ANY-DEGREE-OF-FREEDOM REGISTRATION OF THREE-DIMENSIONAL SURFACES WITH UNBALANCED DEVIATIONS

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INTRODUCTION

Registration of 3D surfaces [1] is one of the most important and most widely used technologies for the characterization of the target 3D surfaces. Since the reference surface and the target surface are normally in different coordinates, coordinate transformation is done by registration to register the target surface to the reference surface for further data processing such as determination of the deviation from the target surface to the reference surface.

A lot of research has been devoted to study various methods for registration of 3D surfaces. The most famous one is iterative closed points (ICP) method [2] and its variations [3]. Other methods are also commonly seen in the literatures such as least square method [4] and intrinsic feature method [5]. Most of the methods are used for full degree of freedoms (DOFs), i.e. for 3D surfaces there are 6 DOFs including 3 DOFs for translations along x, y, z axes and 3 DOFs for rotations around x, y, z axes. For characterization of high precision 3D surfaces such as ultra-precision freeform surfaces, 6 DOF methods may be the most reasonable methods since these methods utilize all the available DOFs for the rigid-body transformation to minimize the deviation from the target surface to the reference surface, i.e. the cost function directly related to the difference between the target surface and the reference is minimized.

In many other cases such as characterization of the influence function of fluid jet polishing [6], bonnet polishing [7], where the target surfaces usually have large unbalanced deviations regarding to the reference surfaces, registration with full 6 DOFs may result in unwanted tilting or shifting, although the deviation from target surface to the reference is minimized. This is because the large unbalanced deviation affects in a specific DOF which is not reasonable according to the a priori knowledge.

In this paper, an any-degree-of-freedom (ANY-DOF) registration method is presented for registration of 3D surfaces with unbalanced deviations. With the a priori knowledge or pre-processing technology, the target surface and the reference surface are firstly aligned with some simple features such as plane and sphere and hence some specific DOFs are fixed. After that, the target surface and the reference surface are then registered with the remaining DOFs using the proposed ANY-DOF method. The K-dimensional-tree (Kd-tree) data modelling and Levenberg-Marquardt method are utilized for solving the ANY-DOF registration problem. With proposed method, the unwanted DOFs alignment can be avoid to have a better characterization result of the target surface.

ANY-DEGREE-OF-FREEDOM (ANY-DOF) REGISTRATION METHOD

The any-degree-of-freedom (ANY-DOF) method is shown in FIG. 1. The reference surface is firstly modelled with the Kd-tree modelling method [8]. The measured surface is then transform using the transformation matrix with the unknown variables according to the desired DOFs registration. The nearest neighbours from the transformed surface to the reference surface are determined and the distances are calculated with the help of the Kd-tree model. The cost function aims to minimize the distance and the nonlinear problem is solved by the Levenberg-Marquardt method. Hence, the unknown variables are determined and the final transformation matrix for the ANY-DOF registration is solved.

It is interesting to note that the number is variables can be from 1 to 6, which means it can be any of the combinations of the translation along x, y, z axes and rotation around x, y, z axes. The Kd-tree data modelling is employed to speed up the search of nearest neighbour points.

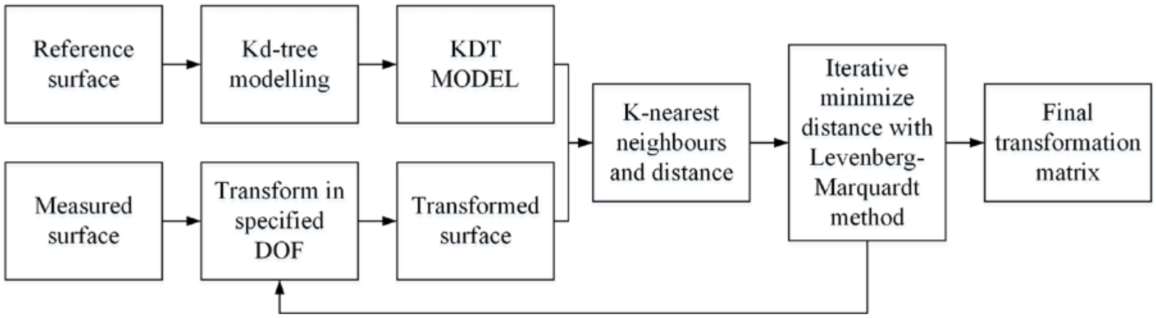

FIGURE 1. Diagram of the ANY-DOF registration method

In the Levenberg-Marquardt method, an initial value is given and usually setting the initial values to zeros is effective. The rigid-body transformation has 6 DOF, i.e. translation along x, y, z axes and rotation about x, y, z axes, representing the yaw, pitch, and roll angles. The translation matrix can be determined by

$$T_x(v_x) = \begin{bmatrix} 1 & 0 & 0 & v_x \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$T_y(v_y) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & v_y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$T_z(v_z) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & v_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where v_x, v_y, and v_z are the translation variables along x, y, z axes. The rotation matrix can be determined by

$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) & 0 \\ 0 & \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$R_y(\beta) = \begin{bmatrix} \cos(\beta) & 0 & \sin(\beta) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\beta) & 0 & \cos(\beta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$R_z(\gamma) = \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) & 0 & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

where α, β, and γ are the rotation variables about x, y, z axes.

The final transformation matrix with all 6 DOFs can be determined by

$$M = R_x(\alpha)R_y(\beta)R_z(\gamma)T_x(v_x)T_y(v_y)T_z(v_z) \quad (7)$$

For the ANY-DOF method, the final transformation matrix is the matrix multiplication of any of translation matrix or rotation matrix of the specific DOF. For the point set P of the target surface, the transformed point set P' can be determined by

$$P' = PM \quad (8)$$

Assume point set X represents the reference surface, the cost function is determined by

$$F = rms(D) \quad (9)$$

where D is the vector of the shortest distances from every point in X to P'. Solving the registration problem is minimizing the cost function which is a non-linear least squares problem, and this is done with the Levenberg-Marquardt algorithm. The variables to solve is the translation and rotation according to the DOF and the variables are initial to be zeros and iteratively solved with the Levenberg-Marquardt algorithm.

EXPERIMENTS AND DISCUSSIONS

In order to verify the effectiveness of the proposed method, two experiments were conducted with different DOFs for the registration and the results are compared to the traditional ICP method so as to demonstrate the advantage of the proposed method.

Registration with 3 translations + 1 rotation

The first experiment considers 3 translations along x, y, z axes and 1 rotation about z axis. The experiment is to register the measured surface to the simulation surface after fluid jet polishing [6]. Since the actual measured surface has large distortion in some area comparing to the simulation surface, this will introduction large rotation error about x and y axes in the traditional 6 DOF registration process. In this experiment, the DOF for rotation about x and y axes are fixed and remains the 3 translation and rotation about z for registration.

The simulation surface is shown in FIG. 2 and the measured surface is shown in FIG. 3. The data shows that there is significant difference between the simulated surface and the measured surface.

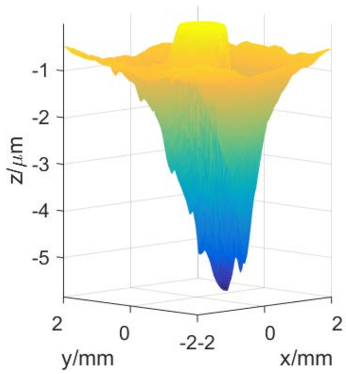

FIGURE 2. Simulated surface

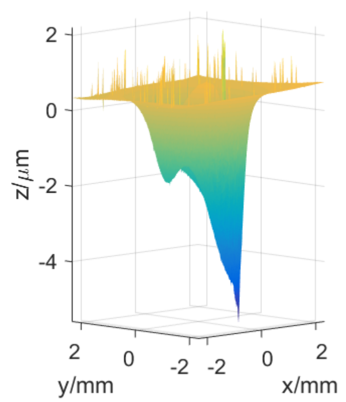

FIGURE 3. Measured surface

The registration result using the proposed method is shown in FIG. 4 while that for ICP method is shown in FIG. 5. The result using the proposed method shows good alignment of the two surfaces while that by using the ICP method shows a large rotation error. Without any constraints, the rotation error is caused by the large difference between the simulated surface and the reference surface. With the proposed method, since the rotation about x and y axes are fixed, the registration is only performed on the specific DOF.

Registration with 3 translations

Another experiment is done where only 3 translations are considered. The data is also obtained from fluid jet polishing. Since the data is supposed to be rotational symmetry, the rotation about z axis is not consider in the experiment. The measured surface was adjusted to be without tilting using the relatively flat area before the measurement. As a result, the rotations about x and y axes are also negligible. Hence, the registration is only performed for the translations along x, y, and z directions.

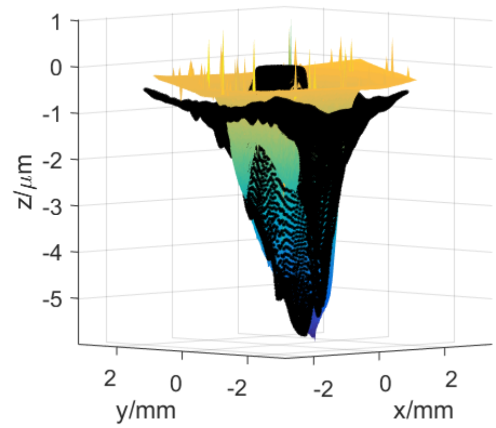

FIGURE 4. Registration result with the proposed method

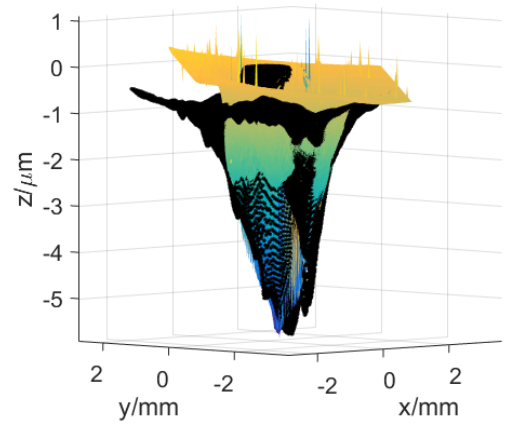

FIGURE 5. Registration result with the ICP method

The simulated surface and the measured surface are shown in FIG. 6 and FIG. 7. The registration result by using he proposed method and the ICP method are shown in FIG. 8 and FIG. 9. Similar to the result in the previous experiment, the proposed method shows a better result regarding the tilting registration using the ICP method. The large tilting result of the ICP method is due to the large unbalanced error in the measured surface, which is not expected in the ideal simulation case.

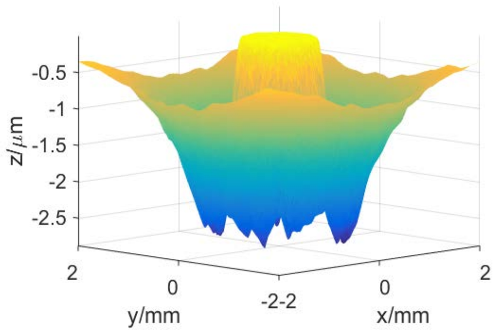

FIGURE 6. Simulated surface

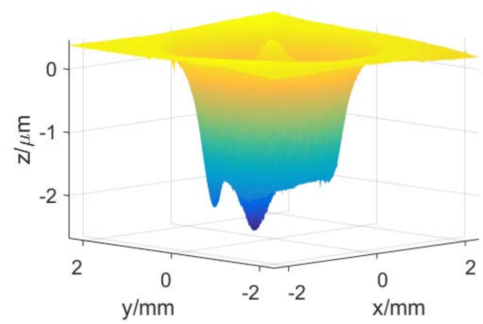

FIGURE 7. Measured surface

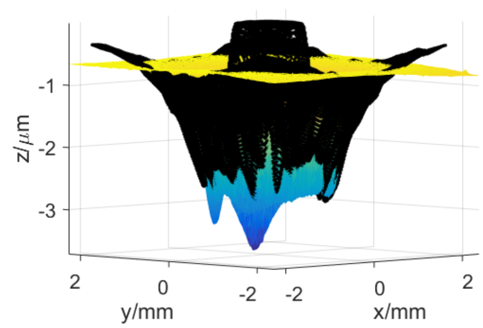

FIGURE 8. Registration result with the proposed method

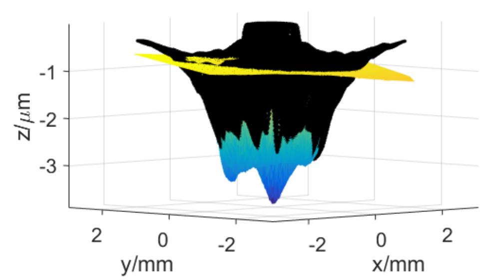

FIGURE 9. Registration result with the ICP method

CONCLUSION

An any-degree-of-freedom (ANY-DOF) method is developed for registration of 3D surfaces. Its advantage is that it can freely determine any of the DOF for registration of the target surface and the reference surface. The successful development of this method is useful for the characterization of 3D surfaces with a large unbalanced deviation to the reference surfaces.

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