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Research on Trajectory and Pose Planning of Robotic Arms for 3D Template Sewing

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Abstract：The technology of template sewing is one of the key techniques in the field of garment stitching. However, traditional flat template sewing often fails to meet the demands of multi-layered stitching structures. Therefore, three-dimensional template sewing is required to address these shortcomings. This paper focuses on three-dimensional template sewing technology, using hat manufacturing as a case study. A simple three-dimensional template model has been designed, employing NURBS curves to fit the sewing path. The adaptive arc-length interpolation method and spherical linear interpolation method are utilized to tackle issues related to speed smoothing and posture adjustment during the sewing process, while also planning the actual stitching pose for the robotic arm. Simulation experiments demonstrate that the proposed approach can accurately fit irregular nonlinear curved paths. The interpolation algorithms exhibit good performance in terms of speed smoothness and posture continuity, ensuring stability and precision throughout the robotic arm's sewing process. This research provides a novel perspective for advancing three-dimensional template sewing techniques.

Key word：Three-dimensional Sewing；Pose Planning；NURBS Curve Fitting;；Spherical linear interpolation

Introduction

The template sewing technology is one of the key techniques in the field of garment manufacturing[1]. By pre-designing and fabricating sewing templates, it allows for precise definition of sewing paths and shapes, combined with automated sewing equipment to achieve efficient and standardized production processes. However, existing template sewing technologies primarily focus on flat templates that typically use flat clamps to secure single-layer fabrics during stitching. When faced with multi-layered textiles or complex geometric shapes in sewing tasks, flat templates lack sufficient structural adaptability and flexibility, making it challenging to meet the demands of intricate processes. In contrast, three-dimensional (3D) template sewing offers advantages over flat template methods by better conforming to complex curved surfaces and being suitable for multi-level structure stitching tasks. Additionally, 3D templates can reduce process adjustments and enhance production efficiency. As demand for high-end custom garments, automotive interiors, and flexible composite materials continues to grow[2,3], the need for 3D template sewing technology has become increasingly prominent.

In template sewing, the fitting and interpolation of sewing trajectories are among the core technologies that significantly impact sewing quality[4]. Reference[5] proposed a trajectory fitting method based on polynomial curves, which is capable of fitting most linear curves but struggles with irregular nonlinear curves. Reference[6] introduced a trajectory fitting approach utilizing NURBS (Non-Uniform Rational B-Splines) curves, achieving optimal fitting results with a minimal number of control points. Furthermore, reference[7] built upon the fifth-order NURBS curve interpolation method and employed an improved artificial bee colony algorithm to achieve further smoothing optimization. However, in three-dimensional sewing applications, it is essential to address not only the factors related to stitching positions but also those concerning posture and speed[8]. Although the aforementioned methods have made significant advancements in optimizing nonlinear curve trajectories, they still exhibit limitations regarding posture considerations and do not ensure stable speeds during the sewing process. Therefore, achieving high precision and flexibility in three-dimensional template sewing on multi-degree-of-freedom motion platforms remains a pressing technical challenge that requires resolution.

This paper proposes a collaborative motion scheme for 3D template sewing based on hat-making tasks by designing a simplified three-dimensional stitching template where the sewing machine is mounted at the end effector of a robotic arm that provides high degrees of freedom in movement capabilities necessary for executing operations on 3D templates effectively. The study employs NURBS curve fitting techniques to model stitch trajectories while utilizing adaptive velocity interpolation based on Taylor expansion alongside spherical linear interpolation methods to plan pose transformations within those trajectories accurately. Simulation experiments validate this approach's feasibility when dealing with complex irregular nonlinear curves under conditions requiring multiple degrees of freedom during stitching operations while ensuring stability in relative stitch speeds as well as continuity in posture transitions.

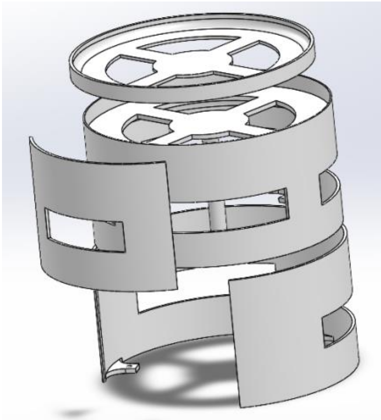
1 Three-Dimensional Template Style Structure

The present study analyzes the common styles of work caps available in the market and their stitching patterns[9]. It is observed that the stitching lines of these caps are located on the interior. As illustrated in Figure 1, the stitching lines are formed by sewing two layers of fabric together in a parallel overlapping manner, with the edges of the fabric standing vertically to its surface. Consequently, during the sewing process, the overall structure of the stitching exhibits a closed configuration; thus, the threads are concealed within the inner side of the cap and display a multi-layered structure.

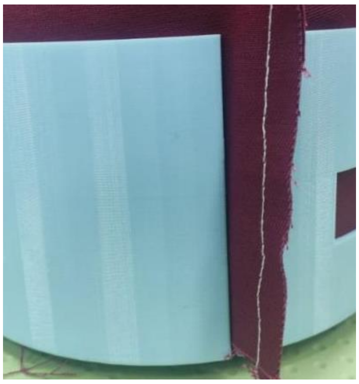
Fig. 1. Hat sewing stitch

In order to overcome the limitations of traditional flat template sewing methods, this paper presents a simplified three-dimensional template for hat sewing, as illustrated in Figure 2. This three-dimensional template allows for the inversion of the hat's interior, bringing the previously concealed stitching lines to the exterior of the template. By expanding the hat, a supportive shape is achieved.

The fabric intended for sewing is positioned between two side pressure plates with an allowance on both sides designated as seam edges, which are then secured by clamping from these pressure plates. The remaining portion of the fabric is firmly pressed by these plates. This setup ensures that the seams remain flat throughout the sewing process and effectively prevents any deformation of the fabric during stitching.



(a). SolidWorks Model



(b). Stitching of Three-Dimensional Templates

Fig. 2. Diagram of the 3D template structure

2 Sewing Trajectory

2.1 NURBS Curve Fitting

In the design of three-dimensional templates, the sewing trajectory is determined by the sewing process, which constitutes one of the inherent properties of the template itself. However, robotic arms are unable to directly recognize and interpret the sewing trajectory of these three-dimensional templates. Therefore, an accurate mathematical model is required to describe this sewing trajectory so that the robotic arm can comprehend it. As illustrated in Figure 3, point P serves as a reference point for establishing a coordinate system OpbaseXYZ within the SolidWorks model of the three-dimensional template. Once this coordinate system is established, we can calibrate the positions of sewing points within it and utilize these points as control points for curve fitting. This approach enables us to precisely fit the sewing trajectory curve present in the three-dimensional template.

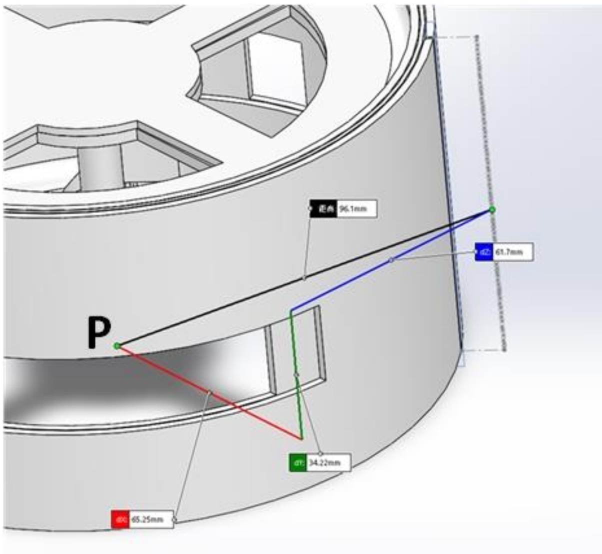


Fig. 3. Marking the control points for stitching

Common curve fitting algorithms include least squares method, cubic spline interpolation, Gaussian fitting, and support vector regression. These methods effectively address various linear and nonlinear fitting problems while providing smooth curves. However, when faced with more complex fitting requirements, Non-Uniform Rational B-Splines (NURBS) offer flexible control over control points, weights, and basis functions that enable precise fitting of intricate geometric shapes. This makes NURBS widely applicable in fields such as computer graphics, CAD modeling, and robotic path planning[10].

Given the advantageous characteristics of NURBS curves, this paper selects NURBS as the algorithm for fitting sewing trajectories. The mathematical expression of a NURBS curve is presented in Equation (1).

$$\mathrm{C(u)} = \frac{\sum_{i=0}^{n} N_{i,p}(u)\omega_i P_i}{\sum_{i=0}^{n} N_{i,p}(u)\omega_i} \tag{1}$$

In this context, C(u) represents a point on the curve where u denotes the parameter along the curve; typically within the range [0, 1]. The points Pi are defined as control points that determine the shape of the fitted curve. The weights Wi influence the significance of each corresponding control point Pi to the overall curve. Ni,p(u) refers to the basis function governing how each control point Pi affects its surrounding area at parameter (u); additionally, p indicates the degree of the curve which dictates its smoothness.

The sewing points calibrated within SolidWorks' 3D template serve as control points for generating a fitted NURBS curve whose results are illustrated in Figure 4.

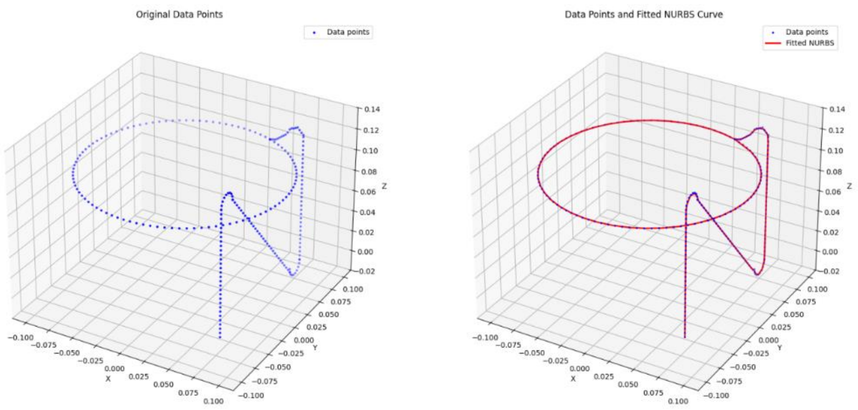


Fig. 4. NURBS curve fitting for the stitching path

2.2 Velocity Adaptive Interpolation

Sewing equipment, when performing sewing tasks, must take into account the existence of stitch length. This necessitates that the motion speed of the robotic arm during three-dimensional sewing aligns with that of the sewing device. Only in this way can the aesthetic and practical quality of the stitching be ensured. Generally speaking, under conditions where both stitch length (d) and the vertical movement speed (n) of the sewing machine needle are predetermined, the motion speed (V) of the robotic arm is determined by the following formula (2).

$$V = \frac{dn}{60} \tag{2}$$

In the task of template sewing, in addition to requiring a mathematical model for sewing speed and sewing curves, it is also essential to determine the feed rate at each sampling time through interpolation algorithms. Interpolation is the process of generating a continuous and smooth path between two positions using mathematical methods, thereby densifying data. The robot must utilize interpolation algorithms to ensure that the task requirements are met.

Furthermore, to achieve consistent stitch lengths for sewing and similar tasks, it is essential that the stitching trajectory points are uniformly distributed. This requirement necessitates the use of interpolation algorithms[11]. Generally, an equidistant arc-length interpolation method can be employed; this method not only ensures uniform distribution of points along spatial curves but also better accommodates the demands for smoothness in velocity and acceleration during practical applications.

When utilizing equidistant arc-length interpolation, it is necessary to compute the total arc length of the curve through numerical integration and then reparameterize to obtain uniformly distributed interpolation points. This process is particularly critical in robotic path planning and motion control. However, directly performing numerical integration on NURBS curves presents significant complexity and challenges[12,13]. In this paper, we adopt a strategy based on reference[14], employing adaptive interpolation on fitted NURBS curves to derive equidistant parameter (u) under fixed sampling times.

For the spatial curve S obtained through NURBS curve fitting, it can also be expressed using Equation (3).

$$S(u) = \begin{cases} x(u) \\ y(u), 0 \le u \le 1 \\ z(u) \end{cases} \tag{3}$$

The trajectory planning of robotic arms typically adheres to the principle of moving from an initial spatial position to a target spatial position within a fixed sampling period. Based on a constant sampling time interval T and a uniform sewing speed V, it is necessary to calculate the distribution characteristics of the parameter increment Δu corresponding to the arc length ΔS using differential geometry methods. Generally, the feed displacement components along the X, Y, and Z axes, denoted as Δx, Δy, and Δz, are expressed as shown in Equation (4).

$$\Delta S = \begin{cases} \Delta x = x(u_{i+1}) - x(u_i) \\ \Delta y = y(u_{i+1}) - y(u_i) \\ \Delta z = z(u_{i+1}) - z(u_i) \end{cases} \tag{4}$$

The velocity for the entire arc segment S is defined as the distance divided by time. By decomposing the velocity, we can establish a relationship between the parameter (u) and the velocity V, as illustrated in Equation (5).

$$\mathrm{V} = \frac{dS}{dt} = \frac{dS}{du}\frac{du}{dt} = \left(\sqrt{(\frac{dx}{du})^2 + (\frac{dy}{du})^2 + (\frac{dz}{du})^2}\right)\left(\frac{du}{dt}\right) \tag{5}$$

The derivation from Equation (5) yields the following result.

$$\frac{du}{dt} = \frac{V}{\sqrt{(\frac{dx}{du})^2 + (\frac{dy}{du})^2 + (\frac{dz}{du})^2}} \tag{6}$$

$$\frac{d^2u}{dt} = \frac{V^2\left[\left(\frac{dx}{du}\right)\left(\frac{d^2x}{du}\right) + \left(\frac{dy}{du}\right)\left(\frac{d^2y}{du}\right) + \left(\frac{dz}{du}\right)\left(\frac{d^2z}{du}\right)\right]}{\sqrt{\left(\frac{dx}{du}\right)^2 + \left(\frac{dy}{du}\right)^2 + \left(\frac{dz}{du}\right)^2}} \tag{7}$$

By analyzing the methods presented in the references, we can employ Taylor expansion to perform parameter interpolation on NURBS curves. The Taylor expansion formula is illustrated as shown in Equation (8).

By analyzing the method presented in reference[15], we can employ Taylor expansion for parameter interpolation of NURBS curves, as illustrated in equation (8).

$$u_{i+1} = u_i + T{u_i}' - \frac{T^2}{2}{u_i}'' \tag{8}$$

In the case where the sampling time T is sufficiently small and the radius of curvature is sufficiently large, the second derivative in Equation (8) can be temporarily disregarded. By substituting Equations (6) and (7) into Equation (8), we can derive the interpolation parameter (u) of the NURBS curve under fixed parameters T and velocity V as follows:

$$u_{i+1} = u_i + \frac{VT}{\sqrt{[x'(u_i)]^2 + [y'(u_i)]^2 + [z'(u_i)]^2}} \tag{9}$$

According to the definition of NURBS curves, the parameter (u) must be within the range [0, 1]; otherwise, it may lead to situations where the calculation of the stitching point is not feasible. However, when using equation (9) to compute all interpolated values of parameter (u), there may be instances where u > 1. Therefore, in cases where u > 1 is encountered during the final computation of this parameter, it can be directly set to u = 1, and subsequently, the sampling time interval should be recalculated accordingly.

When u = 1, the stitching point fitted by the NURBS curve corresponds to the last point of the original data set. From Equation (3), we can determine that at u = 1, this point is associated with the spatial coordinate S(Uend). After performing iterative calculations using Equation (9) to obtain the final spatial coordinate S(Uend-1), its sampling time interval t(end) can be determined by Equation (10).

$$t_{end} = \frac{\|S(u_{end}) - S(u_{end-1})\|}{V} \tag{10}$$

In summary, the values of the sewing trajectory interpolation parameter (u) and their corresponding sampling times are presented as shown in Equation (11).

$$\begin{cases} u_{i+1} = u_i + \dfrac{VT}{\sqrt{[x'(u_i)]^2 + [y'(u_i)]^2 + [z'(u_i)]^2}}, \quad 0 \le u < 1, \quad t_i = T \\ u_{end} = 1, \quad t_{end} = \dfrac{\|S(u_{end}) - S(u_{end-1})\|}{V} \end{cases} \tag{11}$$

By substituting Equation (3) into Equation (11), we can compute the interpolation of all parameters (u) in the fitted sewing trajectory presented in this paper. Consequently, each parameter interpolation parameters (u) corresponds to a set of three-dimensional spatial coordinates (x, y, z) as well as a motion time (t). The robotic arm sequentially traverses the points (x, y, z) according to the motion time (t), thereby ensuring uniform velocity throughout its movement.

2.3 Slerp Linear Pose Interpolation

After interpolating the NURBS curve, we can obtain the precise three-dimensional coordinates of each sewing point. However, it is essential to consider the posture of the robotic arm during its movement[16]. Therefore, in addition to the coordinate position matrix (P), a rotational posture matrix (R) is also required; this is what we refer to as the homogeneous transformation matrix (T).

For the end effector of the robotic arm, its axis joint direction aligns with the Z-axis and runs parallel to the surface of the fabric being sewn. The Y-axis corresponds to the direction of the sewing machine needle, which is perpendicular to that surface. The X-axis points in opposition to the motion direction of the sewing machine.

In SolidWorks models, we calibrate points corresponding to interpolation parameter (u) into three-dimensional space coordinates and establish a Cartesian coordinate system based on these reference points. However, due to an abundance of points generated through adaptive interpolation along sewing trajectories, it becomes impractical to label every single point. Generally speaking, postures change continuously; thus, we only mark key postures while other positions are computed using interpolation algorithms, as illustrated in Figure 5.

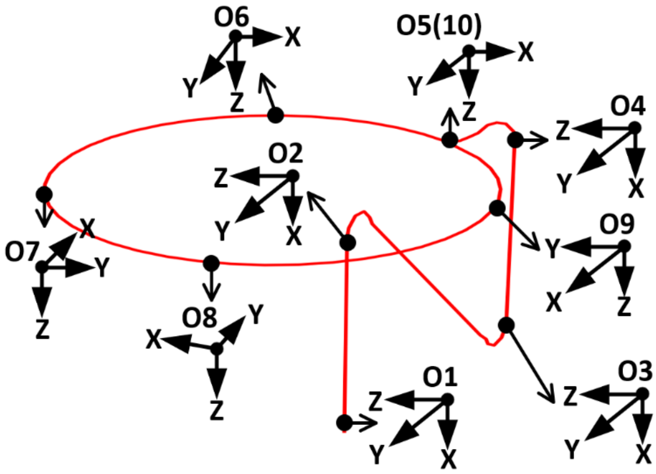


Fig. 5. Key Pose of 3D Template Points

Spherical Linear Interpolation, is a method for smoothly transitioning between two unit quaternions. This technique is commonly employed in computer graphics and robotics[17,18]. As illustrated in Equations (12) and (13), where (q_1) represents the quaternion corresponding to the initial target pose matrix, and (q_2) denotes the quaternion associated with the final target pose matrix. The angle (theta) between (q_1) and (q_2) can be computed using their dot product. If this dot product approaches 1, it indicates that the rotation angle between these two quaternions is minimal; conversely, if it approaches -1, it suggests that the rotation angles are close to 180 degrees.

$$q(t) = \left(\frac{\sin\left((1-t)\theta\right)}{\sin(\theta)}\right) q1 + \left(\frac{\sin(t\theta)}{\sin(\theta)}\right) q2 \tag{12}$$

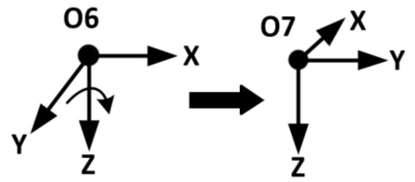
$$\theta = \cos^{-1}(q1 \cdot q2) \tag{13}$$

Furthermore, since the parameter (t) for Slerp (Spherical Linear Interpolation) also ranges from [0, 1], after obtaining the initial quaternion (q_1) and the final quaternion (q_2), the interpolation range of parameters is defined as [(u_1, u_2)]. As shown in Equation (14), by normalizing, we project and scale the interpolation parameter (u) from [(u_1, u_2)] to [0, 1]. Once we compute the mapped interpolation parameter (t) and its corresponding quaternion orientation, it is important to note that because the parameter interpolation (u) matching with (t) is fixed, there is no need for reverse normalization. Thus, we can directly obtain the corresponding orientation of interpolation parameter (u).

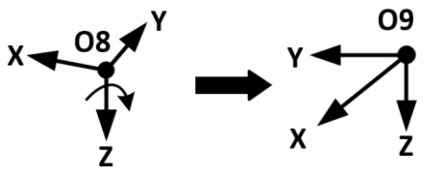
Furthermore, since the parameter (t) for Slerp (Spherical Linear Interpolation) is constrained within the range [0, 1], once the initial quaternion (q_1) and the final quaternion (q_2) are obtained, the interpolation parameter range becomes [(u_1), (u_2)]. As illustrated in Equation (14), by normalizing this process, we project and scale the interpolation parameter (u) from [(u_1), (u_2)] to [0, 1]. After calculating the corresponding mapped interpolation parameter (t) and its associated quaternion orientation, it is important to note that because the interpolation parameter (u) corresponding to a given value of (t) remains fixed, there is no need for reverse normalization. Thus, we can directly obtain the corresponding orientation for interpolation parameter (u).

$$t = \frac{u - u1}{u2 - u1} \tag{14}$$

The Slerp interpolation algorithm computes the shortest rotational path between quaternions; however, the changes in Euler angles may not align with our intuitive understanding of human motion. As illustrated in Figure 6, if we directly interpolate from the coordinate system of keypoint 6 to that of keypoint 7, the rotation direction around the Z-axis is counterclockwise, resulting in a rotation angle of 270 degrees about this axis. Conversely, when transitioning from keypoint 8 to keypoint 9—also involving a counterclockwise rotation around the Z-axis—the Euler angle only rotates by 90 degrees.



(a). Key Point 6 to Key Point 7



(b). Key Point 8 to Key Point 9

Fig. 6 Key Point Rotation Direction

In addition to increasing the key points, it is generally observed that when the angle between two quaternions exceeds 180 degrees, we can perform an inversion operation on the target quaternion, specifically q2 = -q2. This operation effectively reverses the rotation direction of the Euler angles, thereby ensuring the continuity of the entire stitching path.

3 Pose of the Robotic Arm in Sewing

3.1 Establishing a Reference Coordinate System

The three-dimensional template is installed within a simple rotational mechanism that possesses two degrees of rotational freedom, allowing its orientation to vary in space. The standard Denavit-Hartenberg (DH) parameter method is employed for mathematical modeling of this rotational mechanism, resulting in the DH parameter table for the three-dimensional template mechanism, as shown in Table 1.

Table 1: DH Parameter Table for the Spatial Template Mechanism (Units: m, rad)

i	αi	ai	di	θi
1	-π/2	0	0.1	θ1
2	π/2	0	0	θ2

Based on the standard Denavit-Hartenberg (DH) parameter method, reference coordinate systems are established for various mechanisms, including robotic arms. The robotic arm utilized is a general six-axis manipulator, and the entire system resembles a dual-arm configuration[19]. As illustrated in Figure 7, the coordinate system OwXYZ represents the base coordinate system of the robotic arm, while OtoolXYZ denotes the end-effector coordinate system of the robotic arm. The coordinate system OtempXYZ corresponds to the base coordinate system of the stereoscopic template, OpbaseXYZ indicates the reference point coordinate system of the stereoscopic template, and OpXYZ signifies the sewing point coordinate system.

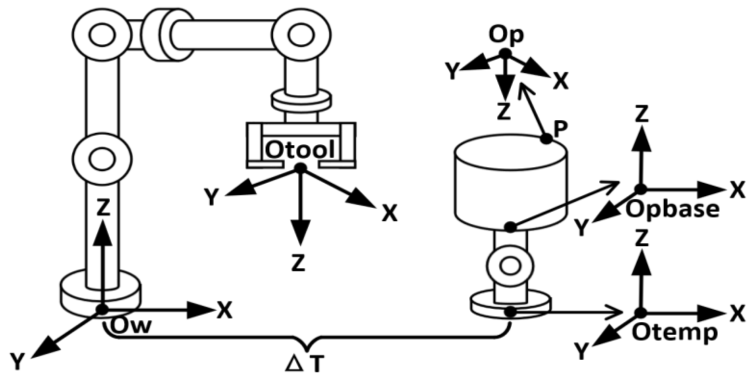


Fig. 7. Diagram of the coordinate system relationships

3.2 Sewing Trajectory of Robotic Arms

The sewing trajectory points P obtained through adaptive interpolation calculations are established within the coordinate system of the stereoscopic template, denoted as OpbaseXYZ. Let us assume that the pose of point P in the stereoscopic template's base coordinate system is Tpbase, while its pose in the robotic arm's coordinate system is Tpworld. Before any pose transformation ΔT is applied to the stereoscopic template, it can be considered that Tpbase is equivalent to Tpworld. However, once the stereoscopic template is installed at a designated workstation, there will be a pose transformation ΔT between the stereoscopic template's coordinate system and that of the robotic arm. Therefore, it becomes necessary to remap the reference coordinate system of sewing points from that of the stereoscopic template to that of the robotic arm in order to achieve accurate sewing.

First, we need to calculate the transformation pose ΔT between Oworld (the origin of world coordinates) and Otemp (the origin of templated coordinates), which will hereafter be referred to as Tworld2temp. Given that this positional relationship between mechanical arms and templates remains relatively fixed, this transformation can be acquired through measurement or visual calibration.

$$T_{world2temp} = \begin{bmatrix} R_{w2t} & P_{w2t} \\ 0 & 1 \end{bmatrix} \tag{15}$$

In this context, Rw2t represents the rotation matrix from mechanical arm base coordinates to those of the stereoscopic template base; Pw2t denotes its translation vector.

Let us denote θ1 and θ2 as current rotational angles for each joint in relation to interpolation parameter (u); their relationship is defined by sewing processes as shown in Equation (16). Ideally speaking, regardless of what value interpolation parameter (u) takes on, these rotational angles should remain constant. However, due either to limitations imposed by workspace constraints on mechanical arms or geometric restrictions inherent within templates themselves at certain sewing points—an angle adjustment may become necessary for ensuring safe operation during tasks.

$$\theta_1 = \theta_1(u_i); \ \theta_2 = \theta_2(u_i) \tag{16}$$

According to the standard Denavit-Hartenberg (DH) parameter method, the homogeneous transformation matrix Ttemp for each joint of the stereoscopic template can be determined, allowing for the computation of the kinematic forward solution of the template. As indicated in Equation (17), when the sewing interpolation parameter (u) is set to (u = u(i)), the joint angles ([θ_1, θ_2]) of the stereoscopic template are obtained from Equation (16). Utilizing the kinematic forward solution formula for robotic arms, one can derive the transformation relationship Ttemp between the coordinate system of the base and that of a reference point on the stereoscopic template.

$$T_{temp}(u_i) = {}_0^1T_{temp}\,{}_1^2T_{temp} = \begin{bmatrix} R_1[\theta_1(u_i)] & P_1 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} R_2[\theta_2(u_i)] & P_2 \\ 0 & 1 \end{bmatrix} \tag{17}$$

In fact, regardless of the joint angles of the stereoscopic template motion mechanism, all sewing point poses Tpbase relative to the coordinate system of the stereoscopic template base remain invariant. However, with respect to the robotic arm's coordinate system, the sampled pose Tpworld at a given interpolation node changes in accordance with the movement of the stereoscopic template. The pose Tpworld can be obtained from Equation (18).

$$T_{pworld}(u_i) = T_{arm2temp}T_{temp}(u_i)T_{ptemp}(u_i) \tag{18}$$

The robotic arm's interpolation parameter (u) corresponds to a specific sewing pose, which also encompasses motion time information. Consequently, the trajectory of the robotic arm's sewing poses, denoted as Omega (Ω), can be expressed using Equation (19). The collection of these pose trajectories constitutes the overall motion trajectory of the robotic arm. In sewing tasks, when the robotic arm moves along the designated sewing trajectory Omega, it is theoretically capable of completing the sewing task as required.

$$\Omega = \{T_{pworld}(u_i), \ 0 \le u_i \le 1\} \tag{19}$$

4 Simulation Experiment

The present study primarily focuses on the design of a three-dimensional template model within SolidWorks (SW). The implementation of NURBS curve fitting and related interpolation calculations is conducted in a Python environment, with subsequent simulation experiments performed in MATLAB. The overall procedure is illustrated in Figure 8.

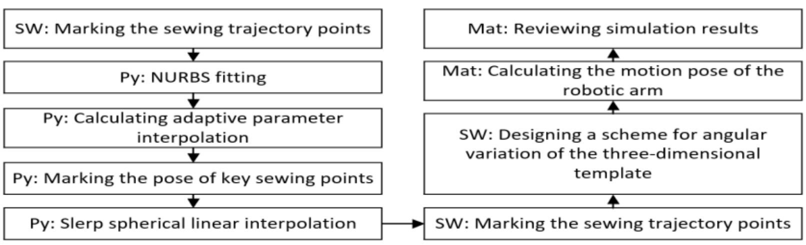
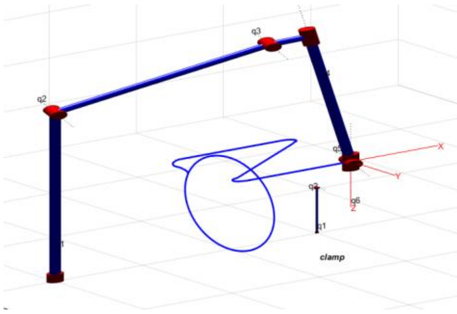


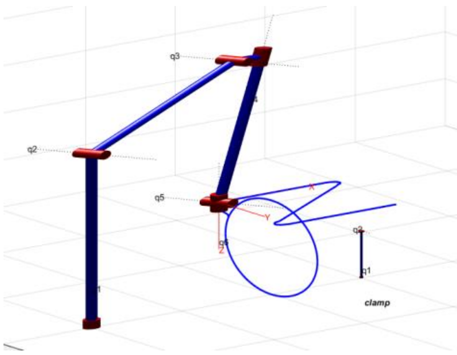
Fig. 8. Simulation experiment workflow

The conditions for the simulation experiment are established as follows: a sampling time of 0.1 seconds, a robotic arm sewing speed of 5 cm/s, and a NURBS curve fitting degree set to 5. The trajectory for sewing along the three-dimensional template has been previously defined, with key sewing points and orientations consistent with those illustrated in Figure 5. To ensure that the robotic arm can achieve feasible solutions, it should preferably be oriented towards its initial state; specifically, the Z-axis of the end effector should be directed vertically downward. Between key points 1 and 4, the joint angles for the three-dimensional template are specified as [0, -π/2]. From key point 5 to key point 10, due to limitations preventing full rotation (360 degrees) at certain joints of the end effector, an initial joint angle configuration of [0, 0] is employed while joint angle one rotates counterclockwise at an angular velocity of (50/360 * π) rad/s. A linear interpolation between joint angles from [0, -π/2] to [0, 0] is implemented between key points 4 and 5.

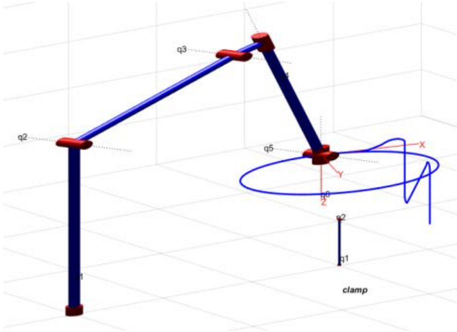
The visualization process captures each parameter node's mechanical arm movements alongside transformations corresponding to their respective angles relative to the three-dimensional template; this effect is depicted in Figure 9. It demonstrates that the robotic arm can move along designated trajectories according to sewing requirements.



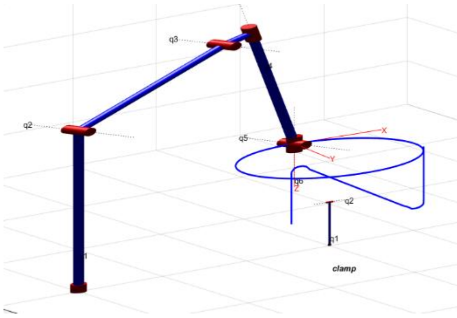
(a). Key Point 1



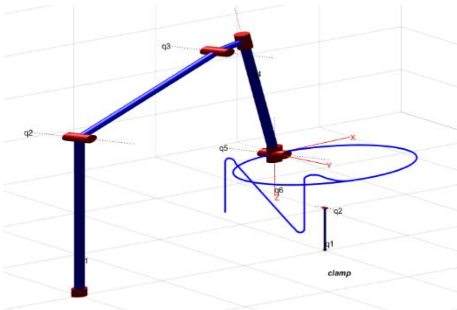
(b). Key Point 4



(c). Key Point 6



(d). Key Point 7



(e). Key Point 8

Fig. 9. Sewing Process Simulation Effects

The analysis indicates that there are 229 interpolation parameters, denoted as (u). By computing the Jacobian matrix of the robotic arm at each interpolation node, we can ascertain the velocity magnitudes in various directions, which facilitates an evaluation of the resultant speed magnitude. The variation in speed magnitude is illustrated in Figure 10, while changes in sewing posture quaternion are depicted in Figure 11.

It is evident that during the sewing process, velocities from Key Point 1 to Key Point 4 remain within the required sewing speed threshold of 5 cm/s. Between Key Point 5 and Key Point 10, due to motion speeds associated with a three-dimensional template, there is an automatic reduction in sewing speed to an appropriate level to ensure compliance with stitch distance requirements. In contrast, other non-sewing segments represent transitional phases where adjustments in velocity are necessary for pose modification; thus, normal fluctuations in speed occur.

Furthermore, regarding quaternion variations, it can be observed that these changes are continuous without any discontinuities. This continuity suggests the feasibility of spherical linear interpolation for attitude adjustment during operation.

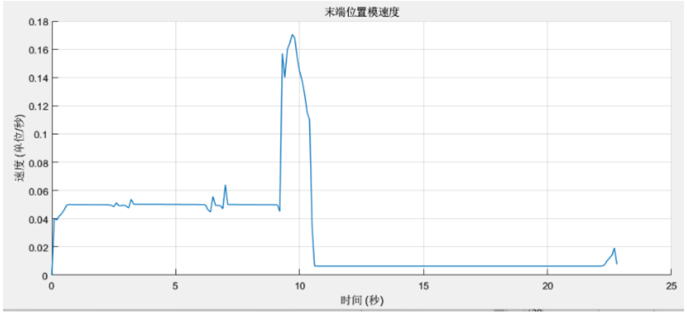


Fig. 10. The variation in the magnitude of velocity at a given position.

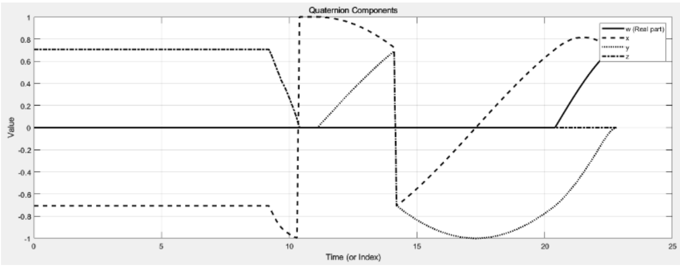


Fig. 11. Variations of Quaternions in Posture

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