm motion. As a result, we identified three skills required to achieve one-handed knotting: loop production, rope permutation, and rope pulling.

Loop production is categorized as a manipulation skill that utilizes the rope deformation. Rope permutation is categorized as a manipulation skill that cancels rope deformation. Rope pulling is a motion required to complete the knot.

In addition, in order to allow handling of the ends of the rope, one more manipulation skill called rope moving is added.

In summary, the essential manipulation skills for knotting are:

- 1) Loop production,
- 2) Rope permutation,
- 3) Rope pulling, and
- 4) Rope moving.

4. Description of Intersection and Hand Skill

First, we define the description of a rope intersection that constitutes the knot, by referring to the method proposed in the previous work (Wakamatsu et al., 2006).

The beginning of a rope is represented by E_l (or l_1 or r_1) as the initial location. In the same way, the end of the rope is represented by E_r (or l_2 or r_2) as the final location. Descriptions of the intersections $C_i^{\{+, -\}}$ ($i = 1, 2, 3 \dots$) are assigned for all intersections from E_l to E_r , where i is an intersection number. The sign "+, -" shows the intersection sign. The sign "+" means clockwise, and the sign "-" means counterclockwise, as shown in Fig. 3. As a result, the description of the intersection is defined as shown in Fig. 3.

Moreover, we introduce a new description here. First, the two directions of the rope at "outlets" of the intersection are summed. Second, the line that connects the two fingers grasping the intersection is considered. Finally, the relationship between the summed rope direction and this connecting line is examined. If the relationship is parallel, the description of the intersection shown in Fig. 4(a) is defined. If the relationship is orthogonal, the

description of the intersection shown in Fig. 4(b) is defined. This description method is used in loop production, in particular.

Fig. 4. Grasp Configurations

Fig. 5. Loop Production

Next, the characteristics of the identified hand skills are clarified based on the intersection description.

In this paper, a skill is defined as a minimum required element to achieve a task. In addition, the objective of this study is to clarify the relationship between the knot production process and manipulation skills. This relationship can be obtained from a description of the knot and analysis of the knot. Thus, recognition of the rope by a visual sensor is not taken into account in this paper.

4.1 Loop Production

Fig. 5 shows the loop production. Loop production is an operation that makes one intersection. Thus, the description of the intersection is given by the followings.

$$E_l - E_r \rightarrow E_l - \overline{C_1^{+, -}} - \overline{C_1^{+, -}} - E_r \quad \text{Fig. 5(a)}$$

$$E_l - E_r \rightarrow E_l - \hat{C}_1^{+, -} - \hat{C}_1^{+, -} - E_r \quad \text{Fig. 5(b)}$$

This skill is equivalent to Reidemeister move I in knot theory. The intersection sign depends on the direction of the loop.

Fig. 6. Rope Permutation

Loop production strategy

In this skill, a loop that serves as the starting point of the knot is produced on the rope. First, the rope is grasped by two fingers. A loop is produced by the two dimensional translational motion of the hand. There are two different types of loop production depending on the grasp configuration of the two fingers, as shown in Fig. 5. This difference is important for performing the actual knotting process by robot fingers. To achieve robust loop production, the hand motion should be controlled by real-time visual feedback (Yamakawa et al., 2008).

4.2 Rope Permutation

Fig. 6 shows the rope permutation. Rope permutation is divided into two types, depending on the grasp configuration. In the case shown in Fig. 6(a), the description of the intersection is the following:

$$E_l - \overline{C_1^{+, -}} - \overline{C_1^{+, -}} - E_r \rightarrow E_l - \overline{C_1^{+, -}} - C_2^{+, -} - C_2^{+, -} - \overline{C_1^{+, -}} - E_r$$

In the case shown in Fig. 6(b), the description of the intersection is the following:

Fig. 7. Strategy of Rope Permutation

$$E_l - \hat{C}_1^{\{+, -\}} - \hat{C}_1^{\{+, -\}} - E_r \rightarrow$$

$$E_l - \hat{C}_1^{\{+, -\}} - C_2^{\{+, -\}} - C_3^{\{-, +\}} - \hat{C}_1^{\{+, -\}} - C_2^{\{+, -\}} - C_3^{\{-, +\}} - E_r$$

The difference between the two types of rope permutation depends on the grasp configuration used in the loop production.

Rope permutation strategy

The strategy of rope permutation is shown in Fig. 7. Both fingers are moved while remaining parallel. At some point, two sections of the rope engage each other by virtue of friction (Fig. 7(b)).

By continuing to move the two fingers in parallel, the two sections of the rope are permuted (exchange places) (Fig. 7(c)). At the moment of permutation, the grasp force is increased. In order to achieve smooth permutation, it is necessary to increase the distance between both fingers at this moment. Therefore, grasp force control based on tactile feedback is implemented (Yamakawa et al., 2007).

4.3 Rope Pulling

Rope pulling is an operation that basically removes the intersection, as shown in Fig. 8. This skill is effective when used together with rope permutation. Two operations can be realized

Fig. 8. Rope Pulling

Fig. 9. Rope Permutation & Rope Pulling (operation type I)

Fig. 10. Rope Permutation & Rope Pulling (operation type II)

by utilizing these two skills: One is the ability to create one intersection. Another is the ability to change the sign of any intersection. When one intersection is produced (Fig. 9), the description of the intersection is given by the following.

$$E_l - E_r \rightarrow E_l - C_1^{\{+, -\}} - E_r$$

When the sign of an intersection is changed (Fig. 10), the description of the intersection is given by the following.

$$E_l - C_1^{\{+, -\}} - \dots - C_i^{\{+, -\}} - \dots - C_1^{\{+, -\}} - E_r \rightarrow$$
$$E_l - C_1^{\{+, -\}} - \dots - C_i^{\{-, +\}} - \dots - C_1^{\{+, -\}} - E_r \rightarrow$$

Rope pulling strategy

In general, rope pulling can be achieved by the translational motion of the robot hand.

4.4 Rope Moving

Rope moving is defined as the three-dimensional free motion of the end of the rope without other parts of the rope acting as obstacles. Assuming that the rope is located in a plane, this skill is the free motion in the space above (or below) the plane. Rope moving is used to cross the two sections of the rope or to set one section close to another. When the two sections are

Fig. 11. Rope Moving

intersected as shown in Fig. 11(a), one intersection is made. The description of the intersection can be written as

$$E_l - E_r \rightarrow E_l - C_1^{\{+, -\}} - E_r.$$

When one section of the grasped rope approaches another, as shown in Fig. 11(b), the intersection is not created.

Rope moving strategy

Rope moving can be carried out by the three-dimensional motion of the robot hand.

5. Analysis of Knot and Skill Synthesis

In this section, we analyze the feasibility of some knots based on synthesis of the individual skills described above. Then, a knot production process can be obtained by using the analysis method.

Wakamatsu et al. have proposed a process of knot manipulation based on four skills that consist of Reidemeister moves and rope crossing (Wakamatsu et al., 2006). Although they described a systematic knot production process, the relationship between the knot production process and the required knot manipulation skills was not discussed.

In order to achieve actual knotting, it is necessary to consider not only the knot production process, but also the relationship between the production process and individual hand skills. For this reason, we propose the following analysis method.

Analysis Method

- 1) Represent a knot based on the description of the intersections that constitute the knot.
- 2) Unravel one intersection of the knot, starting from the intersection nearest the end of the rope.
- 3) Iterate step 2) until the intersections disappear. As a result, a sequence of operations to remove the intersections is obtained.

- 4) Apply appropriate skills to the sequence, while following the sequence obtained in step 3) in reverse.

By this analysis method, the location and sign of each intersection is identified. As a result, it can be determined how to generate the intersections. This method can be applied not only to a knot generated by one rope, but also to a knot generated by one rope and one object and a knot generated by two ropes. Although the knot production process obtained by the

Fig. 12. Analysis of Overhand Knot

Fig. 13. Production Process of Overhand Knot

proposed analysis method may not be optimal, this method can always provide one solution of the knot production process.

5.1 Knot Generated by One Rope

Here, we consider the description and production method of a knot generated by one rope. The start of the rope is located at the beginning of the rope (represented by E_l). The end of the rope is represented by E_r . As an example, here we analyze an “overhand knot”.

Overhand knot (Fig. 12(a))

An overhand knot is the simplest knot that is created on a rope. This knot prevents the rope unraveling.

Analysis of overhand knot

First, the description of the intersection in the overhand knot is

$$E_l - C_1^- - C_2^- - C_3^- - C_1^- - C_2^- - C_3^- - E_r . \text{ (Fig. 12(a)).}$$

Next, removing one intersection (C_3^-), starting from the intersection near the end (E_r) of the rope, gives the following description of the intersections of the overhand knot:

Fig. 14. Production Process of Half Hitch

$$E_l - C_1^- - C_2^- - C_1^- - C_2^- - E_r \text{ (Fig. 12(b))}$$

Iterating this operation until the intersections disappear yields the following description of the intersection

$$E_l - C_1^- - C_1^- - E_r \text{ (Fig. 12(c))}$$

$$E_l - E_r \text{ (Fig. 12(d)).}$$

The production process of the overhand knot can be obtained by following this process in reverse while considering the description of the intersections.

Production process of overhand knot

First, loop production is performed, and the intersection $\hat{C}_1^-$ is created (Fig. 13(a)). Second, the intersection C_2^- is produced. However, it is not effective to produce only the intersection C_2^- . By checking the final type of knot, it is found that two intersections should be made after the intersection $\hat{C}_1^-$. In addition, the final intersection C_3^- should pass under the rope. For these reasons, the state shown in Fig. 13(b) can be produced only by performing rope permutation (Fig. 6(b)). Finally, using rope permutation and rope pulling (Fig. 10), the overhand knot is achieved, as shown in Fig. 13(c). The description of the intersections for the overhand knot production process can be represented by the following:

$$E_l - E_r \text{ (Fig. 13(a))}$$

$$E_l - \hat{C}_1^- - \hat{C}_1^- - E_r \text{ (Fig. 13(b))}$$

$$E_l - \hat{C}_1^- - C_2^- - C_3^+ - \hat{C}_1^- - C_2^- - C_3^+ - E_r \text{ (Fig. 13(c))}$$

$$E_l - \hat{C}_1^- - C_2^- - C_3^- - \hat{C}_1^- - C_2^- - C_3^- - E_r \text{ (Fig. 13(d))}$$

The eight knot and the stevedore's knot can be produced based on skill synthesis in the same way.

5.2 Knot Generated by One Rope and One Object

In this section, we consider the knotting process of a knot generated by one rope and one object. As an example, we analyze a "half hitch".

Half hitch (Fig. 14)

The half hitch is one of the knots that make a connection between a rope and an object. Although it is an easy task to make this knot, the strength of the knot is very low. However, the strength can be increased by combining the half hitch with other knots.

Production process of half hitch

Here, we omit the intersection description of the half hitch. The left end and the right end of the rope are represented by l_1 and l_2 , and the left end and the right end of the object are represented by r_1 and r_2 . The description of intersections on the rope and the object is performed in the order of initial location.

First, the intersection C_1^+ is created by rope permutation (Fig. 14(b), (c)). Second, the rope is wrapped around the stick by rope moving to produce the intersection C_2^+ (Fig. 14(d)). Next, the intersection $\hat{C}_1^-$ is made by loop production (Fig. 14(e)). Finally, the half hitch is finished by performing rope permutation twice and rope pulling once (Fig. 14(f), (g)).

A knot generated by two ropes can be considered in the same way.

5.3 Knot Generated by Two Ropes

In this section, the production process of a knot generated by two ropes is explained. As an example, we analyze the “square knot” (Fig. 15). The description of the intersection is the same as that for the knot generated by one rope and one object.

Fig. 15. Production Process of Square Knot

Square knot (Fig. 15)

Square knot is one of representative knots generated by two ropes. This knot is used when two ropes that have same diameter are connected. To make this knot is very easy, and the strength of this knot is very high.

Production process of square knot

First, the two ropes are set as shown in Fig. 15(a). Second, the intersections (C_1^- , C_2^- and C_3^-) are produced by three rope permutations and rope pulling, as shown in Fig. 15(b)-(e). Third, the two ropes are set as shown in Fig. 15(f) by rope moving. Lastly, the intersections (C_4^+ , C_5^+ and C_6^+) are produced by three rope permutations and rope pulling, as shown in Fig. 15(g)-(j).

As a result, the production process of a knot can be obtained by skill synthesis. Namely, it is considered that the extracted skills are reconfigurable ones.

6. Experiment

6.1 Experimental System

The experimental system is composed of a high-speed multifingered hand (Namiki et al., 2003), high-speed tactile sensors (Ishikawa & Shimojo, 1982), and a high-speed visual sensor (Nakabo et al., 2000).

The high-speed multifingered hand has three fingers and two wrist joints. Moreover, each finger is divided into a top link and a root link. A newly developed compact harmonic drive gear and a high-power miniature actuator are installed in each finger link. The design of this actuator is based on the new concept that the maximum power output should be increased beyond the rated power output. The joints of the hand can be closed at a speed of 180 deg./0.1 s.

The high-speed tactile sensor can measure the centre position of a two-dimensionally distributed load, and the total load can be measured within 1 ms. This sensor is installed to each top link in order to perform the grasp force control during the rope permutation (Yamakawa et al., 2007).

The high-speed vision can measure the centre position and the angle of the principal axis of inertia within 1 ms. This sensor is mounted on the 2-DOF (pan and tilt) active mechanism. This sensor is used for the wrist-joint control during loop production in order to achieve robust control against rope deformation.

The cycle time of sensor feedback and control processing is set at 1 ms. Thus, the robot can react quickly to target motion in unpredictable conditions.

In order to prevent the rope from slipping on the fingers of the robot hand, a fingerstall is attached to each top link. One end of the rope is grasped by the robot hand, and the other end is held in a pulley so as to allow free up and down motion.

6.2 Experimental Results

Fig. 17 and Fig. 19 show sequences of continuous photographs of the knotting tasks (overhand knot and half hitch). The knotting strategy used was the one proposed in the previous papers (Yamakawa et al., 2007, Yamakawa et al., 2008).

Overhand knot

The experimental system is shown in Fig. 16. Fig. 17(a)-(e) show loop production. In Fig. 17(f), the rope sections are pressed by the free finger to strengthen the contact state between the two sections. Fig. 17(g)-(i) show rope permutation. Fig. 17(j)-(l) show rope pulling.

Fig. 16. Overall of Experimental Condition (Overhand Knot)

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Fig. 17. Experimental Result of Overhand Knot

Fig. 18. Overall of Experimental Condition (Half Hitch)

Half hitch

The experimental system is shown in Fig. 18. In the initial state, the rope is wrapped around the object, as shown in Fig. 18. Fig. 19(a)-(c) show loop production. In Fig. 19(d), the rope sections are pressed by the free finger to strengthen the contact state between the two sections. Fig. 19(e)-(g) show rope permutation. Fig. 19(h) and (i) show rope pulling. Finally, Fig. 19(j)-(l) show additional rope pulling by a human hand to tighten up the knot.

These video sequences can be viewed on our web site (<http://www.k2.t.u-tokyo.ac.jp/fusion/SkillSynthesis/>).

7. Conclusion

The aim of this research is to obtain the production process of a knot and to clarify the relationship between the production process of the knot and the manipulation skills for knotting.

First, to identify the necessary skills for knotting, we analyzed a knotting action performed by a human subject. As a result, we identified four skills such as “loop production”, “rope permutation”, “rope pulling” and “rope moving”.

And then, in order to analyze a knot, we suggested a new description method of the intersection that constitutes the knot.

Next, we proposed a method to produce a knot. The proposed method is based on a description of the intersections, and it is described by the sequence of operations achieved using the four identified skills. We analyzed three types of knot: a knot generated by one rope, a knot generated by one rope and one object, and a knot generated by two ropes. These knots could be produced by the synthesis of the four skills. In addition, we also determined the relationship between the knot production process and the individual skills required by the robot hand in knot manipulation.

Finally, we demonstrated productions of an overhand knot and a half hitch by using a high-speed multifingered hand with high-speed visual and tactile sensory feedback. In the future, we will attempt to apply our approach to other types of knots.

Fig. 19. Experimental Result of Half Hitch

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Without a doubt, robotics has made an incredible progress over the last decades. The vision of developing, designing and creating technical systems that help humans to achieve hard and complex tasks, has intelligently led to an incredible variety of solutions. There are barely technical fields that could exhibit more interdisciplinary interconnections like robotics. This fact is generated by highly complex challenges imposed by robotic systems, especially the requirement on intelligent and autonomous operation. This book tries to give an insight into the evolutionary process that takes place in robotics. It provides articles covering a wide range of this exciting area. The progress of technical challenges and concepts may illuminate the relationship between developments that seem to be completely different at first sight. The robotics remains an exciting scientific and engineering field. The community looks optimistically ahead and also looks forward for the future challenges and new development.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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