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RESEARCH ARTICLE

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Strategy for robot motion and path planning in robot taping

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Abstract Covering objects with masking tapes is a common process for surface protection in processes like spray painting, plasma spraying, shot peening, etc. Manual taping is tedious and takes a lot of effort of the workers. The taping process is a special process which requires correct surface covering strategy and proper attachment of the masking tape for an efficient surface protection. We have introduced an automatic robot taping system consisting of a robot manipulator, a rotating platform, a 3D scanner and specially designed taping end-effectors. This paper mainly talks about the surface covering strategies for different classes of geometries. The methods and corresponding taping tools are introduced for taping of following classes of surfaces: Cylindrical/extended surfaces, freeform surfaces with no grooves, surfaces with grooves, and rotational symmetrical surfaces. A collision avoidance algorithm is introduced for the robot taping manipulation. With further improvements on segmenting surfaces of taping parts and tape cutting mechanisms, such taping solution with the taping tool and the taping methodology can be combined as a very useful and practical taping package to assist humans in this tedious and time costly work.

Keywords robot taping, path planning, robot manipulation, 3D scanning

1 Introduction on taping problems and objectives

Taping, covering the surface of an object using masking tapes is useful for many industrial applications such as mechanical part repairing, surface protection, and crack repairing. This taping process depends on manual workers which is time taking and tedious. Therefore, industrial companies aim to automate the taping process using robotic systems.

Robot manipulations with 3D scanning models have been investigated in surface treatment applications like spray painting [1–4] and laser coating removal by Baker et al. [5]. These applications are scenarios that does not have contact constraints and there is no restriction other than the surface geometry [4,5]. Different from other robot tasks as illustrated in Fig. 1, taping path planning is more difficult as it needs surface covering strategy and the attachment of the tape with correct orientation and without wrinkle. Meanwhile, pressing force is required to properly attach the masking tape. Taping regular shapes (tubes, bars, etc.) can be easily done through using some standard taping machines [6,7]. However, when the geometry of the taping part become complex, the taping problem becomes non-trivial. As a result, such taping works are mainly done manually by skilled workers. To automate the taping process using robotic system, the following problems need to be solved: 1) To get the 3D model of the object, 2) to generate the taping path based on some planning strategy according to the geometry of the part, 3) designing a Proper taping end-effector, and 4) a robot platform for the execution of the taping. Previous works [8,9] have been done to tape regular shapes.

Fig. 1 Manual taping

Taping parts can vary a lot in geometry in applications like spray painting, plasma spraying, etc. The common workpieces are with the surface features as follows: 1) Cylindrical-like surface, 2) rotational symmetrical surfaces, 3) freeform surface (including flat surfaces) with no grooves, and 4) surfaces with grooves. A workpiece surface can be segmented into these features. Therefore, if such surface features can be automatically taped properly, the taping work of a variation of workpieces can be handled by a robotic system. This paper mainly discusses on the workpiece taping strategies, the methods and tools for taping different features. The path planning algorithms are introduced separately. The collision checking and avoidance is also considered in the motion planning.

The remaining part of the paper is organized as follows: Section 2 discusses on the details of the surface covering strategies and path generation methods for different classes of geometries; Section 3 introduces the system applied; Section 4 shows some experimental samples; Section 5 briefly concludes the paper.

2 Taping path planning strategy

Given a workpiece, experienced work can tell the strategy to use for the part, including how to segment the surfaces and how to orient the tape (vertical, horizontal, or wrapping around for example). This is the first step. Also, based on the size of the part, the type of tape with fitting width needs to be chosen for taping.

The taping strategy is largely dependent on the surface size and the curvature. For example, how to tape a spherical surface (with r being the radius) choosing a suitable tape width w_t ? To ensure that the tape is suitable for the surface, if the surfaces area is big, we firstly needs to segment entire surface into surface segments for taping.

The minimal curvature radius value on the surface r_m is required to be at least $5w_t$ —The tape is not suitable for taping if the radius is too small. We apply the following constraints to choose the width of the tape. For each workpiece, the type of tapes is determined based on Eq. (1) to make sure it is suitable.

$$20w_t > r_m > 5w_t. (1)$$

In general, the separation of the surface is a very challenging job that needs problem understanding. For example, how to tape a spherical surface? After problem understanding, we evenly divided the sphere surface into six square-like pieces as shown in Fig. 2.

Fig. 2 Surface segmentation

The segmentation of the parts is a complex work that needs human understanding. Due to finite workpiece operations, it is reasonable to just create a database for the surface separation methods of all models based on human experience at the beginning, and apply the strategies in database to plan the taping path for covering a specific workpiece. Fine tuning can be done based on the end-effector control feedback.

After discussion on the surface segmentation, the path planning for different features needs to be elaborated. This chapter will introduce on the methods to cope with different features.

2.1 Taping method and path planning for different features

In practice, the parts to be taped have no standard CAD model because of deformation, broken, abrasion, etc. To realize the task, a 3D model needs to be generated. In this work, the model of the workpiece is scanned using 3D scanners [10,11]. A cheaper and convenient solution is Kinect sensor which provides a position accuracy of 1–2 mm. More accurate scanners can provide better results. Figure 3(a) shows an example of a 3D laser scanner using 3D camera. The position accuracy is claimed to be less than 0.2 mm.

(a) (b)

Fig. 3 (a) The IVC-3D SICK scanner; (b) scanning model from the scanner

The scanners will provide the user with the 3D point cloud data, from where the x , y , z coordinates of the points can be calculated. MeshLab software or some open source codes can be used to calculate the surface normal vectors and do some data filtering. A digital model is generated, which will be used in path planning.

2.1.1 Cylindrical surface and extended surface

The cylindrical-like surface is taped based on a *wrapping-around* strategy as applied by experienced worker. This means the tape is wrapped around the workpiece such that the tape covers the surface with a certain overlapping between two tape layers, as illustrated in Fig. 4.

Fig. 4 Illustration of cylindrical shape taping

For such shapes, the tape wraps around the surface with respect to the workpiece. However, it is not always possible for a robot to continuously wrap around the parts due to the collision and workspace constraints. Therefore, the part is placed on top of a rotating platform which collaborates with the robot manipulator. Because of this, the path planning is firstly done with respect to the workpiece. After choosing proper platform rotating patterns, the end-effector tool path is calculated to fulfill the task requirement.

In path planning on workpiece, the desired points along the workpiece surface are identified, as the point-of-contact with the end of the taping tool. The taping starts from bottom of the object, all the way until the top. Before taping, the tape is chosen, the tape overlapping rate need to be defined and the pitching angle need to be determined:

1) Get the initial point for taping from the digital 3D model with initial height ($h=h_0$), and angle ($\theta=0$) with respect to the reference frame of the platform.

2) Numerically calculate the perimeter (S) of the closed curve on section $z=h_0$. The “pitch angle of the tape (p) can be calculated: Pitching angle (in rad): $p = (1-r)d_r / S$, where r is the overlap rate of the tape, d_r is the tape width.

Detailed information can be found in Refs. [8,12].

Path planning on workpiece

The main idea is to update the pitching angle and robot end-effector pose to make sure the tape is properly attached to cover the surface. The taping points are projected from the previous points following a taping pitch angle, the process ends when the taping height reaches the target value.

3) $\theta = \theta + d\theta$, $i = i + 1$.

4) Search the surface point v_i with normal vector $\mathbf{v}_{n,i}$ in neighborhood best satisfying (h , θ).

Then, $h = h + p/|\mathbf{v}_{i-1}\mathbf{v}_i|$ (this is the contact point in the taping path planning).

5) If $\theta = 360$, then $i = 0$; $\theta = 0$ and update S and p in the same way as in Steps 2) and 3).

6) Calculate the robot pose based on (v_i , $\mathbf{v}_{n,i}$, p).

7) If $h < h_{\max}$, go to Step 4); else, stop.

In the taping process, the robot taping end-effector need to apply pushing force to the surface, preferably along the surface normal direction. Therefore, the surface normal direction is used in defining the orientation of the robot end-effector. After getting this path planning results with respect to the workpiece, a further transformation is needed while the platform rotates, this is mainly a coordinate mapping issue which is detailed in Refs. [8,12].

2.1.2 Freeform surface with no grooves

For a square-like freeform feature, the general idea of the taping method is illustrated in Fig. 5. Firstly, we can have a main taping direction based on the geometry of the area. The main direction is based on database information or human selection. The group of point pairs, (A_i and B_i as shown in Fig. 5) are selected on the edges to make the surface curving with some preferable overlapping between adjacent tape segments.

Fig. 5 Area of interest for taping

After assigning of all the point pairs, for each tape segment (A_i , B_i) to cover the surface is actually a point to point taping across the surface problem. In this case, we need to figure out the taping start orientation at Point A_i in order to tape to Point B on the surface, with minimal wrinkle of the tape. Also, the robot manipulator's path needs to be determined accordingly.

The model of taping on a surface is illustrated in Fig. 6, starting from Point A , the mini tape element with very small length dl is attached on the surface. At a taping Point $\mathbf{P} = [x, y, z]^T$, the taping frame is defined to follow the orientation of the mini taping element. The Z axis is defined by the surface normal at $\mathbf{P}$. The Y axis is along the taping direction. The X axis is simple ($Y \times Z$). The taping starting point $\mathbf{P}_i$ is the middle point of the starting edge of the mini tape element. The

Z axis is defined to be along the normal vector direction, $\mathbf{z}_i = \mathbf{n}_i$. Then, the next taping Point $\mathbf{p}_{i+1}$ is updated based on a prediction as follow:

$$\hat{\mathbf{p}}_{i+1} = \mathbf{p}_i + \mathbf{y}_i dl \quad (2)$$

(a) (b)

Fig. 6 3D surface model for taping. (a) Tape coordinates definition; (b) the displacement of tape elements while taping

Note that the taping point should lie on the surface. Therefore, the predicted Point $\hat{\mathbf{p}}_{i+1}$ is projected to the surface to get the next taping Point $\mathbf{p}_{i+1}$.

In order to match the tape with the surface nicely, it is important to understand the constraints during the taping. As shown in Fig. 7, while the tape attaches to the surface, it is noted that the tape element flips to the surface along a certain screw axis V_i which depends on the surface geometry. The flipping axis is actually the intersection between the small taping element surface (flat) S_i and its next small taping element flat surface S_{i+1} . As a result, this twist axis V_i is perpendicular to both $\mathbf{z}_i$ and $\mathbf{z}_{i+1}$ (the surface normal of S_i and S_{i+1}).

Fig. 7 Flipping of the tape element while taping

Therefore, we have

$$(3)$$

The twist angle φ_i is

$$\varphi_i = \cos^{-1}(\mathbf{z}_i \cdot \mathbf{z}_{i+1}) \quad (4)$$

With such twist motion, it is understandable that the relationship between the orientation of the element frame of S_i , R_i , and that of element frame of S_{i+1} , are connected by the twisting motion, $R_{i+1} = e^{\varphi_i \hat{V}_i} R_i$, where $\hat{V}_i$ is the skew-symmetric matrix of vector V_i . Its corresponding rotation matrix is calculated by the $SO(3)$ matrix $e^{\varphi_i \hat{V}_i}$, details can be found in Refs. [13,14].

Therefore the taping orientation will be $\mathbf{y}_{i+1} = e^{\varphi_i \hat{V}_i} \mathbf{y}_i$. The taping tasks points along the path are determined based on this method.

In order to make sure that the tape correctly goes from starting Point A to the target position B, the initial taping orientation needs to be determined. Numerical method (Newton's method) is used to search for the initial orientation.

With the taping locations, orientations, the surface normal, and the posture of the part with respect to the robot, the robot end-effector pose can be determined.

2.1.3 Surfaces with grooves

For surfaces with groove features, the path planning for the groove covering need to be down separately, this is because the groove has much more restriction on the tool orientations and it may have collision with the tool. Therefore, the path planning need to consider the following:

- Path of 3D position trajectories and roller directions;
- Collision avoidance.

In this work, the taping strategy for groove feature is to cover the groove with the tape straightly crossing the groove. It is reasonable to consider the local area as a two-dimensional problem for a narrow workpiece segment. In this way, the taping path $p(t)$ can be determined based on the intersection between the taping plane and the surface. Taping roller direction $X(t)$ needs to be in line with the groove. In such a manner, the path for taping with respect to the workpiece can be partially defined—The X, Y, Z locations, and the roller direction of the taping tool. The taping angle of the tool head $\varphi(t)$ need to be determined because the surface normal direction does not guarantee a collision free solution.

Collision detection method

Taping process request the taping tip to contact the surface and the tool body not sink into the objects. In addition, the extended tape cannot touch the workpiece as shown in Fig. 8. A collision checking algorithm is proposed based on these requirements. Firstly, based on the scanned mesh of the workpiece and the environment, the collision map of the object is generated. An example is shown in Fig. 9.

(a) (b)

Fig. 8 Illustration on taping of groove features. (a) Actual setup; (b) digital model

Fig. 9 Collision map for the workpiece

Meanwhile, we have the model of the tool. Therefore, we can have the surface of the tool. Here, we use a group of the outer lines $S_l = \{l_1, l_2, l_3, \dots, l_n\}$ to define the boundary of the tool as shown in Fig. 10. It is understandable that as long as all the lines are not intersecting with the objects, the collision is avoided. A method is proposed for this collision checking. The working principle of the algorithm is shown in the following steps.

Fig. 10 Taping tool boundary line model on the workpiece model

Inputs:

1. Collision map of workspace

Mesh format $Z = \text{Mesh}(X, Y)$

2. Defining collision boundary lines of the tool
3. The posture of the tool on top of the workpiece

(For each boundary line segment l_i , pick the points of n -section of the line segment, $\{ls_1, ls_2, ls_3, \dots, ls_m\}$ and check if any of them are outside the collision boundary.)

Bool collision=False;

While $i < n$

Generate the points of n -section of the line segment l_i

$\{ls_1, ls_2, ls_3, \dots, ls_m\}$;

For $j=1, 2, 3, \dots, m$, do

If $ls_j(3) < Z(ls_j(1), ls_j(2))$ {Collision=True; return;}

(The points on the tool boundary should be above the workpiece)

End

End

Remarks: $(X, Y, Z)_i$ denotes the position of Point i in the point cloud model of the workpiece, $(x, y, z)_j = (ls_j(1), ls_j(2), ls_j(3))$ denotes the position of Point j on the boundary segment of the end-effectors, ls_j .

With such collision detection algorithm, we can check the lower and upper boundary of the collision free angle domains. The continuous taping angle path can be determined in many different methods.

Then the end-effector of the robot (the homogeneous transformation matrix with respect to the workpiece) can be determined [15].

$$T(t) = \begin{bmatrix} X(t) & Y(\varphi(t)) & Z(\varphi(t)) & P(t) \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (5)$$

This will provide a collision free path with tape properly attached to the planned area. Figure 11 shows an example of taping path using the taping angle which is the middle value of the collision free domain. The section curve is used in the planning.

Fig. 11 Taping path with no collision

2.1.4 Rotational symmetrical surfaces

There are also features like rotational symmetrical surfaces which take a large portion of the workpiece in the spray painting and plasma spraying for aerospace applications. Such shapes can be taped vertically on the sections. Horizontally taping is not appropriate because the tape will wrinkle a lot if we maintain the tape in the same vertical plane for a shape, as shown in Fig. 12. The section of a rotational symmetric shape is also quite similar to a freeform surface (sometimes with grooves), as shown in the rectangle in Fig. 12. Therefore, through rotation the supporting platform, the surface can be taped by the robot through a section to section method. When segmenting the surface vertically into pieces, each piece can be treated as a freeform surface while doing the path planning.

Fig. 12 Taping rotational symmetrical surfaces

It is also theoretically possible to tape such shapes like and cone surfaces based on the geodesic path [16] on the surface since this line defines the straight line in a curved surface but we haven't implemented algorithm to test it. This work is still in progress and not discussed here.

With the four different methods for cylindrical-like surface, freeform features, groove features, and rotary features, the collision avoidance algorithm, and taping strategy databased, the system can handle a large variation of parts. Once the taping path planning is completed, the taping tool posture trajectories with respect to the workpiece are known. In order to optimize the robot motion, the rotation platform rotates to collaborate with the robot while the robot conducts the taping. Therefore, the path of the robot end-effector is finalized according to the moving pattern of the rotation platform.

3 Robot taping system and taping tools

Figure 13 shows the robot taping system. The system includes a 3D scanner for the 3D model reconstruction, a part fixing platform, a taping robot, the robot taping tool and .A part fixing platform is used to mount the parts for taping. This platform can either be a simple fixed base or a rotating platform. The special design of the end-effector is required in order to meet the proper taping requirement. Meanwhile, the mechanism for cutting and holding the tape is also needed to accomplish the taping process.

Fig. 13 An automatic taping system

3.1 Taping tool design

The taping tool is used as the robot end-effector to handle the tape and conduct the actual taping process. As shown in Fig. 14, the “tape holder” is used to handle the masking tape. The tape comes across the “tape guiding roller” so that it can be transmitted smoothly. The “tape roller” is the one contacting with the taping surface and conducts the tape attachment task. The “compliance spring” mechanism is to allow some tolerance of the “taping roller”. The “fixing flange” is used to fix the taping tool on the robot.

(a) (b)

Fig. 14 Taping tool design. (a) Tool for surfaces without grooves; (b) tool for groove surfaces

For groove taping, the taping head (tip) need to be narrow to make sure it can attach the tape into the groove. Therefore, the taping head need to be redesigned. The tape width and the surface curvature will require taping tips with different dimensions. Therefore, there is a need to have one or a set of optimal taping tips.

3.2 Distance/force feedback

Due to the Scanning model errors and the errors from the robot manipulation, open loop taping sometimes will lose when the taping tool is not contacting the workpiece surface and when the tool pushes the surface too hard. The **Distance/force** feedback is needed in order to cope with this issue. Currently, we are progressing on adding force sensors or distance sensors to do feedback to the errors.

In addition, cutting mechanism and tape retaining mechanism are also needed to cope with tape cutting and applying new tape segments.

4 Execution of the taping process

This module allows the robot system to execute the taping process based on the generated path. An example of taping a cylindrical surface is shown in Fig. 15 (a). Example of taping freeform surfaces and grooves are shown in Fig. 15 (b) and 15(c). With the system capability in taping different features, more complex part can be taped based on proper segmentation into features inside the class. In the actual case, most of the workpiece are either rotationally symmetrical or freeform features. Therefore, the introduced strategy can cover the majority of the parts. The extremely difficult minor parts can be handled by other methods or by human work.

(a) (b) (c)

Fig. 15 Taping process of the automatic robot taping system: (a) Taping of cylindrical-like surfaces; (b) taping of freeform surfaces; (c) taping of grooved surfaces

5 Conclusions and discussion

This paper discusses on the strategies and methods to do the robot path planning for covering a workpiece surface using masking tapes. The strategies in surface segmentation and the methods for the path generation on different surface features are introduced. Based the introduced methods, most of the workpieces can be covered by a taping system automatically. This technology is useful for surface protection of components in plasma spraying, spray painting, etc.

Taping strategy: For a specific application, the number of parts for taping is limited. Therefore, a practical method is to apply human heuristic method to assist in building a taping strategy data. For each part, the experienced workers will advise on the key taping parameters—Area segmentation, taping direction, the type of tape, overlap of tape layers, initial points and tape cuttings, etc. Such database can be applied on the path planning of a part after a part matching process.

Accuracy: Taping is a surface covering process where the surface covering method is the most critical. The accuracy is just moderate since the tasks can be completed within the tolerance of a few millimeters. However, to attach the tape on the surface, the taping tool needs to press the tape to the surface and apply some force for the attachment. This can be achieved based on compliant mechanisms on the end-effector. Precise force feedback can be helpful, but it also adds extra costs to the system.

Taping speed: In surface covering based on taping, the priority is the quality instead of speed. Human taping is very slow, but human can handle very complex surface geometry with good quality (taping speed of human is normally several cm/s). For a robot the taping tools and the path need to be carefully considered in order to ensure good taping quality and a higher speed.

In very complex scenarios, a more suitable method is to let robot tape the major part, and let worker finish the minor but most challenging parts to ensure the efficiency. For a specific part, a standard processing flow can be

provided—Surface, segmenting methods, type of tape, sequence of surface covering and methods to use. Manual work needed could be the last step.

Such taping solution with the taping system and the taping strategies can be applied in many industrial applications involving surface covering process.

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