

Automatic Robot Taping: Auto-Path Planning and Manipulation

Qilong Yuan, Teguh Santoso Lembono, Yuhua Zou, I-Ming Chen, *Fellow, IEEE*

Abstract—Many industrial applications, such as painting, plasma spraying, require people to work long hours to cover the uninvolved part with masking tapes. In this paper, we introduce an automatic robot taping system which can reconstruct the 3D model of the taping part, do path planning and complete the surface covering of the parts using masking tapes automatically. The system uses a Kinect as the 3D scanner to acquire the 3D point clouds of the taping part. Based on the digital 3D points cloud model of the part, we introduce a path planning method to generate the moving path of the systems. A rotary platform and a 6-DOF robot arm collaborate together to execute the robot taping process. For continuous taping, the system and method can handle Tubular shapes. Experiment of taping a cylindrical shape is conducted to validate the system and method. For parts with more complex geometry, further development on the automatic initial tape attaching and cutting mechanism is needed. With such system, the taping work can be much less troublesome. Also, the path planning method applies to applications such as drawing or writing on different surfaces etc. as well.

I. INTRODUCTION

Industrial robot is now widely used in many manufacturing applications. The robot machining, spraying [1, 2], welding, robot finishing [3], pick and place are well developed technologies widely applied in the industrial robot workcells. In these robot automation tasks, the robot end-effectors are specially designed to meet the needs for the specific tasks. The robot-environment interaction during traditional robot manipulation can be point contact, like welding, surface contact, like finishing. In tasks like painting and spraying, there is no direct contact between the robot and the object, but there are orientation requirement on the tools. The geometry of the part to be painted need to be known in order to make a good path planning and auto-painting [1, 2, 4, 5].

A more complex robot automation task is auto-taping. Taping process is required in many industrial applications such as packaging, roping armature paper while making motors, taping for iron pipes etc. Taping regular shapes can be easily done through using some standard taping machine [6, 7]. However, if the geometry of the taping parts become complex, the taping problem becomes complex. As a result, such taping works are mainly done manually. For example, in plasma spraying, the uninvolved parts need to be covered by masking tapes. Such operation based on a skilled works will request half days work for a complex mechanical part. It is expected that this job can be done by robotic system. But, to realize this, we firstly need to acquire the 3D model of the

parts for taping. Also, we need to have way to make the path planning in order to make the automatic taping possible.

Taping requests the tape to be properly attached to the surface of the parts and with some certain overlapping while covering the entire area of interests. This requires: (1). the precise acquisition of the parts to be taped. (2). Special design of the taping robot end-effector. (3). strategies to make the proper taping possible. Because, during the taping, not only the contacting point of taping but also the surface normal vector are all important for the taping end-effector to follow in order to do proper taping.

In the manual taping, the worker see the geometry of the parts and use his hand to control the orientation of the tape. At the same time, the worker uses his finger to press and push the tape to make sure that the tape is nicely attached to the surface of the part. In the overall process, the taping path should be properly planned in order to let the tape cover the entire area of interests.

To realize the automatic robot taping process, we need devices to “see” the objects. Thus, devices to get the model description of the part are needed in order to provide computer understandable data. We also need a robot to realize the taping motion, provided a capable end-effector is designed to realize the human hand function. And we still need to have planning strategies to let the robot to follow the taping path to realize the complete taping task. It is understandable that it is better to have feedback control of the end-effector to cope with the errors in the modelling and robot manipulation. But if it is too complex and/or not economical, we can design some proper compliance mechanism to compensate the errors.

In this paper, we introduce a system and corresponding methods for automatic robot taping. In the system, a 6 degree-of-freedom robot arm and a rotating platform is used to do the auto-taping. To get the geometry of the part, we apply the commercial 3D scanner sensors (Microsoft Kinect, or Artec Eva scanner) to get the point cloud of the part based on the open source KinFusion program [8, 9]. With the point clouds, it is very handy to calculate the surface normal vector [10]. Based on the digital 3D model file of the part reconstructed from the 3D scanner, the taping paths for the robot system to follow and the angular trajectory of the rotation platform are planned, following a path planning strategy that we proposed in this paper.

The remaining part of the paper is organized in the following manner. Section II introduced the system setup for the robot taping. Section III described the path planning of the robot taping motion. Section IV provides the experimental results. Then, the paper is briefly concluded in Section V.

All authors are with School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 597627 (I-Ming Chen, phone: 67906203, e-mail: michen@ntu.edu.sg; Qilong Yuan. phone: 65-84545660, e-mail: yu0017ng@ntu.edu.sg).

II. PLATFORM DESIGN

In this automatic robot taping system, a 6 DOF robot manipulate and a one DOF rotating platform is applied. As shown in Figure 1, the taping part is fixed on the rotating platform. During the system initialization, the relative position between the robot manipulator and the rotating platform is calibrated.

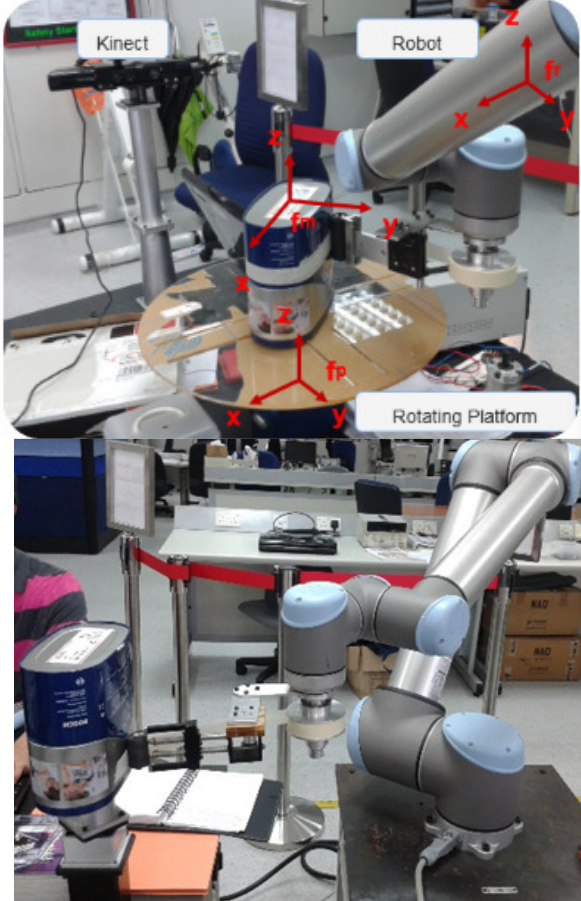


Figure 1: Automatic taping system with rotating platform

Then, a 3D scanner, Kinect sensor is used to get the 3D point cloud model of the taping part. The point cloud model from the scanning results can be processed to digital 3D model of the part with surface location and surface normal information. With the resulting 3D model of the part and the robot kinematics, the taping paths of the rotating platform and the robot manipulator are generated.

A. Rotating platform

The one DOF rotating platform is driven by a controllable stepper motor so that it can be controlled to rotate a certain degree during a short period of time. In this way, the rotation platform can collaborate with the robot manipulate to conduct the taping tasks. The different rotating pattern of the platform will affect the taping path of the robot. Therefore, in this taping process, the rotating pattern can be potentially used for optimization of the robot path planning in terms of working space and manipulability etc.

B. Robot End-Effector Design

The taping tasks require proper contact between surface of the taping object and the tape. In human manual taping, the finger of the worker presses the tape along the taping orientation in order to guarantee the taping quality. In the automatic taping, a special mechanism is designed to replace the function of the human figure. In this work, we designed a taping end-effector as shown in Figure 2, the rear part holds the tape roller and guide the tape. The front part serves as a compliance ‘finger’ to press the tape to the surface and compensate some of the manipulation errors from the rotation platform and the robot arm. The stiffness of the spring is about 2000N/m. During the taping, the spring mechanism is pressed with 0.3cm allowing about 10N contact forces to press the tape. This spring mechanism can compensate the error from the scanning results and the robot manipulation.

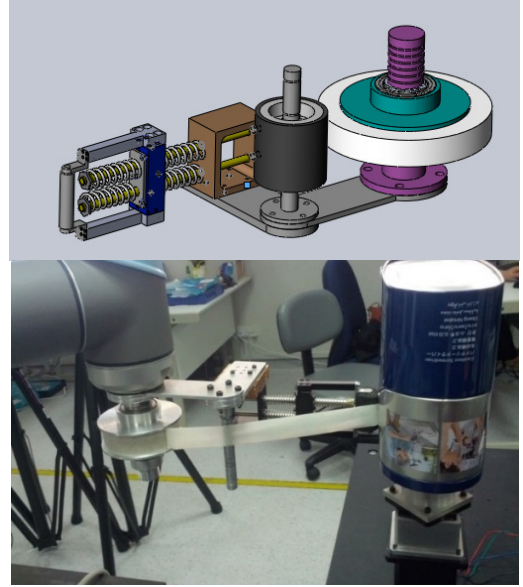


Figure 2: The taping end-effector

C. 3D scanning

In the 3D scanning model generation, the Kinect sensor is fixed aside from the rotating platform with the part fixing on it. The platform rotate for three round, during which the 3D point cloud is generated based on the scanning algorithm, KinFusion for Kinect sensors. After the scanning of the model, some post process of the model are still needed such as hole filling, merging multiple scanning results, deleting internal points etc. Then, the surface normal vector can be calculated based on the point cloud model afterwards. Please take note that, the 3D model after the scanning is with respect to the initial frame of the scanner. It need to be transformed back to the initial reference frame of the rotating platform in order to make the path planning possible. This can be done through putting some reference marker at the platform system and let the scanner “recognize” the relative position between itself and the rotating platform.

Let T_{RC} represent the posture of the camera initial frame with respect to the platform reference frame f_p . Then, all the points $P_{i,C}$ in the scanning model represented in f_p becomes:

$$[P_{i,R}^T, 1]^T = T_{RC} [P_{i,C}^T, 1]^T \quad (1)$$

Accordingly, the normal vectors $v_{i,C}$ in the scanning model represented in f_p becomes:

$$[v_{i,R}^T, 0]^T = T_{RC} [v_{i,C}^T, 0]^T \quad (2)$$

After transforming the model to the platform reference frame, the path planning of the taping manipulation is possible.

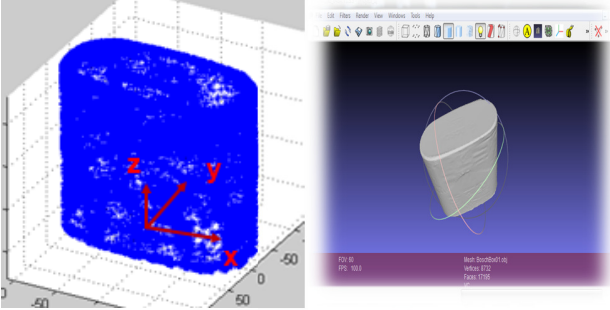


Figure 3: 3D scanning results

III. PATH PLANNING AND OPTIMIZATION

In the general case, a part with arbitrary geometry can be very complex. Thus, the taping of such parts requires detail planning on how to tape specific area and where to cut the tapes in order to cover the entire surface nicely and, try to use as less tape. This request a cutter to automatically cutting the tape and attach the tape subsequently. Currently, without cutting the tape, we mainly discuss on continuous taping without cutting the tape. For a mechanical parts fixed on the rotary platform, surface geometry can be very different. The taping strategies for different shapes are also not unique. Here, we start with Tubular shapes and shapes similar to that as shown in Figure 4, because such shapes are very common and have very high chance for taping in practice. After taping the vertical surface, the flat surface part can be taped based on the flat surface covering method.

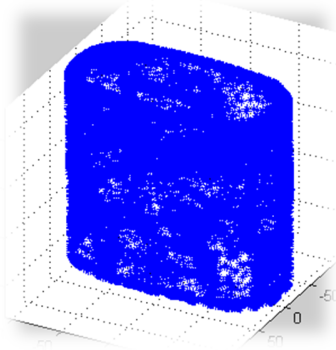


Figure 4: Shapes for taping in this study

In the 3D model reconstruction based on the 3D scanner, the digital model including the point cloud and the calculated surface normal are represented in the scanners initial reference frame. After the taping part is fixed on the rotating platform, the part will rotate together with it. Therefore, this digital model will also change after a rotating motion. Therefore, how the rotating platform moves, will also affect the robot moving path.

In the taping process, the rotating platform holds the part for taping. While the platform rotate, the robot taper need to

contact nicely with the surface of the part and with proper orientation in order to make a nice taping. Therefore, this is actually a collaboration between the robot taper and the rotating platform.

When we observe a manual work taping a mechanical part, the worker sits in front of a desk and puts the part on a passive rotary platform on the desk. He is mainly manual rotating the platform while taping, trying to tape the part mainly in front of himself. By doing so, his operating space is within a very small area and thus saves the cost of energy. Similarly, in order to let the automatic robot taping system save space and energy cost, we also try to let the robot arm move mainly in neighborhood of its “front”. Therefore, in the robot path planning, we can adjust the rotation pattern and the robot taper to optimize the taping process, to minimize effort (energy) of robotic system for example.

A. Path Planning Algorithm

In the taping process, we start from the bottom of the taping area. The path planning method is shown below.

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 detailed method is as follows
 - a. $Int\ i=0; \theta=0$
 - b. When $\theta < 360$, $\theta = \theta + d\theta; i=i+1$; Search the surface point v_i in neighbourhood best satisfying (h_0, θ) . $S=S+|v_{i-1}v_i|$
 - c. $i=0; \theta=0$
3. Determine the “pitch angle” (Equivalent to screw pitch if the part is cylinder) of the tape (p) based on the perimeter:

$$\text{Pitching angle (in rad): } p = (1 - r)d_t / S$$

where r is the overlap rate of the tape. Here $r=20\%$.

Then start the path planning.

The main idea is to update the pitching angle and robot end-effector pose to make sure the tape is properly taped to cover the surface with the given type overlapping.

4. $\theta = \theta + d\theta; i=i+1$.
5. Search the surface point v_i with normal vector $v_{n,i}$ in neighbourhood best satisfying (h, θ) .
Then: $h=h+p|v_{i-1}v_i|$ (This is the press point in the taping path planning).
6. If $\theta > 360$, then $i=0; \theta=0$ and update S and p in the same way as in 2 and 3.
7. Decide on the rotation angle θ_r of the rotary platform and convert the 3D model data to the reference frame:

$$v_i = Rotz(\theta_r)v_i \quad (3)$$

$$v_{n,i} = Rotz(\theta_r)v_{n,i} \quad (4)$$

8. Calculate the robot pose based on $(v_i, v_{n,i}, p)$.
9. If $h < h_{max}$, go to 4.

Using the example Part model for taping, we made a path planning. Figure 5 shows the taping path on the part surface. The purple points cloud represents the model. The blue line shows the surface normal direction (useful for controlling the robot end-effector pressing direction). The green circle shows the taping roller while taping. The red color represents the tape covered on the surface.

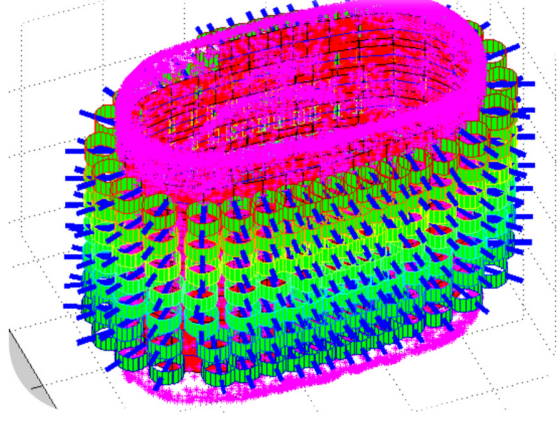


Figure 5: The taping path on the part surface.

Figure 5 only provides the relative path on the end-effector. While the motion of the robot manipulator depends on the moving pattern of rotating platform, as explained in the 7 step of the path planning. The rotating pattern will effects the moving efficiency of the robot arm. For now, we mainly tested on two rotating patterns, one is continuously rotating the platform and the robot mainly move in and out and adjust its taping posture. A better solution is to rotate the platform every 90 degree and stop to let the robot arm finish taping the corresponding part and rotate another 90 degree.

B. Determination of the end-effector pose

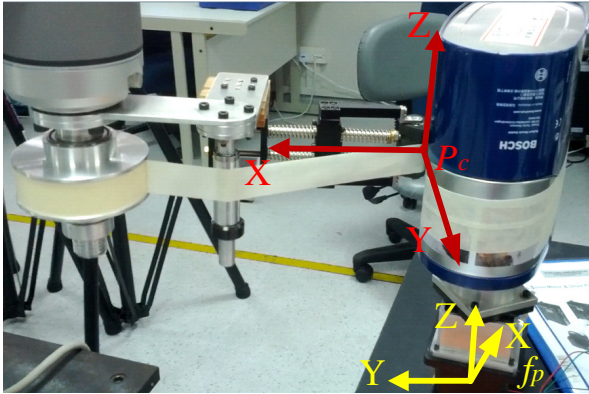


Figure 6: Taping End-Effector Posture Definition.

Once the taping point is known, its position P_c and its surface normal $v_{i,c}$ with respect to the rotating platform is known. In this work, we let the end-effector pressing direction follow the surface normal direction. As indicated in Figure 7, the x -axis of the end-effector follows the normal vector direction on the surface.

$$x_p = v_{i,c} \quad (5)$$

Y axis is defined to be in the tangential direction of the surface and with th pitch angle of p , the pitch angle of the tape.

$$y_p = Rotx(p)([0,0,1]^T \times x_p) \quad (6)$$

$$z_p = x_p \times y_p \quad (7)$$

Then, the posture of the robot with respect to the rotary platform T_p can be determined [11, 12] by the following equation,

$$T_p = \begin{bmatrix} x_p & y_p & z_p & P_c \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (8)$$

This end-effector need to be presented in the robot base frame in order to use the robot inverse kinematics to solve out the robot joint angles. Let T_{BP} be the relative pose between the robot base frame and the platform reference frame determined during the system initialization. In the robot base frame, the end-effector pose is,

$$T_B = T_{BP} T_p. \quad (9)$$

In the actual taping execution, initially, the robot end-effector arrive at the initial taping point with a pre-determined posture. For now, we still need people to assist in the initial attaching of the tape.



Figure 7: Tape attached at the initial point when taping starts

After the path planning, the rotating trajectory of the rotary platform and the corresponding robot manipulating path are determined. Then, the system can apply the data for automatic robot taping.

IV. EXPERIMENT

The process of the robot taping is illustrated in Figure 8. The taping part is firstly fixed on the rotating platform. Then the system initialization is conducted to figure out the relative position between the robot manipulate and the rotary platform. The fixing location of the parts is also calibrated. Then, the scanning of the 3D point cloud is conducted. After a simple editing of the 3D digital model, the model is passed to the path planning software to generate the motion of the robot and rotary platform. Then, the system start to execute the automatic taping.

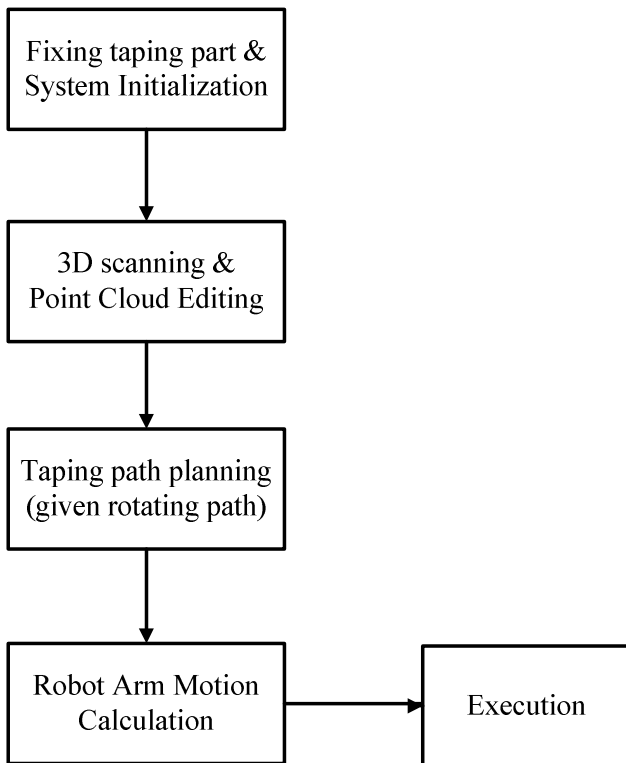


Figure 8: The working flow of the system

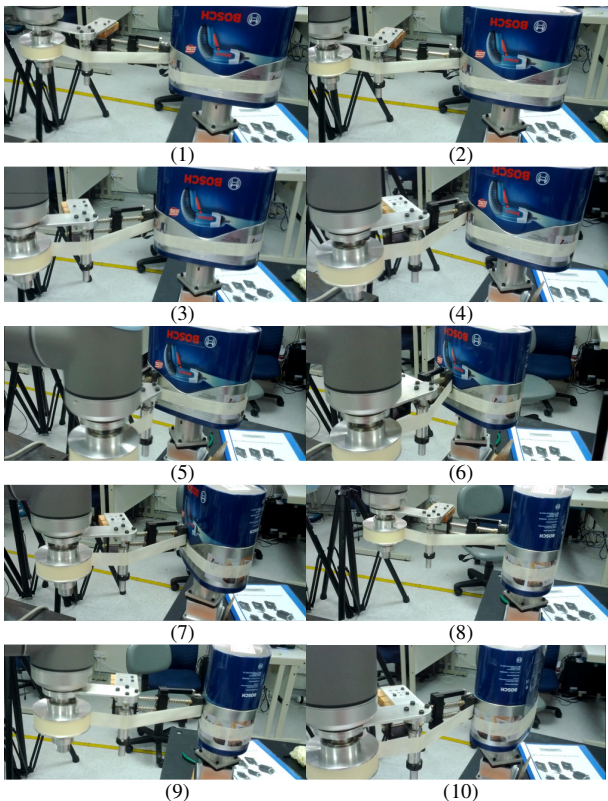


Figure 9: Taping process of the automatic robot taping system
 An example of the taping process is illustrated in Figure 9. Figure 10 shows the completed taping model.

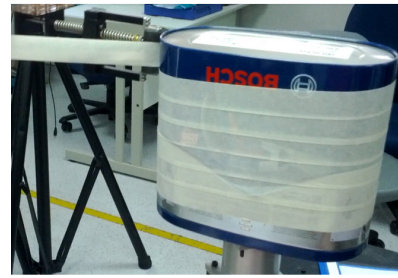


Figure 10: Completed taping results

The whole process takes within 2 minutes for current operating speed. The system can further speed up for fast processing. When we try manually to make the taping, firstly, we cannot attach the tape with a correct pitch angle. Meanwhile, it is very difficult to get the tape go to the correct direction with nice taping results. It takes time to get a worker trained to make faster and better taping or other skillful works. From these point of views, robot automation in such work is helpful. But of course, if the task is very complex with various conditions, it requests more programming works and special design of the mechanical system.

V. CONCLUSION

This paper introduced the setup and corresponding method of an automatic robot taping system. This system includes a 3D scanner, a rotating platform and a 6 DOF robot manipulator to realize the auto scanning and auto-taping task. The 3D scanner is used to reconstruct the 3D model of the parts to be taped. Based on the 3D points cloud, and the robot system, a path planning method is introduced to generate the robot moving path and the rotating platform motion.

Currently, the system and method mainly handle the continuous taping of Tubular like shapes. Further development on the automatic initial tape attaching and cutting mechanism is needed to make the system fully automatic and available for more complex geometry. Considering time consuming manual work of the taping process in workcells, the automatic robot taping system can be more efficient and save people out of this tiring work.

The path planning method based on digital 3D point cloud data introduced in this work also applies to applications such as drawing or writing on different surfaces as well. Therefore, based on the automatic 3D scanning and some robotic system, robotic systems can be developed to do these tasks on not only parts with known regular geometry but also parts with complex shapes.

ACKNOWLEDGMENT

This work was supported in part by the Agency for Science, Technology and Research, Singapore, under SERC Grant 12251 00005.

REFERENCES

- [1] W. Chen and D. Zhao, "Path Planning for Spray Painting Robot of Workpiece Surfaces," *Mathematical Problems in Engineering*, vol. 2013, 2013.
- [2] A. Gasparetto, R. Vidoni, D. Pillan, and E. Saccavini, "Automatic Path and Trajectory Planning for Robotic Spray Painting," in *Robotics*;

Proceedings of ROBOTIK 2012; 7th German Conference on, 2012, pp. 1-6.

- [3] C. Ng, K. Chan, W. Teo, and I. Chen, "A method for capturing the tacit knowledge in the surface finishing skill by demonstration for programming a robot," in *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, 2014, pp. 1374-1379.
- [4] H. Chen, T. Fuhlbrigge, and X. Li, "Automated industrial robot path planning for spray painting process: a review," in *Automation Science and Engineering, 2008. CASE 2008. IEEE International Conference on*, 2008, pp. 522-527.
- [5] S. Larsson and J. A. Kjellander, "Path planning for laser scanning with an industrial robot," *Robotics and autonomous systems*, vol. 56, pp. 615-624, 2008.
- [6] W. J. Hottendorf, "BOX TAPING MACHINE," ed: Google Patents, 1972.
- [7] N. Horiguchi, Y. Kaneko, and S. Uda, "Feeder of wrapping paper for coin wrapping machine," ed: Google Patents, 1992.
- [8] S. Izadi, D. Kim, O. Hilliges, D. Molyneaux, R. Newcombe, P. Kohli, *et al.*, "KinectFusion: real-time 3D reconstruction and interaction using a moving depth camera," in *Proceedings of the 24th annual ACM symposium on User interface software and technology*, 2011, pp. 559-568.
- [9] R. A. Newcombe, A. J. Davison, S. Izadi, P. Kohli, O. Hilliges, J. Shotton, *et al.*, "KinectFusion: Real-time dense surface mapping and tracking," in *Mixed and augmented reality (ISMAR), 2011 10th IEEE international symposium on*, 2011, pp. 127-136.
- [10] N. J. Mitra, A. Nguyen, and L. Guibas, "Estimating surface normals in noisy point cloud data," *International Journal of Computational Geometry & Applications*, vol. 14, pp. 261-276, 2004.
- [11] J. McCarthy, *Introduction to theoretical kinematics*: MIT Press, Cambridge, MA, 1990.
- [12] R. Murray, Z. Li, S. Sastry, and S. Sastry, *A mathematical introduction to robotic manipulation*: CRC, 1994.