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Tying Path Design of a Belt-Like String to Bind Wire Harness

Ibuki Kitano, Hidefumi Wakamatsu, and Yoshiharu Iwata, The University of Osaka

Abstract— **In aircraft manufacturing, wire harness bundling is performed manually, requiring significant time and labor. Therefore, this study presents a new design for bundling tools aimed at improving the efficiency of the bundling process. A belt-like string used for bundling is modeled using a discrete model, and constraints based on the knotting method are formulated. Under such constraints, a path of the string to knot it is optimized. From the obtained path, a mold capable of actual bundling was fabricated, and the resulting knot formed using this mold was consistent with the tying methods required for wire harness bundling.**

I. Introduction

Inside an aircraft, numerous electrical wires are arranged in a complex manner to supply signals and power. A wire harness is an assembly that prevents such wires from tangling, with components such as terminals and connectors attached to each wire.

In aircraft-specific wire harness manufacturing, wires are manually arranged on a board in a factory according to design drawings and bundled before being installed in the aircraft. The bundling process uses belt-like polyester strings with a special surface coating, which are called lacing tapes, rather than conventional bundling materials such as cable ties or adhesive tapes. This is because plastic cable ties can become brittle over time, potentially breaking and scattering debris inside the aircraft, posing a risk of failure. Additionally, adhesive tape can obscure wire markings, making it difficult to identify and address wire disconnections. Tying wire with a string is one of the ways to keep high levels of safety and durability. There is a standard way to tie an aircraft wire harness. First, the harness is tightly bundled with a clove hitch, and then secured with a double overhand knot, as shown in Fig. 1.

Currently, wire harness bundling of aircraft is performed manually in Japan. Typically, wires extending tens of meters must be bundled at intervals of 10 to 30 cm. So, one harness bundling process takes more than 10 minutes. As an aircraft is equipped with over 1,500 harnesses, the total bundling work can require more than 250 hours. Furthermore, bundling processes in an aircraft to install harnesses in its ceiling or underfloor result in significantly lower efficiency compared to those in a factory. Therefore, efficiency improvement is necessary through the automation of such bundling processes. Considering the increasing global demand for aircraft, such efficiency improvement is an urgent issue because it can affect overall productivity of aircraft manufacturing. Therefore, the objective of our study is to improve the efficiency of wire harness bundling for aircraft.

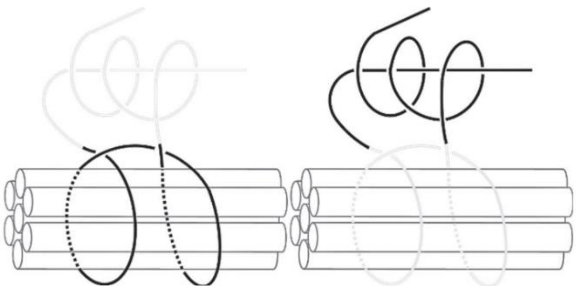
In previous studies on automatic knotting, methods using robots and molds have been widely explored.

In research with respect to knotting with robots, a hand-eye system using visual information has been proposed, where the manipulator performs knot-tying operations [1]. Additionally, methods that attempt to bind cords through the coordination of visual information and motion planning have been developed [2]. However, the accuracy of visual information processing is influenced by environmental conditions. Furthermore, large working space is required for robots.

Methods using molds have garnered attention as an approach that enables stable binding without relying on visual information. In this approach, the binding path inside the mold is designed based on the topology of the knot, and efforts have been made to design the path shape and opening/closing mechanisms to suppress friction and twisting [3]. For example, there are methods where the path is composed of multiple parts that match the topology of the knot, and the mold is disassembled after the binding to make it easier to remove the knot [4].

We have aimed at efficient harness bundling with molds. The reason for adopting molds is that they enable stable bundling, reducing variations in bundling time and quality caused by operators. Additionally, molds can be designed to be small and lightweight, making them easier to introduce in environments where space is limited. Furthermore, stable work can be achieved regardless of environmental conditions because visual information is not required.

However, from the perspective of bundling force, the broad surface of the lacing tape must tightly adhere to the wire bundle, and unexpected twisting must be avoided. Therefore, it is necessary not only to fulfill the topology of the knot but also to quantitatively control the twisting of the tape within the mold. Based on this, our previous studies have proposed a method to model a lacing tape continuously and to optimize the path shape in a mold where a lacing tape passes through as shown in Fig. 2[5]. Furthermore, a method was proposed to determine how a mold should be divided to extract a lacing tape from the mold easily[6]. A dynamic model of a lacing tape also was proposed to verify that it can pass smoothly through a designed



(a) Clove hitch (b) Double over hand knot

Fig. 1 The sketch of the knot.

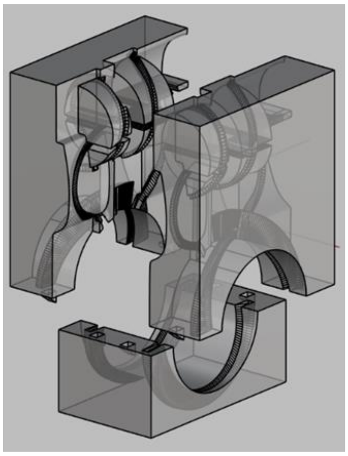


Fig. 2 Designed mold to bundle wire harness.

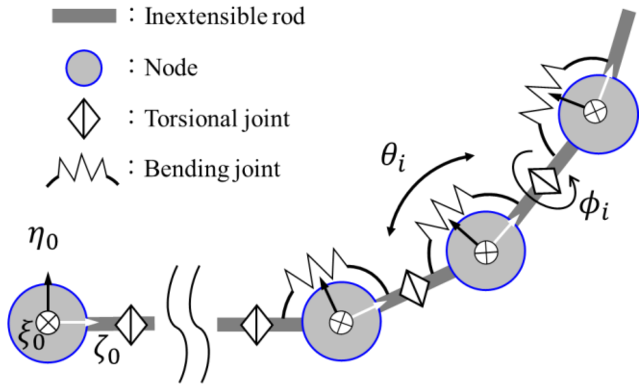


Fig. 3 Illustration of the belt-like string model.

path in a mold[7]. However, in the case of all those molds, the tape got jammed in the path and did not pass smoothly through it.

A tool for wire harness bundling with mold should be compacted to bring it anywhere. So, a path must bend in the mold with a limited size. In the previous studies, the tape shape was represented as a weighted sum of trigonometric functions. Then, to describe a sharp bend, many high-frequency functions must be prepared. It leads to an increase in computation time. Furthermore, such high-frequency functions can affect the shape of gentle bends. Therefore, a path was optimized after being divided into several parts and the whole path shape could not be optimized. It may be one of the causes of jamming.

In this study, we optimize the whole path shape to knot a belt-like lacing tape towards the development of a bundling tool of wire harness for aircraft. First, a lacing tape is represented with a discrete model which can represent a developable surface. Next, constraints are formulated to satisfy the topology of required knots. After that, the optimized path shape is derived by minimizing the potential energy under topological constraints. Finally, a mold is fabricated based on the optimized path shape, and it is verified that actual bundling can be successfully performed.

II. Modeling of Lacing Tape

To design a path so that a lacing tape can pass through it, it is important to predict the shape of the tape in the path. So, in this section, a lacing tape is modeled. A lacing tape for bundling wire harness is easy to bend but hard to stretch. Then, its surface can be regarded as a developable surface. The developable surface can be unfolded onto a plane without stretching or compressing. In other words, it is a surface generated by sweeping a straight line, which is referred to as a generatrix, along a certain trajectory in a three-dimensional space. So, a lacing tape has generatrices on its surface and no curvature in the wide direction. In addition, to maintain developability, the generatrices do not intersect with each other on the tape. Therefore, in the modeling of a lacing tape, it is essential to consider the following four conditions:

Condition 1: No stretching or compression.

Condition 2: No bending in the wide direction.

Condition 3: Generatrices exist on the surface.

Condition 4: Generatrices do not intersect on the surface.

Based on these conditions, a discrete modeling of the lacing tape is considered in this study.

First, a model is constructed that satisfies Condition 2, which imposes no bending in the wide direction. In general, the rotation of a rigid body in a three-dimensional space can be represented using quaternions or Euler angles. Quaternions consist of four parameters, but since they must satisfy the normalization condition for unit quaternions, the effective degrees of freedom (DOF) are reduced to three. Furthermore, one degree of freedom in rotation is fixed by applying the constraint from Condition 2. As a result, a final DOF becomes two. When using Euler angles, rotation is typically expressed with three DOF. However, due to Condition 2, DOF also becomes two. Thus, whether using quaternions or Euler angles, Condition 2 reduces rotational DOF to two. This reduction leads to an adjustment of redundant parameters and increases computational costs. To address this issue, this study proposes a new two-DOF model that always satisfies Condition 2.

First, let L be the length of a lacing tape. To satisfy Condition 1, the tape is discretized into n non-extensible line segments connected by n+1 nodes. The length of each segment is given by $l = L/n$. A local coordinate system P_i-$\xi_i\eta_i\zeta_i$ is assigned to each node, where the ζ_i-axis is aligned with the central axis direction, the η_i-axis is aligned with the normal direction of the tape, and the ξ_i-axis is aligned with the wide direction, respectively. Here, ξ_i, η_i, and ζ_i represent the unit direction vectors of each coordinate axis, expressed in the world coordinate frame. Note that the ζ_i-axis of the local coordinate system at the i-th node is aligned with the central axis direction of the next segment. Due to Condition 2, bending around the η_i-axis is restricted. Therefore, torsional joints are introduced around the ζ_i-axis on each segment, while bending joints are introduced around the ξ_i-axis at each node. In other words, the lacing tape is modeled as an alternating series of torsional and bending joints. The rotation angle at the i-th torsional joint is denoted as φ_i, and the rotation angle at the i-th bending joint is denoted as θ_i. Fig. 3 illustrates the conceptual diagram of this model. The relationship between the local coordinate systems P_i-$\xi_i\eta_i\zeta_i$ and P_{i-1}-$\xi_{i-1}\eta_{i-1}\zeta_{i-1}$ is given by the following equation.

$$\begin{bmatrix}\boldsymbol{\xi}_i\\ \boldsymbol{\eta}_i\\ \boldsymbol{\zeta}_i\end{bmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & \cos\theta_i & \sin\theta_i\\ 0 & -\sin\theta_i & \cos\theta_i\end{bmatrix}\begin{bmatrix}\cos\varphi_i & \sin\varphi_i & 0\\ -\sin\varphi_i & \cos\varphi_i & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\boldsymbol{\xi}_{i-1}\\ \boldsymbol{\eta}_{i-1}\\ \boldsymbol{\zeta}_{i-1}\end{bmatrix} \tag{1}$$

The spatial coordinate $\boldsymbol{x}_i$ of point P_i in the world coordinate frame is given by:

$$\boldsymbol{x}_i = \boldsymbol{x}_0 + \sum_{k=1}^{i} l\boldsymbol{\zeta}_{k-1} \tag{2}$$

Next, let us consider the developability of the tape concerning Condition 3 and Condition 4. First, the curvature $\kappa_{\xi,i}$ and the torsional ratio $\kappa_{\zeta,i}$ at P_i are approximately expressed as follows:

$$\kappa_{\xi,i} = \frac{\theta_i}{l} \tag{3}$$

$$\kappa_{\zeta,i} = \frac{\varphi_i}{l} \tag{4}$$

Fig. 4 shows the surface of a lacing tape. In this figure, d_2 represents one of the principal curvature directions at P_i, indicating the direction of the generatrix. The other principal curvature direction, $d_{1,i}$, is perpendicular to $d_{2,i}$ and corresponds to the direction with the maximum curvature. Thus, the tape bends only in the $d_{1,i}$ direction and does not bend in the $d_{2,i}$ direction. If the angle between the ζ_i-axis and the $d_{1,i}$ direction is denoted as α_i, then tan α_i is expressed as the ratio of the curvature and torsional ratio, and

$$\tan\alpha_i = \beta_i = \frac{2\kappa_{\zeta,i}}{\kappa_{\xi,i-1} + \kappa_{\xi,i}} \tag{5}$$

is obtained. To satisfy Condition 3, the torsion $\kappa_{\zeta,i}$ is constrained by $\kappa_{\xi,i-1}$, $\kappa_{\xi,i}$, and β_i as follows:

$$\kappa_{\zeta,i} = \frac{\kappa_{\xi,i-1} + \kappa_{\xi,i}}{2}\beta_i \tag{6}$$

Using (3) and (4), this can be rewritten in terms of φ_i and θ_i:

$$\varphi_i = \frac{\theta_{i-1} + \theta_i}{2}\beta_i \tag{7}$$

To satisfy Condition 4, the following inequality constraint must be satisfied using β_i:

$$-\frac{2}{W} \leq \frac{\beta_i - \beta_{i-1}}{l} \leq \frac{2}{W} \tag{8}$$

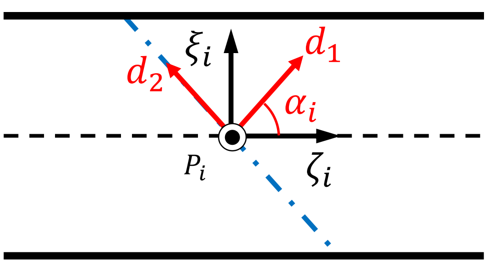


Fig. 4 Definition of the rib angle $\boldsymbol{\alpha}$.

Therefore, the shape of a lacing tape is represented by two parameters, φ_i and θ_i, which must satisfy the constraints given by (7) and (8). Furthermore, defining the objective function as the potential energy U, it can be expressed as follows:

$$U = \frac{R_\xi}{2}\sum_{i=1}^{n-1}\frac{\theta_i^2}{l} + \frac{R_\zeta}{2}\sum_{i=1}^{n}\frac{\varphi_i^2}{l} \tag{9}$$

where R_ξ denotes the flexural rigidity and R_ζ denotes the torsional rigidity, respectively.

III. Constraints Based on the Knotting Method

As mentioned in the previous section, a wire harness for aircraft is bound by knotting a clove hitch first and a double overhand knot next. To realize such knotting, the path shape must satisfy the topology of those knots. This means that qualitative constraints must be represented quantitatively. So, in this section, constraints to tie two knots are formulated.

A clove hitch is a knot in which the tape is wrapped around the bundled object twice, forming two crossing points near the center of the knot. In the first loop, the end of the loop passes over its beginning, while in the second loop, the opposite occurs. First, the wrapping around the bundled object is considered. Let $\boldsymbol{a}_i$ be the direction vector from each node P_i to the central axis of the bundled object, defined as the vector pointing from node P_i to the closest point on the central axis, and let $\boldsymbol{c}$ be the direction vector of the central axis of the bundled object. When defining the wrapping direction of the tape around the central axis as counterclockwise relative to the vector $\boldsymbol{c}$, the following two constraint equations must be satisfied.

$$(\boldsymbol{a}_i \times \boldsymbol{\zeta}_i)\cdot\boldsymbol{c} \geq 0 \tag{10}$$

$$(\boldsymbol{a}_i \times \boldsymbol{a}_{i+1})\cdot\boldsymbol{c} \leq 0 \tag{11}$$

Equation (10) constrains the rotational direction in which the tape wraps around the bundled object at each node. Note that the vector $\boldsymbol{\zeta}_i$ indicates the progression direction of the tape. By taking the cross product of the vector $\boldsymbol{\zeta}_i$ with the vector $\boldsymbol{a}_i$, the wrapping direction is determined. Ensuring that this cross-product vector is either aligned with or opposite to the vector $\boldsymbol{c}$ guarantees that the tape wraps around the bundled object in a consistent direction. If this condition is not satisfied, the wrapping direction may reverse and the tape cannot be properly wound around the object. Therefore, this constraint is necessitated. Equation (11) also constrains the wrapping direction by considering the wrapping behavior between adjacent nodes. The cross product of the direction vectors $\boldsymbol{a}_i$ and $\boldsymbol{a}_{i+1}$ represents the change in the tape's progression direction between adjacent nodes. Ensuring that this cross product vector becomes opposite to the vector $\boldsymbol{c}$ maintains a consistent wrapping direction. This condition preserves the wrapping structure. If not satisfied, the tape will fail to form the proper loop structure, preventing the correct formation of the knot.

Next, let us consider the intersection points of the tape. In a clove hitch, there are two crossing points, meaning that there are four points on the tape associated with these intersections. Let s_1, s_2, s_3, s_4, be design variables representing the distances from the starting point to these four points, ordered sequentially from the closest to the farthest. Thus, s_1 and s_2 form the first intersection, while s_3 and s_4 form the second intersection. Assuming that the intersection points are formed along the x-axis as shown in Fig. 5, s_1 and s_2 must satisfy the following constraints:

$$x(s_1) \leq x(s_2), \quad y(s_1) = y(s_2), \quad z(s_1) = z(s_2) \quad (12)$$

These constraints define the physical arrangement of the intersection points. The first inequality ensures the correct ordering of the intersection points by determining their relative positions. The equality conditions indicate that the intersections are formed along the x-axis, ensuring that the two crossing points on the tape share the same y and z coordinates. This prevents unintended displacement of the intersection points in other directions.

Additionally, a part from points s_1 to s_2 of the tape completes one full revolution around the bound object. Therefore, the total sum of the rotation angles from s_1 to s_2 relative to the central axis of the bound object must be 2π. This leads to the following constraint:

$$\sum_{i=1}^{\lfloor \frac{s_2}{l} \rfloor - \lfloor \frac{s_1}{l} \rfloor + 1} \psi_i = 2\pi \quad (13)$$

where ψ_i represents the rotation angle at each node between points s_1 and s_2, ensuring that the tape completes a full turn around the bound object. Since the distance between adjacent nodes is l, the number of nodes between s_1 and s_2 is given by $\lfloor \frac{s_2}{l} \rfloor - \lfloor \frac{s_1}{l} \rfloor + 1$. This condition guarantees that the intersection is formed at the correct position. Similarly, the points s_3 and s_4 must satisfy the following constraints:

$$x(s_4) \leq x(s_3), \quad y(s_4) = y(s_3), \quad z(s_4) = z(s_3) \quad (14)$$

$$\sum_{i=1}^{\lfloor \frac{s_4}{l} \rfloor - \lfloor \frac{s_3}{l} \rfloor + 1} \psi_i = 2\pi \quad (15)$$

Next, let us consider the constraints for the double overhand knot. The double overhand knot is formed by wrapping the tape around itself in a helical manner twice. Note that the helix is formed so that the endpoint of the helical part moves away from the endpoint of the wrapped part. To express this, as shown in Fig. 6, let P_0 be the endpoint of the tape to be wrapped. The tape progresses a certain distance in a straight line before bending. The double overhand knot is represented as wrapping around this straight section. For the helical part to be properly formed, its starting position and wrapping height must be clearly defined. Therefore, similar to the clove hitch, we introduce s_5, s_6, and s_7 as the distances to the points where the helix reaches the same x coordinate as the straight section. By defining the height direction as the x-axis and the helical formation direction as the y-axis, the constraint equations are given as follows.

$$x(s_i) = x_0, \quad y(s_5) \geq y(s_6), \quad y(s_6) \geq y(s_7) \quad (16)$$

This constraint ensures that the helix is formed correctly. The first equation indicates that the points constituting the helix are positioned at a constant height, preventing the tape from deviating from the specified straight-line height. The second and third inequalities express that the helix wraps in the correct sequence, guaranteeing that the tape wraps in the intended order. Additionally, since the tape loops around itself between points s_5 and s_6, and between s_6 and s_7, a rotational constraint, similar to the one in the clove hitch, is needed. Therefore, the following constraints must be satisfied:

$$\sum_{i=1}^{\lfloor \frac{s_6}{l} \rfloor - \lfloor \frac{s_5}{l} \rfloor + 1} \psi_i = 2\pi, \quad \sum_{i=1}^{\lfloor \frac{s_7}{l} \rfloor - \lfloor \frac{s_6}{l} \rfloor + 1} \psi_i = 2\pi \quad (17)$$

By combining these geometric constraints with the rotational constraints, the clove hitch and the double overhand knot are formed qualitatively. Note that such constraints do not determine the geometrical shape of two knots completely.

A path for binding a wire harness must have the shape that a developable lacing tape can form. Otherwise, the tape may be jammed in the path. At the same time, it must form a clove hitch and a double overhand knot. Therefore, the path shape is determined by optimizing the tape shape under knotting constraints. This study assumes that the shape with the minimal potential energy of the tape is the most appropriate as the path shape.

Since the wrapping axes and constraints differ depending on the knot type, it is necessary to switch the knot at some point along the tape. Let the distances from the starting point to the points where the knot changes be s_8 and s_9, respectively. As shown in Fig. 7, from point P_0 to point s_8, no knotting constraints are applied; from s_8 to s_9, the clove hitch constraint is applied; and from s_9 to P_n, the double overhand knot

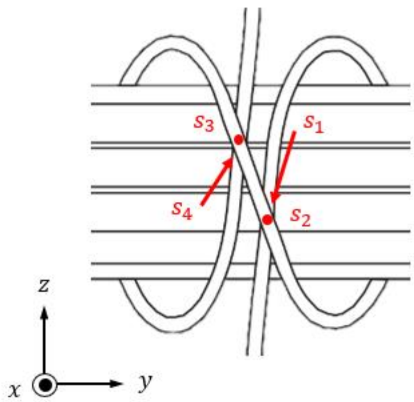


Fig. 5 Cross state of clove hitch.

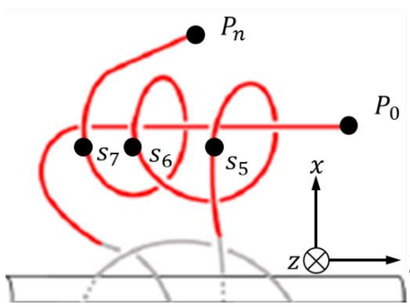


Fig. 6 Cross state of double over hand knot.

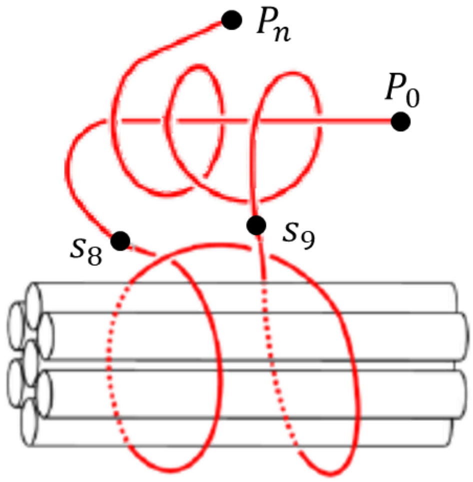


Fig. 7 Application range of knot types in optimization of bundling shape.

constraint is applied. By optimizing variables φ_i, θ_i, s_1 through s_9 so that the tape has minimal potential energy forming two knots, the whole path shape can be derived.

IV. Calculation Results

In this study, the optimization of a tying path was performed using the Nelder-Mead method. The optimized path is shown in Fig. 8. For the initial conditions of the optimization, the total length of the tape L was set to L=710 mm, and the number of divisions n was set to n=142.

A mold was designed based on the obtained optimized path to develop a bundling tool for wire harnesses. First, a hose-shaped mold without any division was prototyped to verify whether the lacing tape could pass along the computed path. This mold was created with translucent plastic using a 3D printer through the layered manufacturing method. In a layered 3D printer, the support material is inserted into a hollow part during the manufacturing process. However, such material is difficult to remove from a narrow space such as a curved tubular part. Therefore, in this study, a structure with one open side was used, and the tubular mold was constructed by covering the hole after manufacturing. Fig. 9 shows a successful result of actually passing the tape through the mold. It was confirmed that the tape could pass through the mold without jamming. This means that our proposed method can design the optimal whole path so that a developable lacing tape can pass through.

Next, to make the mold applicable as an actual tool, a separable mold was designed to ensure that the lacing tape can be reliably removed after bundling. To extract the tape without obstruction, the separation surface must pass through all passage paths inside the mold. Therefore, in the clove hitch part, the separation surface was designed to pass through the center of the cylindrical passage hole for the wire, and a groove-shaped path opening toward the center of the cylinder was constructed. In the double overhand knot part, the helical portion was designed as a groove-shaped path opening toward the center of the helix, while the portion penetrating the center was designed as a tubular path. Fig. 10 shows the structure of

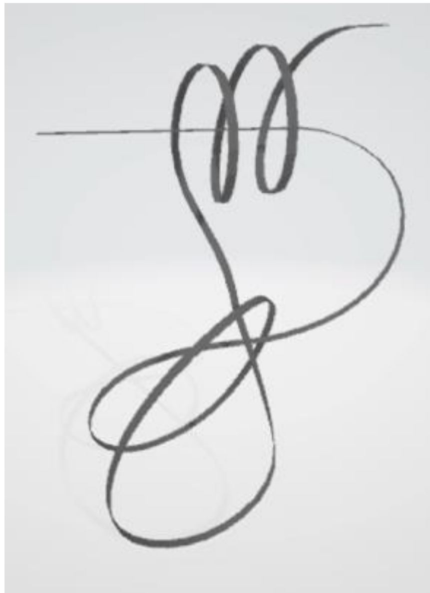


Fig. 8 Optimized Path for the Passage of the Belt-like Cord.

Fig. 9 Test results of the lacing tape passage using the hose-shaped mold.

the separable mold fabricated based on these design principles.

The separable mold was fabricated using a 3D printer, and bundling experiments were conducted using manual operation. The bundling procedure consisted of the following steps: (1) assembling the mold around the wire bundle, (2) inserting one end of the lacing tape into the mold entrance and threading it through the path, (3) confirming that the tape exits from the mold outlet, (4) disassembling the mold to release the tape, (5) pulling both ends of the tape to form and tighten the knot, and (6) cutting the excess tape. As shown in Fig. 11, the tape successfully passed through the entire path without jamming. Fig. 12 shows the resulting knot formed on the wire bundle. This knot is a combination of a clove hitch and a double

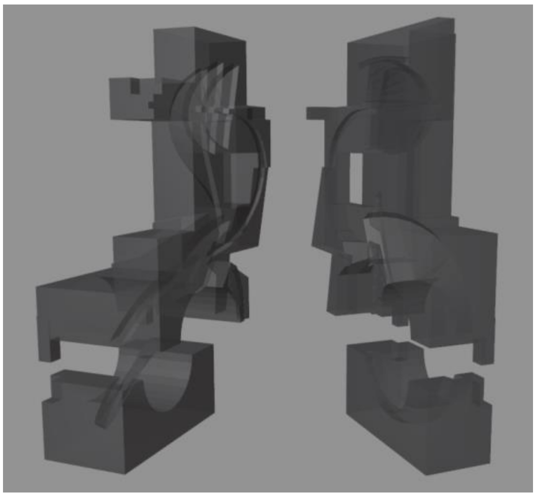


Fig. 10 A model of a separable mold.

overhand knot, which are both required for bundling wire harnesses. The entire bundling process took approximately 1 minute per bundle, whereas manual bundling by skilled workers typically takes about 20 seconds. Although the current manual implementation does not yet match the speed of manual work, significant time reduction is expected through automation of tape feeding, mold assembly/disassembly, and parallel processing of multiple bundling operations.

However, the resulting knot exhibited insufficient holding strength, failing to securely fix the wires in place. As future work, we will investigate the cause of this reduced bundling strength and work toward developing a mold that fully satisfies the functional requirements for wire harness bundling.

V. Conclusion

This study proposed a method to optimize the path shape to knot a belt-like lacing tape towards the development of a bundling tool of wire harness for aircraft. An inextensible and developable lacing tape was modeled with two variables discretely. Constraints satisfying the topology of a clove hitch and a double overhand knot were formulated. Assuming that the path shape can be identified with the tape shape, the tape shape was optimized under knotting constraints. A tubular mold was fabricated from the obtained shape, and it was confirmed that the lacing tape passed smoothly through the path in the mold. Furthermore, a separable mold suitable for actual bundling was designed and fabricated based on the optimized path. Using this mold, wire bundling was successfully performed, and the resulting knot formed a combination of a clove hitch and a double overhand knot, which conforms to the tying methods used in wire harness assembly.

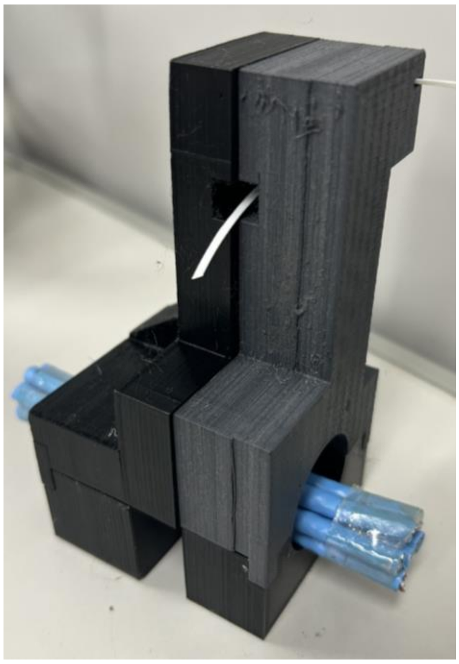


Fig. 11 Test results of the lacing tape passage using the separable mold.

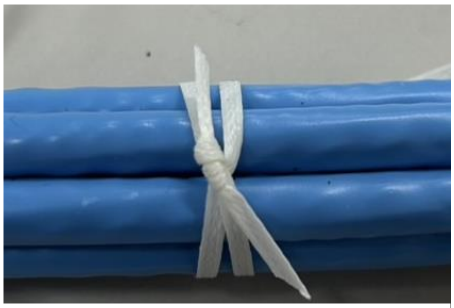


Fig. 12 the knot tied using the mold.

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