# An Automatic Laser Scanning System for Objects with Unknown Model

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***Abstract*—Laser scanning has been widely used in the industrial manufacturing, especially in reverse engineering, quality control and surface defect detection. Achieving automatic scanning can succeed in reducing production costs and increasing production efficiency. This paper proposes an automatic intelligent scanning system based on ROS, including robot arm, RGBD camera and line laser scanner. The system is designed to scan objects with unknown model and we use high precision calibration methods to improve the accuracy of the system. A novel scanning trajectory planning strategy is developed, including three steps. Firstly we plan preliminary trajectory based on the RGBD camera data. Then the robot arm pose is adjusted with PID controller in real time to optimize the scanning results. Finally, according to the distribution of point cloud density, the portion whose density is lower than the threshold will be re-scanned. The experiment we illustrate shows the feasibility and high accuracy of our system.**

***Index Terms*—Automatic scanning, Hand-eye calibration, Trajectory planning, Point cloud processing**

## I. Introduction

Laser scanning widely exists in the industrial manufacturing field and abundant research results have been reported so far, see for example [1]–[4]. Many companies have produced high-precision arm laser scanners for manual scanning. These devices are expensive, and the operators need professional training before doing scanning tasks. With the development of social economy, labor costs are constantly increasing. Automatic scanning can reduce production costs and improve production efficiency.

A common method of automatic scanning is to mount a laser scanner on a mechanical device. By accurately measuring the displacement of the mechanical device, the scanned data is converted into a unified coordinate system for stitching. S. Larsson proposed a flexible and controllable laser profile scanning device, in which industrial robots are used as translation devices [5]. But for objects with unknown model, Larssons thinks that automatic measurement is inferior to manual measurement, especially when measuring accuracy is concerned. In [6], S. Yin demonstrated an integrated robotic system, including precise linear guides and laser sensors, to improve system efficiency and measurement accuracy. But, the system can not adapt to different measured objects.

We believe that the key technologies for achieving real automatic scanning including scanner and mechanical calibration as well as mechanical scanning trajectory planning. In terms of calibration, J. Li proposed a calibration method for three-dimensional(3D) laser scanning system, in which the Levenberg-Marquardt algorithm is used for the calibration of the laser scanner and the robot arm to solve the rotation matrix part [7]. But he did not mention the automatic trajectory planning of sensor scanning. Dong [8] and Francisco Vasconcelos [9] proposed methods for extrinsic calibration of a camera and a line laser scanner. However, these methods require a high-precision camera, and the calibration error between the camera and the machine affects the final scanning result. In terms of trajectory planning, S. Y. Chen proposed a model-based automatic positioning method for robot vision sensors [10]. Tasks included determining the optimal location of the sensor and the shortest path through those viewpoints. In [6], the CAD files of known objects were used as reference data, which were transformed into 3D point cloud data to automatically generate robot arm trajectories. This trajectory did not provide an optimal sensor orientation but set it to a constant value, which can only accommodate two-dimensional simple planar conditions. These researches can only be applied to the field of inspection and verification processes. Moreover, it is often only possible to achieve good results for a few objects. For objects with unknown model, it may be necessary to redesign the algorithm.

In many cases we are unable to obtain the CAD model of the workpiece in advance. For active 3D target recognition and unknown object models, the system tends to be an iterative active sensing system. This system typically performs the acquisition of multiple views of the target, establishes a random

3D model of the target, and determines the position of the next best view [10]. S. Y. Chen developed a new mathematical model to describe the surface trend. The next best view of the sensor pose can be decided on the partially known model [11]. But this system lacks sufficient stability and requires manual intervention. In [12], a complete automatic scanning strategy for unknown objects was developed, which was based on classifying the measured surfaces into barely and well visible, and combined with the best view selection algorithm. However, this method requires a large amount of calculation, which is not conducive to real-time adjustment of the trajectory. This produces errors between the two optimal viewpoints.

In this article, we present a ROS-based automatic intelligent scanning system consisting of robot arm, RGBD camera and line laser scanner, which is for scanning objects with unknown model. The RGBD camera is used to automatically recognize the workpiece on the processing platform, and extract the point cloud with low quality of the work piece. The preliminary scanning trajectory is planned based on the results of this rough scanning result. The line laser scanner is fixed to the end of the robot arm. During the actual scanning process, the end of the robot arm scans along the preliminary trajectory. The PID controller is used to control the scanner pose in real time to optimize the scanning results. The final scanning results will be transformed to the robot arm coordinate system, and the transformed data can be directly used for trajectory planning of painting or welding operations.

## II. Unifying Coordinate Systems

The intelligent scanning system proposed in this paper is shown in Fig. 1. It consists of a robot arm, a RGBD camera, a line laser scanner and a processing platform. The flow of the system is shown in Fig. 2. Before the use of the whole system, an essential step is to unify the coordinate systems by connecting the visual sensor coordinate systems with robot arm base coordinate system, which is called hand-eye calibration.

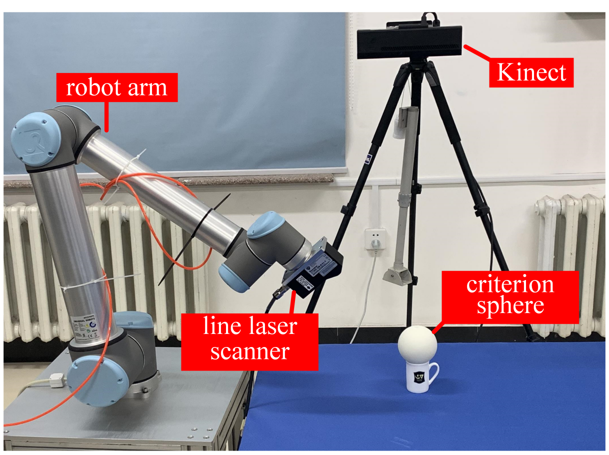


Fig. 1. Hardware diagram of the automatic scanning system.

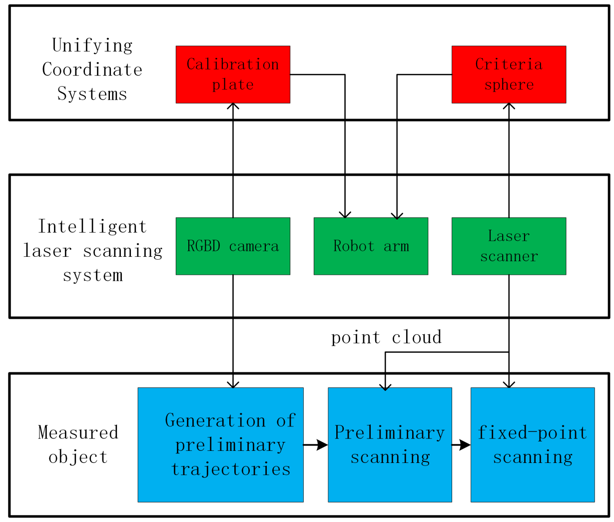


Fig. 2. The flow of the automatic scanning system.

The entire system involves two hand-eye systems: an eye-to-hand system consisting of an RGBD camera and a robot arm, and an eye-in-hand system consisting of a line laser scanner and a robot arm. The final accuracy of the scanned data will be affected by the calibration accuracy, so it is necessary to improve the hand-eye calibration accuracy.

### A. Calibration of RGBD camera and robot arm

For workpieces with unknown model, RGBD camera can be used to locate and identify them, and then the scanning trajectory can be used to plan preliminary scanning trajectory. The system uses Kinect V2 as the visual device to collect point cloud information in the workspace. Kinect V2 is a common cheap RGBD camera. Its accuracy is low, but its field of vision is large, which meets the needs of the system. The collected point cloud will be used for preliminary trajectory planning of the robot arm in the base coordinate system. Therefore, eye-to-hand calibration of the robot arm and the camera is needed to get the transformation matrix which is used to convert the point clouds into the base coordinate system of the robot arm.

In this system, the Kinect V2 and the base of the robot arm are relatively fixed to form eye-to-hand system. A calibration plate is fixed at the end of the robot arm during the calibration. The eye-to-hand calibration involves the calibration plate coordinate system $C_b$, the robot base coordinate system $C_r$, the robot end coordinate system $C_e$ and the Kinect camera coordinate system $C_k$.The homogeneous transformation matrix from $C_b$ to $C_e$ is $\mathbf{T}_b^e$, which is difficult to measure accurately. The homogeneous transformation matrix from $C_c$ to $C_b$ is $\mathbf{T_c^b}$, which can be obtained by Zhang's calibration method [13]. The homogeneous transformation matrix from $C_e$ to $C_r$ is $\mathbf{T}_e^r$, which can be obtain by getting data from the robot arm control cabinet. The homogeneous transformation matrix from $C_c$ to $C_r$ is $\mathbf{T}_c^r$, which is to be determined by calibration. The transformation relation of coordinate system satisfies the equation:

$$(\mathbf{T}_b^c)_i = \mathbf{T}_r^c (\mathbf{T}_e^r)_i \mathbf{T}_b^e \tag{1}$$

By measuring the corresponding data of different positions and postures of robots, we can get simultaneous equation:

$$(\mathbf{T}_b^c)_{i+1} (\mathbf{T}_b^c)_i^{-1} \mathbf{T}_r^c = \mathbf{T}_r^c (\mathbf{T}_e^r)_{i+1} (\mathbf{T}_e^r)_i^{-1} \tag{2}$$

Assume that $\mathbf{A} = (\mathbf{T}_b^c)_{i+1} (\mathbf{T}_b^c)_i^{-1}$, $\mathbf{B} = (\mathbf{T}_e^r)_{i+1} (\mathbf{T}_e^r)_i^{-1}$. $\mathbf{A}$ represents the transformation relation of the coordinate system of the calibration plate in two motions, and $\mathbf{B}$ represents the transformation relation of the coordinate system of the end of the robot arm in two motions. The solution of $\mathbf{T}_c^r$ converts to the solution of $\mathbf{AX} = \mathbf{XB}$ [14].

After hand-eye calibration, the point cloud is transformed into the base coordinate system of the robot arm. The point cloud coordinates are limited to the region of interest by using a through filter. In this way, the background information in the collected point cloud can be deleted, and only the point cloud within the processing platform can be retained. In order to locate the workpiece accurately and extract the workpiece point cloud precisely, we use random sample consensus algorithm to extract the processing plane point cloud, so as to segment the workpiece point cloud.

### *B. Calibration of line laser scanner and robot arm*

The line laser scanner is fixed to the end effector of the robot arm, which is controlled to scan along the planned trajectory. In order to stitch the point cloud data collected by the laser scanner, it is necessary to transform them into the same fixed coordinate system. The robot arm base coordinate system is chosen as the unified reference coordinate system. Therefore, hand-eye calibration of the line laser sensor and the robot arm is needed.

For a point in space, its coordinates in the line laser scanner coordinate system are $\mathbf{p}$. And its coordinates in the robot base coordinate system are $\mathbf{q}$. The homogeneous transformation matrix of the line laser sensor coordinate system $\mathrm{C}_l$ to the arm end joint $\mathrm{C}_e$ is $\mathbf{T}_l^e$. The homogeneous transformation matrix of the end effector coordinate system to the robot arm base coordinate system is $\mathbf{T}_e^r$. Then there is a conversion relationship: $\mathbf{T}_e^r \mathbf{T}_l^e \mathbf{q} = \mathbf{p}$.

For a fixed point in space, its coordinates $\mathbf{q}$ are unchanged in the base coordinate system. Assume that $\mathbf{T}_\mathrm{x}$=$\mathbf{T}_l^e$, $\mathbf{T}_\mathrm{o}$=$\mathbf{T}_e^r$. In the two measurements, it is easy to obtain $\mathbf{T}_{oi}\mathbf{T}_\mathrm{x}\mathbf{q}_i$=$\mathbf{p}_i$, $\mathbf{T}_{oj}\mathbf{T}_\mathrm{x}\mathbf{q}_j$=$\mathbf{p}_j$. According to $\mathbf{p}_i$=$\mathbf{p}_j$, we can get the simultaneous equation

$$\mathbf{T}_{oi}\mathbf{T}_\mathrm{x}\mathbf{q}_i = \mathbf{T}_{oj}\mathbf{T}_\mathrm{x}\mathbf{q}_j \tag{3}$$

Expand equation(3) to obtain

$$\mathbf{R}_{oi}\mathbf{R}_\mathrm{x}\mathbf{q}_i + \mathbf{R}_{oi}\mathbf{t}_\mathrm{x} + \mathbf{t}_{oi} = \mathbf{R}_{oj}\mathbf{R}_\mathrm{x}\mathbf{q}_j + \mathbf{R}_{oj}\mathbf{t}_\mathrm{x} + \mathbf{t}_{oj} \tag{4}$$

The calibration process is carried out in two steps.

- Assume that $\mathbf{R}_o$ is unchanged in the two measurements, in other word, the robot arm has only translational motion. Equation (4) can be resolved as

$$\mathbf{R}_\mathrm{x}(\mathbf{q}_i - \mathbf{q}_j) = -\mathbf{R}_o^{-1}(\mathbf{t}_{oi} - \mathbf{t}_{oj}) \tag{5}$$

  The optimal solution of $\mathbf{R}_\mathrm{x}$ can be obtained by SVD algorithm.
- Assume that $\mathbf{R}_\mathrm{o}$ is changing in the two measurements, equation (4) can be resolved as

$$-(\mathbf{R}_{oi} - \mathbf{R}_{oj})\mathbf{t}_x = (\mathbf{t}_{oi} - \mathbf{t}_{oj}) + (\mathbf{R}_{oi}\mathbf{R}_x\mathbf{q}_i - \mathbf{R}_{oj}\mathbf{R}_x\mathbf{q}_j) \tag{6}$$

  The optimal solution of $\mathbf{t}_\mathrm{x}$ can be obtained by least squares method.

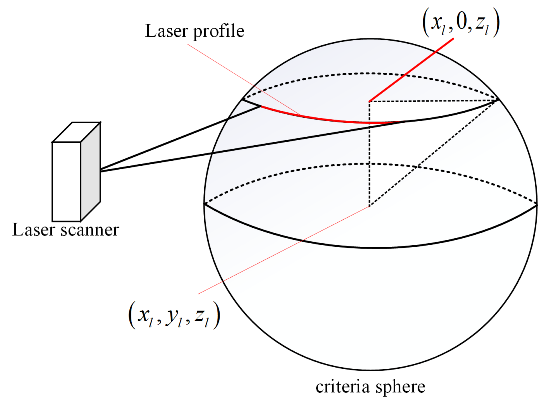


Fig. 3. Geometric constraints of the laser projection on the sphere

In practical scanning, the cross section of the standard sphere is scanned to ensure that the line laser scanner scans the same point in space accurately. As shown in Fig. 3, the laser projection on the sphere is an arc. We fit the arc by least squares and calculate the center of the cross section. From the geometric constraints, it can be seen that in the sensor coordinate system, the $x$,$z$ coordinates of the center of the sphere and the center of the cross section are equal. It is easy to know that the $y$-axis component of the spherical coordinate satisfies $|y| = \sqrt{R^2 - r^2}$, and its positive or negative sign needs to be determined according to the actual situation in the actual measurement. In the calibration process, the ball remains stationary in the robot base coordinate system, so the above method indirectly ensures that the line laser scanner scans the same point.

## III. AUTOMATIC SCANNING SYSTEM

In 3D reconstruction or reverse engineering, most of the researches are carried out in two directions: focusing on the method of manually specifying the scanning process [5] and focusing on finding the next best view [12]. The former has the disadvantage of being too experienced, and the latter also has the disadvantage that the modeling process is complicated and cannot adapt to complex situations in real time. The overall scanning process of the trajectory planning algorithm used in this system is divided into three steps: the preliminary trajectory generated by rough point cloud information, the preliminary scanning based on follow-up control, and the fixed-point scanning based on the partially known model.

In order to obtain point cloud data with sufficient accuracy, the line laser scanner needs to maintain a reasonable positional relationship with the measured object. The sensor needs to be kept in the optimal sampling state when planning the trajectory, so we need to make the following constraints on the optimal measurement distance and the optimal measurement angle of the laser scanner.

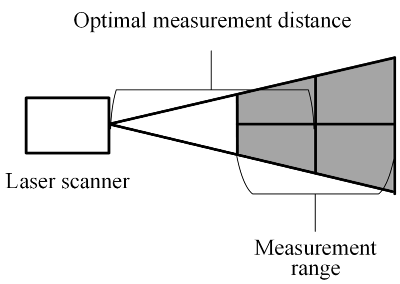


Fig. 4. Optimal measurement distance of the laser scanner.

- Optimal measurement distance $d_0$ of the laser scanner. According to the user manual of the laser sensor, in order to ensure the reliability and accuracy of the data, the laser sensor scanning has a certain range of requirements. In this system, the optimal measurement distance is 130mm, which is the optimal distance from the origin of the laser sensor coordinate system to the surface of the measured object.
- Optimal measurement angle $\theta_0$ of the laser scanner. When the Z-axis unit vector of the laser sensor $\overrightarrow{Z}$ is parallel to the normal vector of the surface of the measured object $\overrightarrow{n}$, the reliability of the data is the highest [15]. Therefore, the optimal angle of the laser sensor is 0 degrees.

### A. Generation of preliminary trajectory

The Kinect can approximate information such as the size, height, and center of mass of the object. This information can be used to plan the preliminary trajectory. The system adopts a layered scanning strategy, and the scanning process from the top to the bottom can be approximated as a general plane scanning.

*1) Determination of the number of slices:* The number of slices is related to the length of the object on the slice direction, the lateral measurement range of the sensor, and the geometry of the object. The slice direction is determined by the direction of the main axis of the actual scanned object point cloud. The number of slices can be estimated by dividing the length of the object on the slice direction by the field of view of the sensor. When scanning, the point cloud information can be used to re-correct the data while calculating the appropriate number of slices.

*2) Determination of single layer trajectory:* Trajectory computation based on the point cloud is actually the intersection of a set of planes and point clouds. Kinect scans back the data information to get the point cloud data of the workpiece. The whole process is divided into three steps:

- In the first step, one slice plane is placed along the slice direction, and the outline of the workpiece point cloud data on the slice is obtained. However, it is impossible to strictly determine the points on the slice plane to form contour lines. Therefore, before the intersection contour is obtained, the point cloud data is divided into blocks along the slice direction. That is, two planes are placed at equal positions on the left and right sides of the slice plane, and the distance is 1/2 slice thickness.
- In the second step, find the matching point pair between the left area and the right area.
- In the third step, the intersection of the matching point and the slice plane is found by the matching point, and thus the slice contour is connected.

### B. Preliminary scanning based on follow-up control

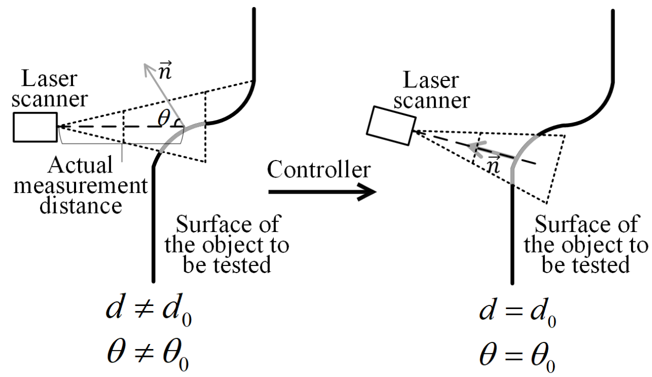


Fig. 5. Real-time adjustment of laser sensor scanning parameters

In order to make the laser scanning effect the best, the optimal measurement distance and the optimal measurement angle of the laser sensor must be met during the scanning process. Therefore, it can be converted into a control problem of the horizontal displacement and the angle $\theta$ of the laser sensor in the original planned path. These two quantities are controlled separately using a PID control algorithm.

As shown in Fig. 5, through the PID controller, the position and orientation of the end joint of the arm at each control cycle can be obtained, thereby controlling the laser scanner to be within a reasonable working range.

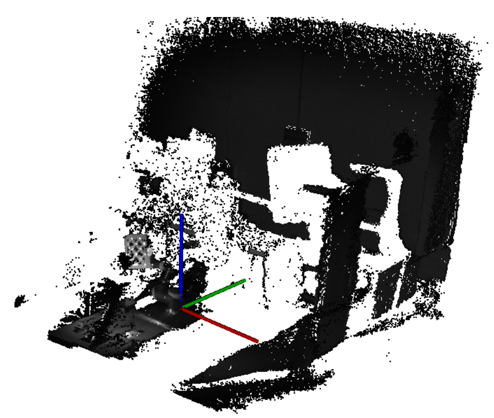

Fig. 6. Hand-eye calibration result of the Kinect and the robot arm

### C. Fixed point scanning

A rough model of the object can be obtained after the preliminary scanning, but there are cases where the local model is inaccurate or not collected. Through these point cloud data, the distribution of point cloud density will be calculated. The parts below the set threshold will be found. A fixed-point scanning of the part is performed to ensure the accuracy of the scanned model. It is assumed that there are $n$ points or regions to be scanned at this process. The reasonable viewpoints of the laser sensor can be approximated according to the constraints of the laser sensor. We plan a shortest path to make the laser scanner pass through these reasonable viewpoints.

## IV. EXPERIMANTAL RESULT

### A. Calibration part

The calibration result of transformation matrix $\mathbf{T}_c^r$ is

$$\begin{bmatrix} 0.9997488 & -0.0120486 & 0.0188955 & -0.2295753 \\ -0.0195863 & -0.0600595 & 0.9980026 & -2.2819675 \\ -0.0108897 & -0.9981220 & -0.0602804 & 0.0728615 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The raw point cloud collected in Kinect V2 camera coordinate system can be transformed into the robot base coordinate system as shown in Fig. 6. It can be conveniently used for further processing in the robot arm base coordinate system.

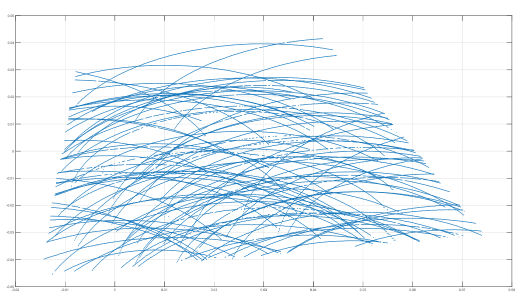

Fig. 7. Raw data in the line laser scanner coordinate system

The raw data of the laser sensor is shown in Fig. 7. It can be seen that all the data are in the $x-z$ plane of the line laser sensor coordinate system. The calibration result of transformation matrix $\mathbf{T}_l^e$ is

$$\begin{bmatrix} 0.6900752 & 0.7137504 & 0.1198181 & -0.0396042 \\ 0.703790 & -0.7003962 & 0.1188428 & 0.0050568 \\ 0.1687443 & 0.002316 & -0.9856571 & 0.1973421 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

According to the calibration result, the original data arm transformed into the robot arm base coordinate system, as shown in. 8. These data are the projection of the laser on the calibration sphere, so when converted to the robot arm base coordinate system, they will be on a sphere.

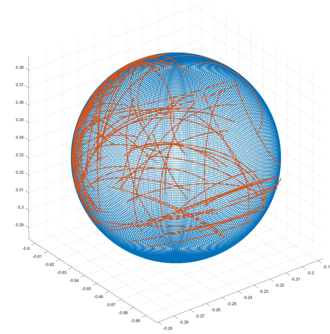

Fig. 8. Line laser scanner data transformed to the robot arm base coordinate system

### B. Scanning part

In the test scenario, there is a mouse to be scanned on the processing platform. The raw point cloud obtained by Kinect V2 is shown in Fig. 9. The result of segmentation of the processing platform and the mouse is shown in Fig. 10. The extracted mouse point cloud from the original point cloud is shown in Fig. 11.

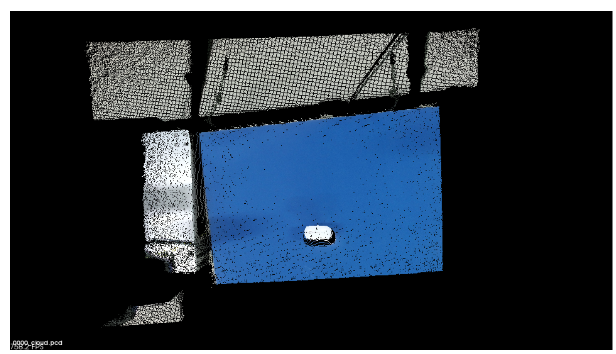

Fig. 9. Raw point cloud obtained by Kinect V2

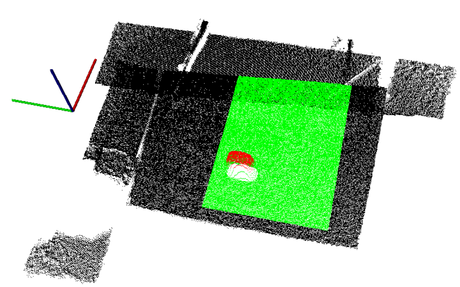

Fig. 10. Result of segmentation of the processing platform and the mouse

The tarjectory planned based on the extracted point cloud is shown in the Fig. 12. The scanning result of the mouse shown in Fig. 13 is shown in Fig. 14. Experiments show that the calibration methods adopted in this system can accurately transform the point cloud collected by the Kinect and the line laser scanner into the robot arm base coordinate system. It can accurately locate the workpiece and plan the scanning trajectory in the robot arm base coordinate system. The final scanning results show that the system can be used to scan objects with unknown model.

## V. CONCLUSION

This paper presents a low-cost, high-precision intelligent scanning system. The system combines a line laser sensor, an RGBD camera, and a robot arm to enable automatic scanning of unknown objects. The composition of the system is described in detail. We also detail the calibration of the RGBD camera and the laser sensor, and verify the accuracy and reliability of the calibration through experiments. After calibration, we can convert the scan results of the laser sensor into the base coordinate system of the robot. Then, the stitching of the point cloud of the measuring object is completed. In terms of trajectory planning, we propose an innovative step-by-step scanning strategy. The point cloud of the RGBD camera is used to plan the preliminary trajectory, and the PID controller is used for real-time adjustment during scanning. Finally, the parts of the model that need to be refined will be scanned again. This trajectory planning strategy achieved good results in the experiment. However, this system may have large errors for complex objects with unknown model, and human intervention is still needed in these cases. The future work is mainly to enhance the adaptability and accuracy of the scanning system and achieve automatic scanning of complex objects.

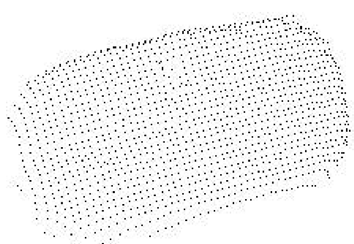

Fig. 11. Mouse point cloud extracted from raw point cloud

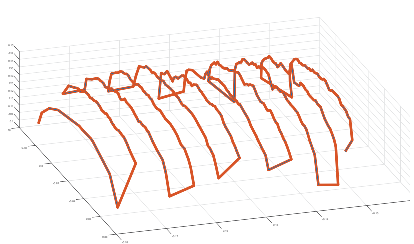

Fig. 12. Trajectory planned based on the point cloud of the mouse

Fig. 13. Mouse with unknown model

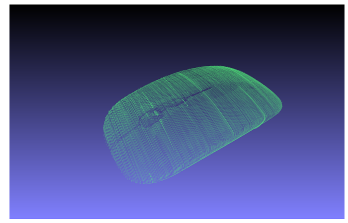

Fig. 14. Scanning result

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