A Robotic Vision System for Turbine Blade Cooling Hole Detection

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Abstract: Gas turbines are extensively used in flight propulsion, electrical power generation, and other industrial applications. During its life span, a turbine blade is taken out periodically for repair and maintenance. This includes re-coating the blade surface and re-drilling the cooling holes/channels. A successful laser re-drilling requires the measurement of a hole within the accuracy of ±0.15mm in position and ±3° in orientation. Detection of gas turbine blade/vane cooling hole position and orientation thus becomes a very important step for the vane/blade repair process. The industry is in urgent need of an automated system to fulfill the above task. This paper proposes approaches and algorithms to detect the cooling hole position and orientation by using a vision system mounted on a robot arm. The channel orientation is determined based on the alignment of the vision system with the channel axis. The opening position of the channel is the intersection between the channel axis and the surface around the channel opening. Experimental results have indicated that the concept of cooling hole identification is feasible. It has been shown that the reproducible detection of cooling channel position is with +/- 0.15mm accuracy and cooling channel orientation is with +/- 3° with the current test conditions. Average processing time to search and identify channel position and orientation is less than 1 minute.

Keywords: robotic vision, turbine blade, cooling hole, calibration

1. INTRODUCTION

Gas turbines are extensively used in flight propulsion, electrical power generation, and other industrial applications. Since turbine engines operate at very high temperature (1200-1400°C), it is very important to cool the turbine blades/vanes to reduce the thermal stress. Cooling holes/channels are passages of the coolant on the blade/vane for this purpose (Fig. 1). During its life span, a turbine blade is taken out periodically for repair and maintenance. This includes re-coating the blade surface and re-drilling the cooling holes. A successful laser re-drilling requires the measurement of a hole within the accuracy of ±0.15mm in position and ±3° in orientation.

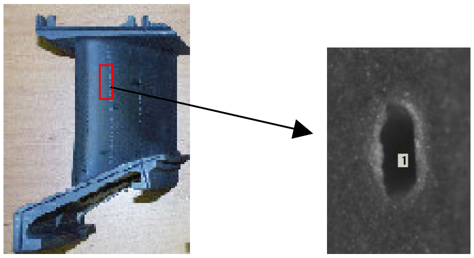

Fig.1 Turbine blade and its cooling hole (zoomed)

Conventionally, this measurement is done on a Coordinate Measurement Machine (CMM) using a cylindrical gauging pin. The pin is first inserted into a hole on a blade with the coating stripped. A number of points on the pin are then measured using CMM to construct a cylinder. The centroid position of the cylinder gives the location of the hole. This is a manual process and it is time consuming, considering that there are hundreds of cooling holes on one blade, and the measurement of a single hole takes about 2 minutes. It is also error prone due to the difficulty in tightly fitting the pin into the hole; it is obviously costly due to the lengthy occupation of CMM. Automation of the measurement process is therefore a very demanding task in the industry.

In this paper, a robotic vision system is presented as the solution. Section 2 introduces the overall system configuration. Section 3 is devoted to the calibration of the vision system. Section 4 focuses on the measurement process. The test results are then presented in section 5. The last part is the conclusion and the future work.

2. OVERVIEW OF THE MEASUREMENT SYSTEM

The implemented work cell for cooling hole measurement is basically a robotic vision system, consisting of an industrial robot, a CCD camera and a laser displacement sensor, as shown in Fig. 2. The CCD camera and the laser sensor are mounted on the end effecter of the robot. The images of cooling holes are acquired from an image grabber. The laser displacement sensor measures one-dimensional linear displacement based on the triangulation principle. Its reading can be obtained from an A/D card.

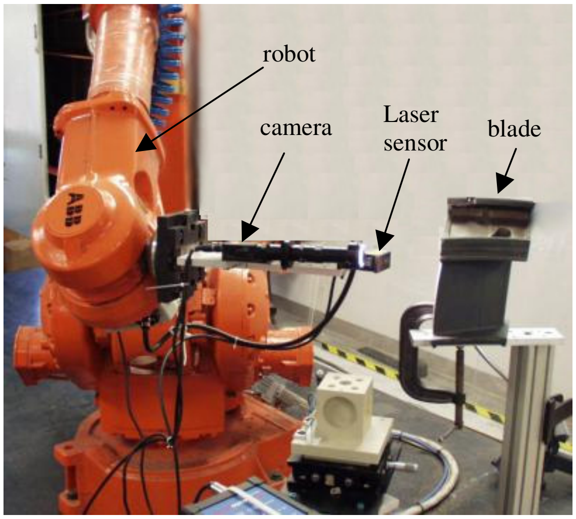

Fig. 2 Robotic Vision System

A remote PC is used for the graphic interface and the calculation. This PC controls the robot through network using communication software. The calibration & measurement software is the core of the system. On one hand, it communicates with the robot and laser sensor to acquire the current robot and tool positions; on the other hand it processes the cooling hole images to identify the hole position and orientation.

The basic idea for the determination of the cooling hole orientation is to align the camera optical axis with the hole axis. This is done by sweeping the camera around the hole axis and searching for the alignment. The criterion for the alignment is the maximization of an image feature function. When alignment is achieved, the image center of the hole opening is then detected. The orientation of the hole can be readily obtained as the ray connecting the image center and the camera lens center. The position of the hole opening is simply the intersectional point between the hole axis and the surface around the hole opening. This surface is measured by the laser displacement sensor.

3. CALIBRATION PROCEDURE

Calibration of the vision system includes laser tool coordinate system calibration, camera intrinsic and extrinsic parameter calibration, and camera tool coordinate system calibration.

3.1 Laser Tool Frame Calibration

Assume that there is a virtual reference point *P0* on the laser beam corresponding to laser sensor zero reading. Its 3D position is (X0, Y0, Z0) in robot mounting flange (tool0) coordinate system. Also assume that the laser beam orientation is (nx, ny, nz) relative to the tool0. Then for any point *P* on the laser beam that corresponds to laser sensor reading *L*, the 3D coordinate of the point in tool0 can be calculated. The task of laser tool calibration is to determine (X0, Y0, Z0) and (nx, ny, nz) such that the laser's one-dimensional reading can be converted into a 3D position. The calibration procedure proceeds as shown in Fig. 3. The laser displacement sensor is used as a robot measurement tool to measure a reference sphere with known diameter *R*. All points measured have to satisfy the sphere equation. A nonlinear optimization algorithm then solves the unknown laser tool parameters.

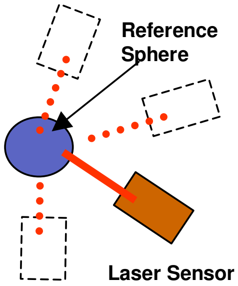

Fig. 3 Laser tool calibration

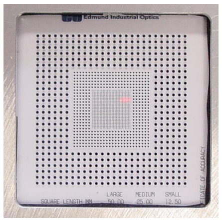

Fig. 4 distortion target for camera calibration

Table 1 shows the laser tool calibration results. The diameter of the sphere is 14.28mm. In test case 1 to 3, the sphere is located in the same position. In test case 4 and 5, the sphere is shifted 0.1mm and 0.25mm respectively.

Table 1. Laser Tool Calibration Result (length unit is mm)

test	X0	Y0	Z0	nx	ny	nz
1	-5.44	22.58	413.44	-0.02371	-0.1825	0.9836
2	-5.54	22.59	413.41	-0.01499	-0.1718	0.9856
3	-5.47	22.59	413.42	-0.00710	-0.1718	0.9856
4	-5.54	22.58	413.39	-0.00342	-0.1640	0.9867
5	-5.39	22.63	413.42	0.008924	-0.1682	0.9826
mean	-5.48	22.59	413.42	-0.0067	-0.1717	0.9848
std	0.062	0.019	0.016	0.013	0.0068	0.0016

3.2 Camera Tool Frame Calibration

Camera calibration is performed in two steps. First, the intrinsic and extrinsic camera parameters are calibrated with respect to a reference based on the well-known Tsai's coplanar RAC algorithm [1][2]. A commercially available dot-patterned distortion target is used as the reference (Fig. 4). The dot center-to-center spacing accuracy is within +/-2.5um.

In the second step, the camera tool coordinate system relative to the robot mounting flange (tool0) is obtained from the chained relations among the camera, the distortion target and the robot. The relative location of the distortion target in the robot base frame is measured using the calibrated laser tool.

Camera calibration accuracy was verified with several tests. The first test was to compare measurements made with the calibration target in several different positions. The second set of tests was to compare measurements made with the calibration target in several different orientations. For translation tests the target has been shift from –1.1mm to +1.1mm around its best focus position. The increment size is 0.127mm (0.005 inch). For rotation tests the target has been rotated 2, 4, 6, and 8 degrees. Fig 5 compares the measurement results of the target movement by using a micrometer and the developed vision system.

4. Measurement Procedure

Since the laser re-drilling and the hole measurement system use different work cells, all the measurement results have to be converted with respect to a local coordinate system defined on the measured blade/vane. This requires the calibration of the blade/vane coordinate system with respective to the robot base coordinate system, which is done by using the laser sensor.

With the current accuracy of the industrial robot, it is extremely difficult to achieve the 150um measurement error. Instead, a relative measurement strategy is adopted which relies only on the robot's 70um repeatability. For each type of turbine blades, a reference blade (called master blade) is first measured with the traditional method using CMM. Then this master blade is measured again by the robotic vision system. An error compensation scheme is determined. During the measurement of the actual blades, the robot moves with the same path, and the measurement results are compensated according to the identified error scheme.

4.1 Determination of cooling hole orientation

The hole orientation is searched by rotating the robot around its nominal orientation to align with the channel axis. The area of the cross section of the channel opening image (shown in Fig. 1) is used to determine the best alignment position, as illustrated in Fig. 6.

4.2 Determination of cooling hole position

The position of the hole opening is simply the intersectional point between the hole axis and the surface around the hole opening. This surface equation is obtained by measuring several points on the surface using the laser displacement sensor.

5. TEST RESULTS

The robot used for the tests is an IRB 4400 from ABB. The laser displacement sensor is Opto NCDT 1800 from Micro-Epsilon, having the measurement range of +/- 5mm, the working distance of 25 mm and the resolution of 1um. The camera used for image acquisition is a Sony XC-ST 50 with the resolution 640x480 pixels. The lens used (VZM 200i from Edmund Industrial optics) has a working distance of 152mm and focus depth of about 3mm. The resolution in object space is about 26 lp/mm. In order to have adequate illumination a ring light fiber optics illuminator is attached to the head of the lens.

The laser tool and camera tool are calibrated according to the procedures stated in section 3. The calibration error for the laser tool is about 80um in translation and 1 degree in orientation. The error from Tsai's coplanar RAC algorithm is about 20um in the field view of 5mm*5mm. The measurement error of the camera tool is about 70um in translation in the area of 50mm*50mm.

Limited tests have been performed on the turbine vanes following the measurement procedure in section 4. Table 2 shows the measurement result for a single hole on the turbine vane. The position and orientation of the hole as calculated from its CAD are:

X = 91.694 mm
Y = 99.404 mm
Z = -24.440 mm
nx = 0.0000
ny = -0.123412
nz = -0.992355

The results show that the measurement repeatability is about 100um for hole positions, and 2.6 degree for the orientations. The error compensation scheme is simply an offset compensation. This offset is a function of hole poison and orientation

6. CONCLUSION AND FUTURE WORK

In this paper a robotic vision system is presented to automate the measurement of turbine blade cooling holes. To meet the high accuracy requirement, a relative measurement strategy is adopted in conjunction with the sophisticated calibration of individual components in the vision system. Limited test results show that the measurement repeatability for hole position is within +/- 0.15mm and for the orientation is within +/-3 degree in the laboratory test condition. More tests are needed to investigate the system performance in terms of accuracy, easy-to-use and efficiency. In addition, the measurement results will be used by laser re-drilling process to verify the accuracy and applicability. Illumination is expected to create problems in the industrial environment. Future work is needed on automatic adjustment of the illumination and the improvement of the related image processing algorithms.

REFERENCES

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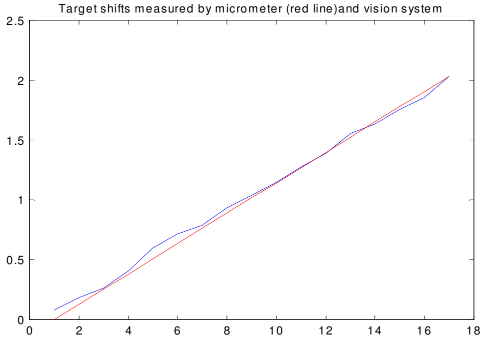
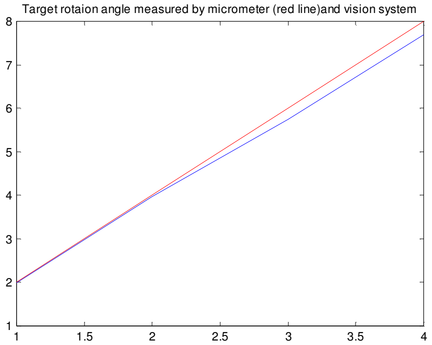


(a) target translation measurement



(b) target rotation measurement

Fig. 5 Target movement measured by micrometer and vision system (horizontal axes are commanded movement, vertical axes are measurement. The shift is in mm, the rotation angle is in degree)

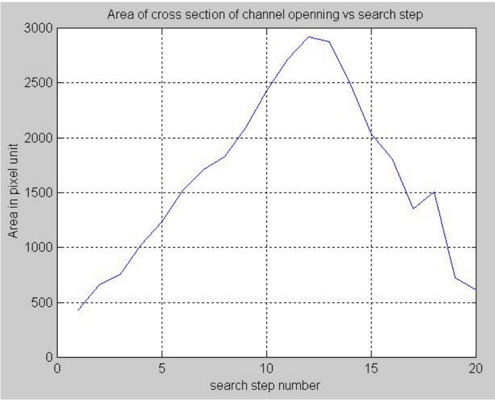


Fig. 6 Determination of alignment position based on the maximum area of the cross section of the channel opening image

Table 2. Repeatability test result for a single hole

Test number	X (mm)	Y (mm)	Z (mm)	nx	ny	nz
1	89.209	99.314	-26.011	0.005122	-0.069185	-0.997595
2	89.213	99.322	-26.002	0.005167	-0.069111	-0.997600
3	89.190	99.246	-26.082	0.005023	-0.052214	-0.998627
4	89.272	99.174	-26.153	0.005418	-0.070100	-0.997527
5	89.272	99.176	-26.150	0.005415	-0.070099	-0.997595
6	89.192	99.106	-26.225	0.005088	-0.070431	-0.997595
Mean	89.224	99.223	-26.104	0.0052055	-0.066857	-0.99773
Std Dev	0.038	0.086	0.087	0.0001500	-0.007193	0.000441
Max Dev	0.047	0.1169	0.1206	0.0002125	0.01464	0.0008968