Proceedings of the 2003 IEEE/RSJ
Intl. Conference on Intelligent Robots and Systems
Las Vegas, Nevada · October 2003

Knotting/Raveling Manipulation of Linear Objects

Hidefumi Wakamatsu, Akira Tsumaya, Keiichi Shirase, Eiji Arai
Dept. of Manufacturing Science, Graduate School of Eng., Osaka Univ.
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
{wakamatu, tsumaya, shirase, arai}@mapse.eng.osaka-u.ac.jp

Shinichi Hirai
Dept. of Robotics, Ritsumeikan Univ.
1-1-1 Noji Higashi, Kusatsu, Shiga 525-8577, Japan
hirai@se.ritsumei.ac.jp

Abstract — A planning method for linear object manipulation including knotting/raveling in the three-dimensional space is proposed. Firstly, topological states of a linear object are represented as finite permutations of crossing points including the crossing type of each crossing point. Secondly, transitions among the topological states are defined. They correspond to operations that change the number of crossing points or crossing point permutation. Then, we can generate possible sequences of crossing state transitions, that is, possible manipulation processes from an initial state to a given objective state. Thirdly, a method for determination of grasping points and their moving direction is proposed in order to realize derived manipulation processes. Furthermore, criteria for evaluation of manipulation processes are introduced in order to reduce the candidates of manipulation plans. Finally, it is demonstrated that our developed system based on the above method can generate manipulation plans for raveling from an overhand knot.

1. Introduction

The majority of manipulative tasks, including grasping and assembly, are performed through mechanical contact. As rigid object manipulation can be represented as a sequence of finite contact states, planning methods using contact state graphs have been studied[1][2]. However, systematic approach to the planning of deformable object manipulation has not been established yet. We have proposed a qualitative representation method of thin object manipulation considering the contact state of the object and applied it to manipulation planning[3].

Deformable linear objects such as tubes, cords, and wires are used widely ; data transmission, object transportation, fixing or packing of objects, and so on. Such manipulative tasks include knotting. Linear objects can also be knotted to make them compact for their storage or transportation. On the other hand, self-entwining of linear objects should be avoided during their manipulative processes. Therefore, it is important for linear object manipulation to analyze knotting or entwining. Hopcroft et al. have devised a grammar of knots to express various knotting manipulation[4]. Leaf has described deformed shape of threads in a fabric geometrically[5]. Phillips et al. have simulated knot tying of a thread using a particle-based model of the thread[6]. Morita et al. have been developing a system for knot planning from observation of human demonstrations[7].

When a linear object is either knotted or entwined, it contacts with itself at some regions. Conventional representation methods for rigid object manipulation do not deal with such self-contact of the object. Therefore, a modeling of manipulation processes of a linear object considering its self-contact is needed for analysis of its manipulative tasks and planning of its manipulation. In this paper, we propose a method for automatic planning and execution of linear object manipulation considering the self-contact of a linear object.

Firstly, a qualitative representation of the crossing state of a linear object in three-dimensional space is proposed. Secondly, transitions among those states are defined by introducing four kinds of basic operations. Then, a manipulation process of a linear object can be represented as a sequence of crossing state transitions. Thirdly, a procedure to determine grasping points and their moving direction for realization of manipulation processes is explained. Furthermore, criteria for evaluation of manipulation processes in the qualitative analytical phase are introduced. Finally, we demonstrate a raveling of overhand knot performed by a vision-guided manipulator system to show the usefulness of our approach.

2. Representation of Crossing States

In general, we can represent a manipulation process as finite contact states among objects and contact state transitions. In the manipulation of a linear object, the object may contact with itself. Thus, self-contact of a linear object should be considered because it occurs when the object is knotted or entwined. Moreover, an overhand knot, a granny knot, and a bow knot depend on the self-contact of a linear object. Therefore, we propose a method in order to represent self-contact of linear objects as finite states.

0-7803-7860-1/03/$17.00 © 2003 IEEE

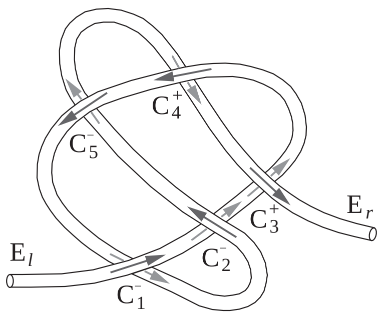


Fig. 1 Example of knotted linear object

First, let us project the 3D shape of a linear object on a 2D projection plane. The projected 2D curve may cross with itself. The self-contact of the object can be regarded as the self-crossing of the 2D curve on the projection plane. Note that the self-crossing of the 2D curve depends on the projection plane.

Next, let us number crossing points of the object along it. Fig.1 shows an example of a knotted linear object. It has 5 crossing points and their sequence is E$_l$-C$_1$-C$_2$-C$_3$-C$_4$-C$_5$-C$_1$-C$_2$-C$_5$-C$_4$-C$_3$-E$_r$, where E$_l$, E$_r$, and C$_1$ through C$_5$ represent the left endpoint, the right endpoint, and crossing points, respectively. Then, we can identify the state of a linear object considering the sequence of its crossing points. Furthermore, we can distinguish two types of crossing; one is the crossing that the front part overlaps from the left side of the rear part and the other is the opposite crossing. Let us define the former as the right hand helix crossing C$^+$ and the latter as the left hand helix crossing C$^-$. Then, crossing point sequence of the object shown in fig.1 yields E$_l$-C$_1^-$-C$_2^-$-C$_3^+$-C$_4^+$-C$_5^-$-C$_1^-$-C$_2^-$-C$_5^-$-C$_4^+$-C$_3^+$-E$_r$.

Thus, we can represent the state of linear objects, especially knotted ones as finite crossing states regardless of their length, girth, or other physical properties.

3. Definition of State Changing Operations

Next, let us consider transitions among crossing states presented in the previous section. In order to change the crossing state of a linear object, an operation must be performed on the object. Therefore, a state transition corresponds to an operation that changes the number of crossing points or permutates their sequence. In this paper, four basic operations are prepared as shown in fig.2. Operation type-I, type-II, and type-III are equivalent to Reidemeister move type-I, type-II and type-III in the knot theory[8], respectively. Type-IV operation is needed because a linear object has endpoints in general while knot theory does not focus on the endpoints of the object. By type-I, type-II, and type-IV operations, the number of crossing points is increased or decreased. Type-III operation does not change the number of crossing points but change their sequence. Furthermore, let us define operations to increase crossing points as crossing operations CO$_{\mathrm{I}}$, CO$_{\mathrm{II}}$, and CO$_{\mathrm{IV}}$, operations to decrease them as raveling operations RO$_{\mathrm{I}}$, RO$_{\mathrm{II}}$, and RO$_{\mathrm{IV}}$, and an operation keeping the number of them as an arranging operation AO$_{\mathrm{III}}$.

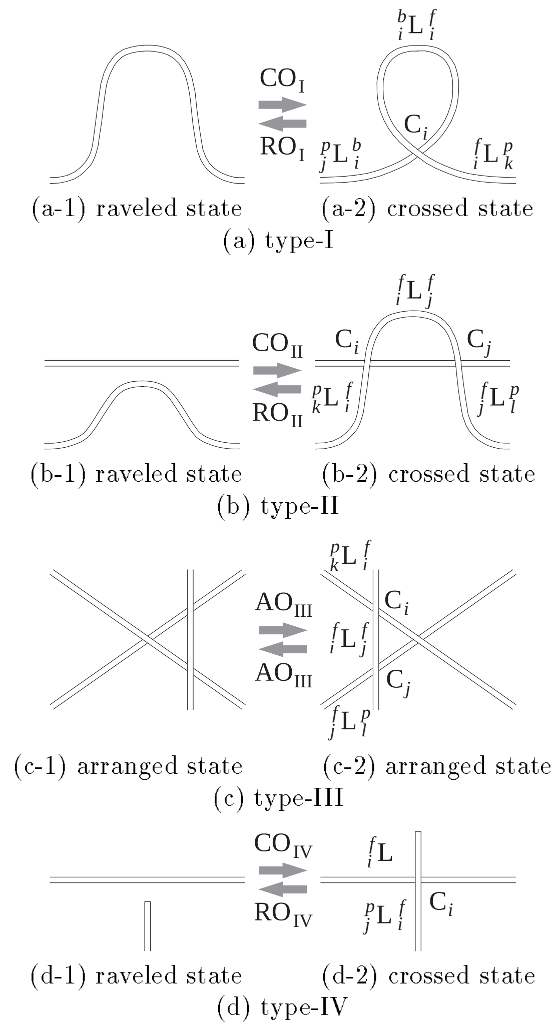
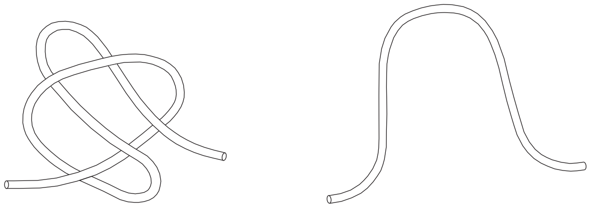


Fig. 2 Basic operations

The number of possible crossing operations with respect to one crossing state can be larger than that of possible raveling operations. Therefore, we define that a state transition is caused by a raveling operation alone. When the initial state in which an object has no crossing points and the objective state in which it is knotted are given, we search for possible sequences of raveling operations where the crossing state is changed from the objective one to the initial one at first. Next, by following found sequences backward, possible sequences of crossing state transitions, that is, qualitative manipulation processes can be derived.



(a) initial state (b) objective state

Fig. 3 Example of required manipulation

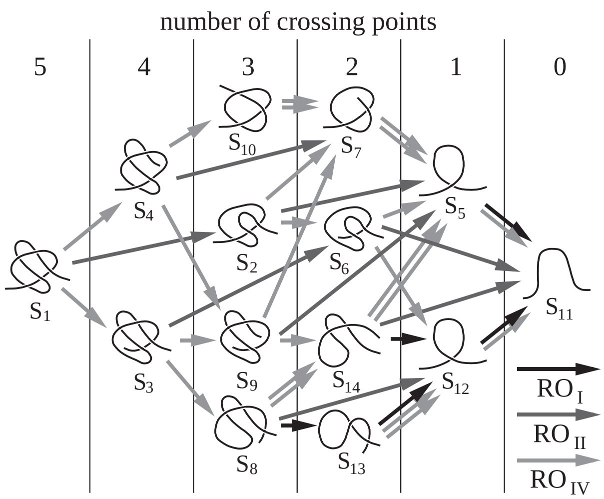


Fig. 4 Result of manipulation process planning

Fig.3 shows an example of a required manipulation. The initial state in fig.3(a) can be represented as E_l-C_1^--C_2^--C_3^+-C_4^+-C_5^--C_1^--C_2^--C_5^--C_4^+-C_3^+-E_r and the objective state in fig.3(b) can be represented as E_l-E_r. Assuming that only raveling operations can be used, that is, without RO_{III}, 14 crossing states and 32 state transitions are derived as shown in fig.4. Including operation RO_{III}, we can derive 21 crossing states and 69 state transitions.

Thus, we can represent a manipulation process of a linear object as a sequence of finite crossing states. Moreover, we can plan the process qualitatively once the initial state, the objective state, and several intermediate states are given.

4. Determination of Grasping Points and Their Moving Direction

In this section, we explain a procedure to determine grasping points and their moving direction in order to realize a derived sequence of state transitions. We assume that manipulators grasp not a crossing point but a segment between two neighboring crossing points. Let us describe a segment between C_i and C_j as ${}_i^p L_j^p$ where p indicates that the segment exists whether in front of $(p = f)$ or behind $(p = b)$ another segment at point C_i and C_j. Terminal segments that adjoin the left and the right endpoints are described as L_i^p and ${}_i^p L$, respectively. For example, a crossing region as shown in fig.2(a-2) consists of three segments; ${}_j^p L_i^b$, ${}_i^b L_i^f$, and ${}_i^f L_k^p$ where j and k mean the previous and the next crossing point number, respectively. Let ${}_j^p L_i^b$ and ${}_i^f L_k^p$ be end segments of this crossing region. Segment ${}_i^b L_i^f$ is deleted by raveling crossing point C_i. Therefore, let us call a segment such as ${}_i^b L_i^f$ a target segment. We assume that a target segment or both end segments in each crossing region should be grasped in order to realize each raveling operation. For example, in fig.2(a-2), segment ${}_i^b L_i^f$ or segments ${}_x^p L_i^b$ and ${}_i^f L_y^p$ should be grasped.

Furthermore, we define the approach direction of manipulators with respect to the projection plane; from the front side or the back side. Realizability of each operation depends on this direction. For example, in fig.2(d-2), RO_{IV} can not be realized when terminal segment ${}_i^f L$ is grasped from the back side. Then, 17 grasping patterns that can realize each basic operation are derived as shown in fig.5, where a circle with dot, a circle with cross, and a open circle represent a point to be grasped from the front side, the back side, and whichever side, respectively. Fig.5(g) and (h), fig.5(k), and fig.5(p) and (q) indicates the opposite of a crossed state shown in fig.2(b-2), fig.2(c-2), and fig.2(d-2), respectively.

Next, let us consider moving direction of a grasping point to realize each operation. We define four unit motions; translation parallel to the central axis of an object, translation perpendicular to the axis, rotation around the axis, and rotation around a line perpendicular to the axis. Then, by selecting feasible combinations of grasping points and unit motions, basic operations can be realized. In this paper, we classify the combinations into three groups. Group-A corresponds to translation/rotation of the whole front/back part as shown in fig.6(a). In this group, each part is regarded as a rigid body, and motions for raveling can be derived by considering qualitative geometry of a crossing region. Group-B indicates the motion of a target segment by grasping it directly as shown in fig.6(b). We can also select feasible unit motions with respect to each crossing region. Group-C means the motion of a target segment by grasping its adjoining segments. When the object is moved as shown in fig.6(c), grasped parts become straight somewhile. Therefore, these motions can realize raveling operations regardless of actual physical properties of the object. In fig.6(c-1), the object may be raveled out when both end segments are twisted in opposite directions each other. However, its realizability depends on object properties. Therefore, a quantitative analysis is needed for verifying feasibility of selected combinations. In this paper, we assume group-C consists of

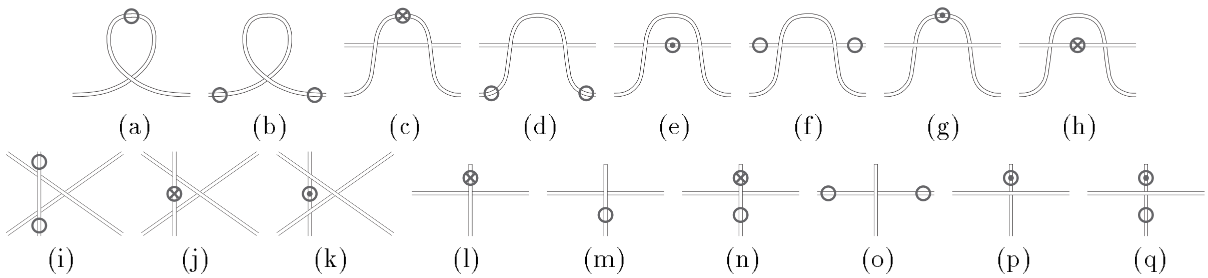


Fig. 5 Grasping patterns

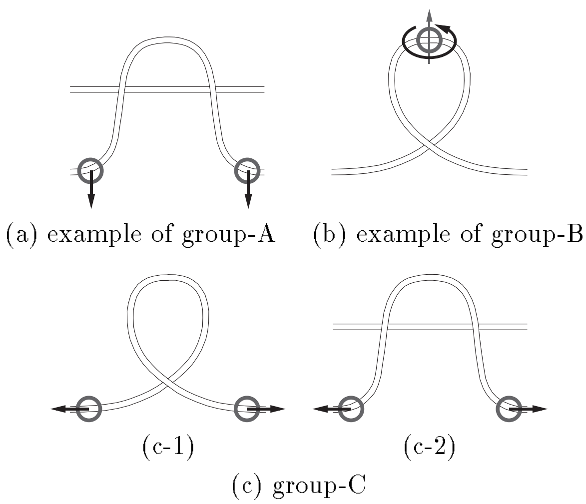


Fig. 6 Motion combinations

only two combinations as shown in fig.6(c).

Thus, we can derive finite sequences of crossing state transitions of a linear object and feasible combinations of grasping points and unit motions with respect to each sequence, that is, rough manipulation plans.

5. Evaluation of Manipulation Plans

In this section, we introduce criteria for evaluation of generated rough manipulation plans represented as sequences of crossing state transitions.

First, let N_m be the number of grasping points in one crossing state. We assume that the number of available manipulators is limited. Then, N_m must not exceed the number of manipulators in order to realize a transition sequence including the state. Next, let N_t be the number of state transitions through one sequence. In this paper, we prefer a sequence including fewer intermediate states, that is, less state transitions. Finally, let N_c be the changing times of grasping points through one sequence. If a grasping point is changed during manipulation, the position/direction of a segment to be moved next must be estimated in the detailed planning. Furthermore, it takes much time to change a grasping point. Therefore, a sequence in which grasping points are not changed frequently is preferable.

By using the above criteria, we can limit candidates for manipulation plans. After that, quantitative analysis should be performed in order to check whether a selected manipulation can be realized practically or not considering physical properties of a linear object such as rigidity.

6. Case Study

In this section, we demonstrate the effectiveness of our proposed method. Fig.7 shows an overview of a system consisting of a PC, a 6 DOF manipulator, and a CCD camera. A linear object, made from rubber but whose physical properties are uncertain, is laid on a table and its shape is captured by the camera fixed above the table. The table corresponds to the projection plane.

Fig.8 shows a required manipulation. It corresponds to raveling out of an overhand knot. The initial state shown in fig.8(a) can be represented as E_l-C_1^--C_2^--C_3^--C_1^--C_2^--C_3^--E_r and the objective state shown in fig.8(b) can be represented as E_l-E_r. Assumptions of this case study are as follows :

- The left endpoint of the object is fixed during manipulation; an open square in fig.8 indicates the position of a fixure.
- One manipulator can be used.
- The manipulator can approach to the object from only the front side of the projection plane.
- The manipulator releases the object whenever one raveling operation is finished.
- The manipulator can not move the fixed endpoint and its adjoining segment of the object.

Then, one sequence of state transitions is derived by our proposed method. It consists of three steps, that is, $N_t = 3$, and corresponds to a sequence; $\mathrm{S}_{10} \rightarrow \mathrm{S}_7 \rightarrow \mathrm{S}_5 \rightarrow \mathrm{S}_{11}$ in fig.4. Furthermore, manipulation plans illustrated in fig.9 are selected by considering criteria N_m and N_c with respect to each step.

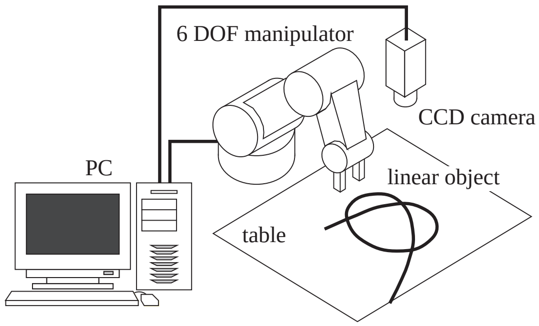
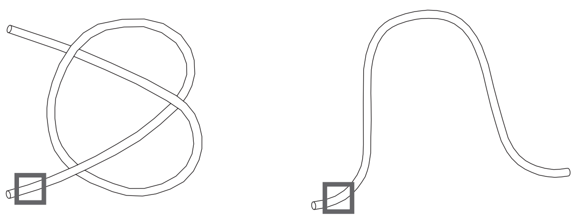


Fig. 7 Overview of developed system



(a) initial state (b) objective state

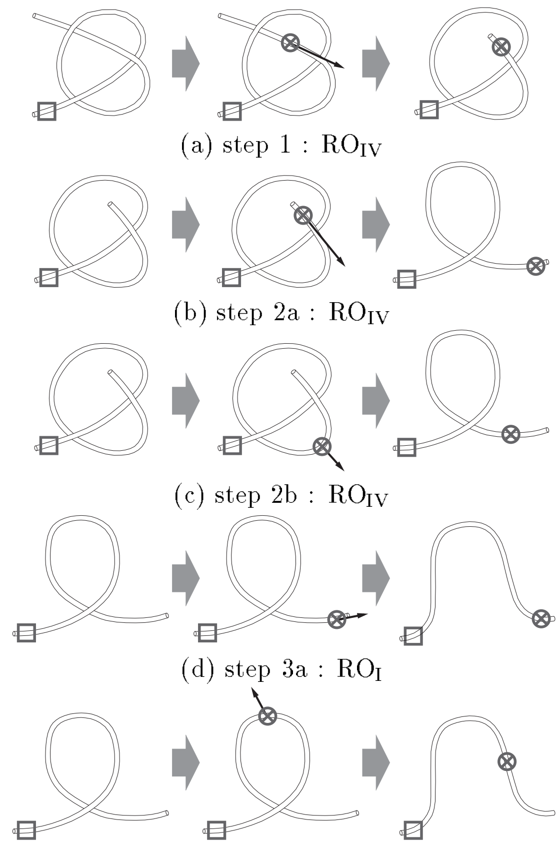
Fig. 8 Required manipulation – raveling of overhand knot

Next, the system recognizes the current crossing state of the object from a grayscale image. The position of individual crossing points can be identified by analyzing the image. In this experiment, information which part is above at each crossing point is given for simplicity. However, it can be obtained automatically using a stereo camera. We regard the position of each grasping point as be the midpoint of each segment. Direction of the axes for four unit motions can be calculated from the tangent at a grasping point. As adequate moving distance for a state transition is unknown, the system checks whether its crossing state is changed or not after moving the object. Thus, the manipulator can grasp, move, and release the object according to the generated qualitative plan.

In this case study, the system selects step 2a and step 3b by considering the size of space for insertion of a gripper and motion range of the manipulator. Fig.10 shows the result of this manipulation. Thus, we conclude that our proposed method is useful for automatic planning and execution of linear object manipulation.

7. Toward Detailed Planning

We can plan linear object manipulation qualitatively by applying our method proposed in the previous sections. It is not enough to determine grasping points of manipulators and their trajectories in detail. However, we had developed an analytical method to model the shape of a deformable linear object[9]. Fig.11 shows a numerical



(a) step 1 : RO_{IV}

(b) step 2a : RO_{IV}

(c) step 2b : RO_{IV}

(d) step 3a : RO_{I}

(e) step 3b : RO_{IV}

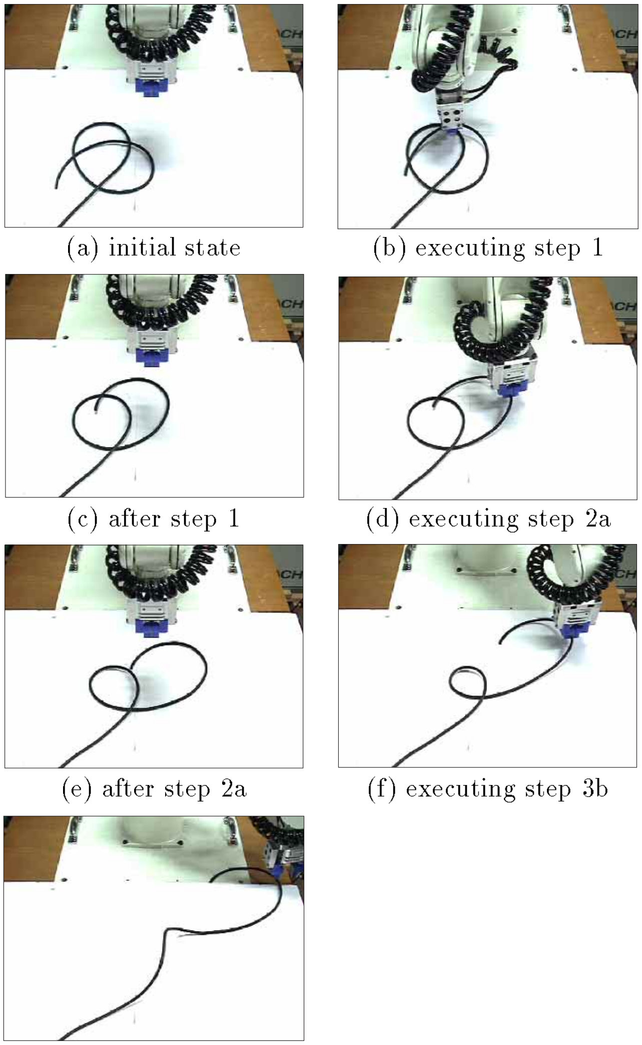
Fig. 9 Generated manipulation plans

example of an overhand knot. Therefore, the manipulation strategy can be derived automatically by combining a qualitative planning proposed in this paper with the quantitative analysis.

8. Conclusions

In this paper, a rough planning method for linear object manipulation including knotting/raveling was proposed.

Firstly, a representation of topological states of a linear object in three-dimensional space was proposed considering self-contact. Its topological states can be represented as finite crossing states including the number of crossing points and the crossing type of each crossing point. Secondly, transitions among those states were defined by introducing four basic operations. A state transition corresponds to a basic operation that changes the number of crossing points or permutates their sequence. Then, possible sequences of crossing state transitions, that is, possible manipulation processes can be generated once the initial state and the objective state are given. Thirdly, a method for determination of grasping points and their moving direction was proposed in order to realize derived



(a) initial state (b) executing step 1

(c) after step 1 (d) executing step 2a

(e) after step 2a (f) executing step 3b

(g) final state

Fig. 10 Result of manipulation

manipulation processes. Furthermore, criteria for evaluation of manipulation processes were introduced. Finally, we have demonstrated that our proposed method can be applied to linear object manipulation.

It is expected that this method will be useful for the establishment of systematic approach to the planning of linear object manipulation.

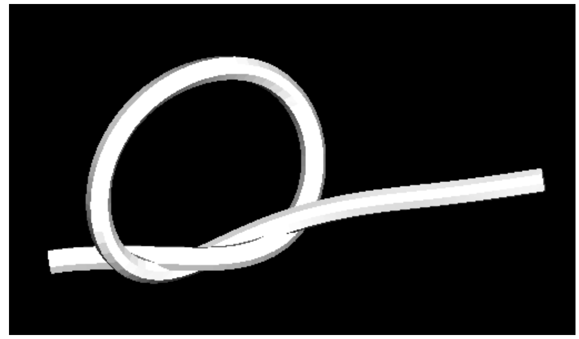


Fig. 11 Computed shape of overhand knot

References

[1] T. Lozano-Pérez, M. T. Mason, and R. H. Taylor, *Automatic Synthesis of Fine Motion Strategies for Robots*, Int. J. of Robotics Research, Vol.3, No.1, pp.3–24, 1984.

[2] R. S. Desai and R. A. Volz, *Identification and Verification of Termination Conditions in Fine Motion in Presence of Sensor Errors and Geometric Uncertainties*, Proc. of IEEE Int. Conf. Robotics and Automation, pp.800–807, 1989.

[3] H. Wakamatsu, A. Tsumaya, K. Shirase, and E. Arai, *Representation of Deformable Thin Object Manipulation Based on Contact State*, Proc. of the 5th Japan-France Congress & 3rd Asia-Europe Congress on Mechatronics, pp.519–524, 2001.

[4] J. E. Hopcroft, J. K. Kearney, and D. B. Krafft, *A Case Study of Flexible Object Manipulation*, Int. J. of Robotics Research, Vol.10, No.1, pp.41–50, 1991.

[5] B. G. A. V. Leaf, *Models of the Plain-Knitted Loop*, Journal of the Textile Institute Transaction, pp.49–58, 1960.

[6] J. Phillips, A. Ladd, and L. E. Kavraki, *Simulated Knot Tying*, Proc. of IEEE Int. Conf. Robotics and Automation, pp.841–846, 2002.

[7] T. Morita, J. Takamatsu, K. Ogawara, H. Kimura, and K. Ikeuchi, *Knot Planning from Observation*(Japanese), Proc. of The 20th Annual Conference of the Robotics Society of Japan, 3G26, 2002.

[8] C. C. Adams, *The Knot Book: An Elementary Introduction to the Mathematical Theory of Knots*, Henry Holt & Co, 1994.

[9] H. Wakamatsu, S. Hirai, and K. Iwata, *Modeling of Linear Objects Considering Bend, Twist, and Extensional Deformation*, Proc. of IEEE Int. Conf. Robotics and Automation, pp.433–438, 1995.