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Integrated computer-aided verification of turbine blade

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ABSTRACT

Computer-aided verification plays an important role in turbine blade quality control as it provides a valid means to quantify the blade geometry and thereby governs the engine performance. However, this dependency on measurement accuracy could raise significant problems and present a major drawback if the computer-aided verification results were inaccurate. Since the complex blade shape poses challenge in data acquisition, measurements have to be taken from multi viewpoints to achieve the total coverage. Registration is an important step for merging multi-view data but complex for freeform blades as which do not possess distinctive intrinsic topology to guide the registration. Many researchers made efforts to solve the registration problem by hardware or software solutions. In current industry practice, the 3-2-1 approach is commonly used to determine a reference coordinate system. However, the shortcomings are that the parts are required to have plane surfaces, and very sensitive to errors. And the alignment quality cannot be guaranteed. The Iterative Closed Point (ICP) algorithms are also popular for data alignment but high computational cost. In practice, error still exists when using the ICP algorithm. Therefore, a new system is proposed by integrating inexpensive opto-mechatronic hardware as well as intelligent algorithms to simplify the turbine blade reverse engineering for downstream quality evaluation. Alignments are computed using mechanical based transformation. A k-d tree structure is used to facilitate the data matching.

Keywords: turbine blade, registration, k-d tree, reverse engineering

1. INTRODUCTION

Metrology of the complex blades shape is indispensable to ensure safety and efficiency of engine performance. Among aero-engine components, turbine blade comprises a lot of free-form surfaces based on aerodynamic/thermodynamic theory. With increasing requirements on life-span and security of aero-engines, the computer aided verification of freeform blade is of great interest in aerospace industry.

Computer-aided verification becomes a standard practice for quality control of freeform structure as it provide a valid means to quantify the complex geometry and profile tolerance. However, this dependency on measurement accuracy could raise significant problems and present a major drawback if the computer-aided verification results were inaccurate.

Coordinate measuring machines (CMM) is a well-accepted contact based solution for data acquisition because of its precision and potential automation [31]. However, its drawback for blade surface measurement is inherent slow in speed and probe accessibility problem at strong curvatures. With the advance on high speed optical technologies and the improvement on accuracy, laser systems have been widely applied for freeform measurement with efficiently capture dense point clouds. In order to build a complete 3D model, measurements data are often acquired from different viewpoints to overcome the problem of occlusion and limited field of view. As such, captured data usually are represented in its own local coordinate system; the registration process is required to relate the position and orientation of one data set to the other and integrates them into a unique reference. The process involves an initial alignment of data set followed by a refined matching procedure.

In current industry practices, the “3-2-1” approach is a common used to locate the part orientation from the reconstructed model to the CAD, in the case of “CAD to part” inspection which involves specifying six datum points from the reconstructed model manually and pairing to the counterpart on the CAD reference model for initial alignment. Then followed by

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iteration based optimization process to computationally alignment two sets of corresponding points and continually transform their motions until threshold value or zero deviation is reached for fine registration.

However current "3-2-1" practices suffer from the following limitations in blade measurement:

1. Feature point is difficult to be identified among the point clouds whether manually or automatically due to the large number of points acquired, and the lack of topological information in blade data.
2. Lack of planer surfaces is available to establish the datum plane for freeform blades
   1.3.19 Datum, Simulated: a point, axis line, or plane (or combination thereof) coincident with or derived from processing or inspection equipment, such as the following simulators: a surface plate, a gage surface, a mandrel, or mathematical simulation [ASME Y14.5-2009] [2].
3. Planes are not mutually orthogonal as points are defined on irregular blade surfaces, as depicted in Fig. 1, three on curved surface, two on the twisted edge and last on the root.
   1.3.13 Datum: a theoretically exact point, axis, line, plane, or combination thereof derived from the theoretical datum feature simulator [ASME Y14.5-2009] [2].
4. Sensitive to selection of datum points for the quality of definition of reference frame

For achieving valid blade inspection, one of the most challenging problems is to develop an efficient registration method for complex shapes. Research efforts have extensively considered solving the registration problem with either mathematic algorithms or hardware based solutions. Algorithms solutions are based on exploiting geometrical clues from the measured data; while hardware approaches are based on adding fiducial markers or external reference objects/fixtures. The solution of adhering markers is fast and reliable, but blade surfaces may not be convenient to affix labels.

In a previous work of the authors [10,14,25], the 3-2-1 method was used to determine a reference coordinate system for freeform blades. And, the fine matching of blade data is carried out by Iterative Closest Point (ICP) algorithm. In practice, however deviation between views data still exists.

Therefore, in this paper, a new system is proposed by integrating inexpensive opto-mechatronic hardware and intelligent algorithm to simplify and enhance the efficiency of the turbine blade reverse engineering (RE) for downstream quality evaluation. The system is to exploit a low-cost active positioning mechanism, non-contact laser triangulation acquisition system supported by reconstruction module based on efficient registration.

In the proposed system, we introduced the following main contributions:

1. The design of an integrated system with low-cost mechatronic hardware, developed software modules and alongside a non-contact 3D digitization system which is able to acquire full turbine blade surface data from different controlled viewpoints.
2. The development of an innovative registration procedure, which is able to perform simple alignment estimation based on the mechanical device. The concept is making use of movement parameters of the device to compute the geometric transformation between the data sets that leads to more correct initial alignment that should eliminate premature convergence.
3. Fast data searching capabilities with K-d tree which can be enhanced the efficiency of fine registration. In contrast, conventional iteration-based ICP methods require long times to calculate the correspondence set.

An overview of the related works is provided in section 2. System outline and operation are presented in section 3 and 4. The related mathematics is presented in section 5. Section 6 presents conclusion.

2. RELATED WORKS

With increasing requirements of higher precision and efficiency, and the complexity of geometry, quality control of complex shape is indispensable in aerospace industry to ensure the safety use of aerospace parts.

2.1. Turbine Blade and Freeform Structure

Blades are the most critical parts of an aero-engine, which have a lot of complex functional surfaces based on aerodynamic/thermodynamic theory. A small change in blade geometry can lead to a large change in engine performance [26]. The geometrical accuracy is the widely used to index the blade quality. However, the measurement based on the CAD model of the blade may lead to incorrect analysis as the nominal model does not represent the real geometry of physical blade due to process tolerance and subsequent wear.

For data acquisition, the whole blade is difficult to obtain from a single setup because of the complexity of the geometry. Strong curvatures at the leading and trailing edges of blades also pose challenges for measuring systems both CMM and laser. Therefore most practice of blade inspection is mainly based on the analysis in partial, in section or at the tip area. In order to build a complete 3D model, data are often acquired from different views. These captured

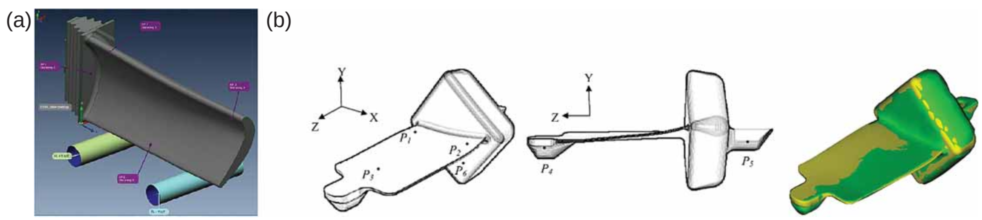

Fig. 1: Data Registration: (a) 3–2–1 approach, (b) ICP localization.

data are normally represented in their own coordinate systems, and geometrically aligning them to a common coordinate system is the registration problem. There is much evidence that an inattentive or inaccurate definition of the reference frame can lead to incorrect alignment of multi-view blades data.

Registration for the freeform blade based on the geometry approach is complex. Blades in most cases do not possess distinctive intrinsic topology and identifiable datum frames could help guide the registration was assumed. Moreover, a larger volume of measurement point is generated from non-contact system which not be organized, it also costs high processing time for data matching.

2.2. Registration

Registration process is the crucial step of an accurate shape reconstruction, to assure the blade geometry is correctly quantified. The goal is to find the Euclidean motion between a set of range data of a given object taken from different positions in order to represent them all with respect to a reference frame. The process usually takes place in two stages: an initial alignment and fine registration. Many solutions have been proposed based on exploiting clues from the measured data by mathematical algorithms. In coarse alignment, the main goal is to compute an initial estimation of the rigid motion between two sets of 3D points using correspondences between both surfaces. The most common correspondence used is point-to-point, typically established by analyzing some salient features, such as the Point Signature [8], the Spin Image [15] and the Principle Curvature [10]. Moreover, the 3-2-1 method is commonly used to determine a reference coordinate system for coordinate frame alignment. [33]

2.2.1. 3-2-1 approach

Many researchers made use of 3-2-1 approach to solve the registration problem. Hsu TH, Lai JY, Ueng WD [12] developed algorithms based on six-point principles to enhance the efficient of coordinate setup for CMM inspection of airfoil blades. However, this method only saves the coordinate setup time for CMM but not precise. Makem et al. [23] used 6 points approach to establish the coordinate system for align the blade part with the FEM model for virtual inspection of forged aerofoil blades. As shown in Fig. 1a, the 3–2–1 approach relies on six (= 3 + 2 + 1) distinct points for point clouds captured from different perspectives to be merged into one. Similarly, Yilmaz [33] presented using 3-2-1 method to align between the setting of five-axis machining operation and the dealing of digitized blade data in further inspection and surface reconstruction process with respect to a common reference frame.

However, the shortcomings of 3-2-1 approach are that the parts are required to have plane surfaces, and very sensitive to errors. Moreover, feature point is difficult to be identified among the point cloud whether manually or automatically. Besides, because of the freeform nature on the datums, the alignment quality is sensitive to the selection of those points, there is no accurate result can be uniquely decided by choosing these number of points.

As shown in Fig. 1a, the 3–2–1 approach relies on six (= 3 + 2 + 1) distinct points for point clouds captured from different perspectives to be merged into one. In fact, a minimal of three [18] instead of six corresponding points can be used for coordinate frame registration. Katz [17] presented using 3 external tooling balls to calculate the motion transformation for registering all components of the multi-sensor in the turbine blade finishing cell into a common coordinate reference.

2.2.2. Iterative Closest Point (ICP) algorithms

When an initial estimate of the relative pose is known, the Iterative Closest Point (ICP) proposed by Besl and McKay [4] is widely used for fine registration. This algorithm is one of the most popular geometry based methods for registration of the freeform shapes, which is refined the initial transformation based on minimizing the gaps in overlapping areas of adjacent views or between temporal correspondences.

Makem et al. [23] presents a virtual inspection system to assess the dimensional accuracy of aerodynamic turbine blades formed from hot-forging. They proposed ICP algorithms to refine the initial transformation results from 3-2-1 to establish the corresponding relationship between the forged model and nominal model, Fig. 1b. In practice, deviation between the measured profile and the nominal one still exists.

Zheng [34] applied points to surface best fitting technique to merge the scanned data with nominal CAD for extracting the worn area boundary for the repair process of turbine blades. The methodology included modeling the worn areas with best fitting registration technique and automation of the repair process with reconstructed model. However, they have not mentioned how to obtain the initial correspondence and define the reference coordinate system between scanned data and nominal CAD prior to the best fitting registration.

Many alternative solutions have been proposed. Chen and Medioni [27] used the distance of two surface normal as the evaluation function, instead of the point-to-point distance, but this method requires high computational cost on the nonlinear least squares optimization, and it also needs good initial pose. Masuda and Yokoya [24] introduced the least median of squares estimator to reduce the outlier effects, but it requires re-sampling in per iteration. Park and Subbarao [30] proposed the point-to-plane registration technique, but still cannot solve the complex multi-view positioning issue. Many other variants of the ICP algorithm have been proposed to improve its implementation [31–32].

However, the ICP in registration suffers from the problem of high computation cost, local minima convergence; greatly depends on good initial pose and sensitive to measuring errors. This also partially explains why the industrial solutions to in-process registration problem still resort to hardware solution. Chang and Lin [21] made use of five-axis fixture for the axial fan measurement. The proposed methodology tried to solve the overlap interference problem of fan blades. Employing targets and fixtures [33] is a fast and reliable solution to realize the registration in the measuring process.

In this work, a solution with a mechanical device and intelligent algorithms in order to address the limitation of current practices is proposed. The hardware is based on a mechanical device with positioning mechanism to obtain the initial set of transformation estimation. This approach is fast and simple when compared with the 3-2-1 approach. Fine registration is based on incorporates iteration-based algorithms.

3. SYSTEM OVERVIEW

In this research, the proposed system is based on the integration of a new design mechanical hardware system with positioning mechanism and intelligent algorithms with a non-contact 3D data acquisition system.

The idea of the system design is to perform initial transformation estimation based on the mechanical system. The concept is considering the data sets as implicitly connected by a common arbitrary oriented axis via the mechanical hardware system leads to more accurate initial alignment that should eliminate premature convergence.

The solution was made possible by positioning efficiency of the encoded stepping motor and cylindrical reference. A mechatronic device is developed to control the movement of the blade to be measured for full view capture. The movement parameters of the device are used to compute the coordinate transformation between the data sets. Iteration-based routines are used to refine the transformation for registration. Efficiency was further improved by using k-d tree structure to organize the acquired data.

The procedure consists of a number of stages which are explained below with reference to Fig. 6.

3.1. Architecture

The new integrated system (Fig. 2) consists of a new mechanical rig design, a motorized position controlling mechanism, a non-contact 3D data acquisition system, and three software modules.

The hardware rig system is designed with universal fixture hardware and a motorized control positioning mechanism. The rig is built by combining an interchangeable mechanical fixture with a motorized control mechatronic device and two positioning guides to extend the measurement flexibility.

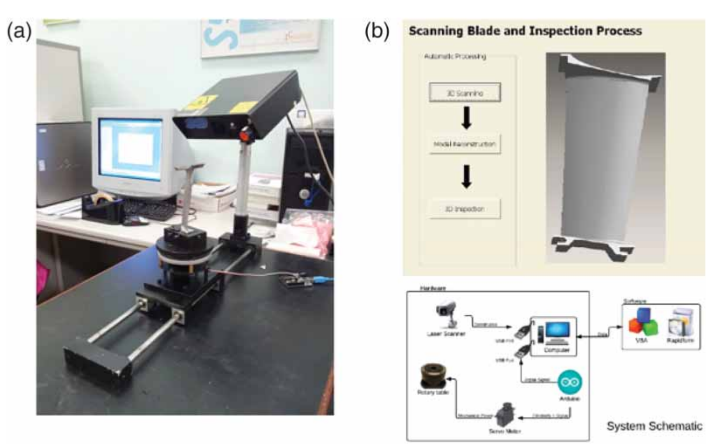

Fig. 2: (a) Integrated blade inspection system overview, (b) Software modules and hardware control.

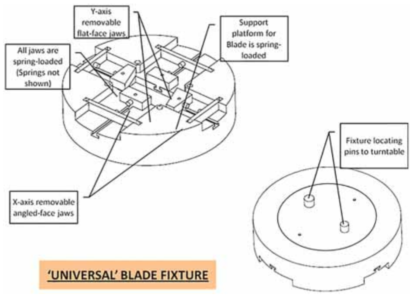

Fig. 3: Universal blade fixture.

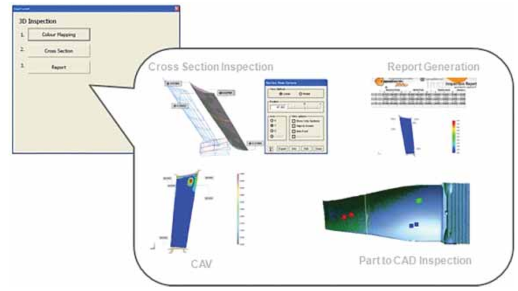

Fig. 5: Software modules : Data evaluation.

This hardware is mainly responsible for holding the blade in position and pose to pre-defined orientations for data acquisition. The placement of the blade is determined by the positioning mechanism (Fig. 4) which allows an inverse calculation of the respective position of each measurement in the global reference frame.

The universal fixture (Fig. 3) was designed to achieve adaptability to a range of blades sizes with self-centering location function.

A 3D digitizing system is capable of performing the measurements on a complex blade with sufficient accuracy. In this work, an active triangulation based 3D laser scanner, the RealScan non-contact optical measurement system is employed, shown in Fig. 2.

Three modules (Fig. 4) are developed with Visual Basic, C++ and commercial API. The first module is an interface between the user and the motor controller, mainly for controlling the movement of the mechanical rig which is developed by Arduino 1.05 Open-source software. The second module incorporates regression and transformation algorithms as well as k-d binary space partitioning tree to automatically register the multi-view scans into one point cloud. The third module is blade quality evaluation for validating the accuracy of the blade surface by analyzing 3D error and comparing cross-sectional data between the measured and the nominal solid model. Sample result is given in Fig. 5.

3.2. Operation

As presented in the paper, we built an integrated system for turbine blade inspection. The integration process as well the description of the operation is summarized in a block diagram (Fig. 7).

3.2.1. *Positioning mechanism and scanning process*

A scanning procedure has been developed to be integrated with the mechanical positioning mechanism. The design of hardware rig is shown in Fig. 3, to achieve the objective of wrap around measurement of the blade surface. The blade in a clamped position via the fixture head is located onto the rotary table, which is connected to mechanical positioning mechanism in order to control the position of the blade pose and facilitate simple multi-view data alignment.

The scanner captures data from the surface of the blade. During a scan sequence, the hardware module is rotated in order to pose different sides of the blade in front of the laser scanner for data acquisition. The

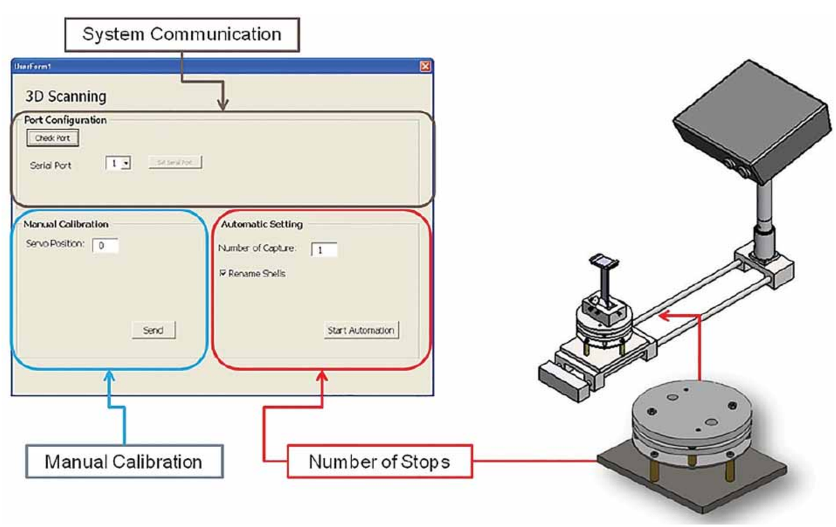

Fig. 4: Software module for part positioning and 3D scanning.

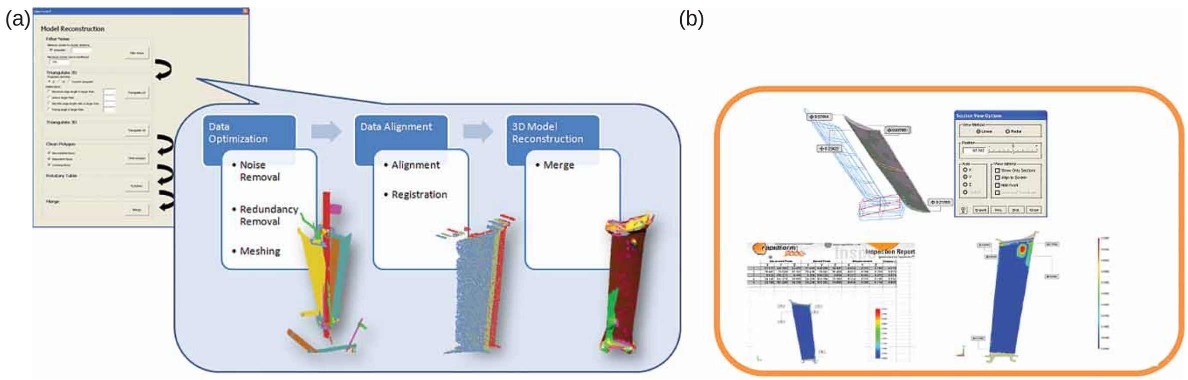

Fig. 6: (a) Workflow of 3D modeling, (b) Inspection.

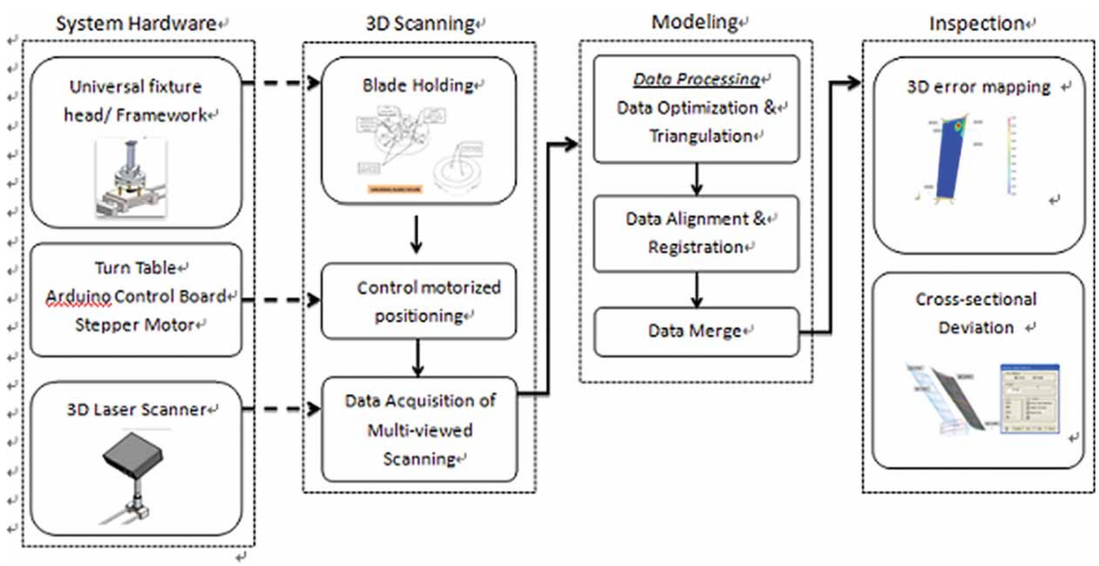

Fig. 7: Schematic diagram of the proposed system.

procedure was used to implement with the software module in Visual Basic with Rapidform API. A developed GUI was allowing users to calibrate the positioning mechanism, determine measurement setting and scanner setting.

The scanning process consists of three main phases- mechanic calibration, determine number of capture per measurement and perform data capture, as show in the flowchart shown in Fig. 6.

3.2.2. *Point clouds processing*

The "Model reconstruction" button permits the software to perform data optimization, compute the initial alignment of blade data, and refine the transformation; as shown on the GUI (Fig. 6a). Once the data acquired from the scanner, data optimization can be carried out before alignment procedure such as removal of noise and redundancy data. As the placement of the blade surface is governed by the positioning mechanism in this work. Then the initial alignment can be done based on this hardware device by an inverse calculation of the respective position of each measurement into the common reference. The registration process is further refined by minimizing the distances between temporal correspondences based on iteration-based least square algorithms. The transformation parameters are obtained by error value of minimization routines converge to a user-defined criterion.

3.2.3. *Computer-aided inspection*

Commercial Reverse Engineering software, Rapidform, inspection module has been integrated into the developed system for the 3d error analysis and cross section comparison operations (Fig. 6b). Once the acquired blade data is transformed into the coordinate system of the qualified reference model, the data points can be compared with surface of the reference blade. When the data points are matched to a reference surface, the distance between the points and surface is measured.

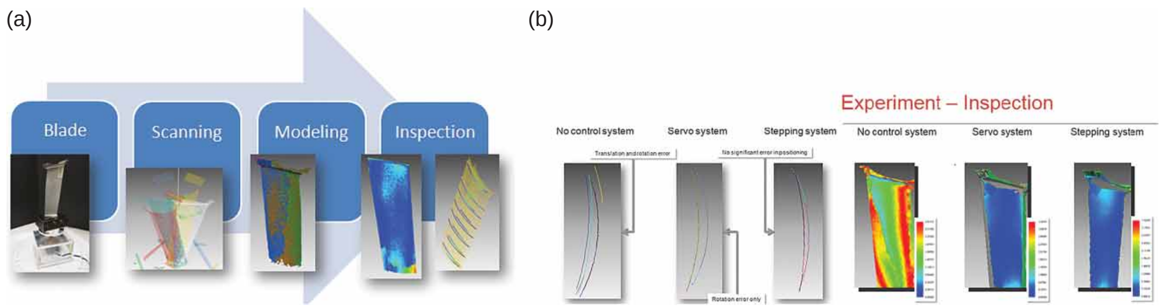

Fig. 8: Experiment (a) sample and procedure, (b) Results with different positioning approaches.

4. EXPERIMENTAL RESULTS

The feasibility of the developed system has been tested on the blade. The blade airfoil surface has a bidirectional twist and a thin cross-section as well as small edge radii. Fig. 8a, shows the blade sample, intermediate results of acquisition, modeling and inspection.

The proposed scanning process proved to be a fully automated approach for acquiring multi-view of the blade data. One of the crucial steps in the digitizing process is the determination of the number of measurements to be taken around the blade, since total digitizing time and registration results are affected. After a series of trials in our work, the optimized one is six, in order to have sufficient overlapping area between adjacent scans for data alignment. The 3D data was directly imported the modeling software for data pre-processing.

In aligning the data sets, the proposed registration process was performed. The rotation recovery in the proposed scheme was used to compute the initial transformation (Fig. 6a). In the next step, the fine registration was performed by applying a least square method and the k-d tree data storage. To obtain transformation parameters, the threshold value of error minimization routines is defined as the convergence criteria of the fitting process.

In this study, the threshold value was set to 0.3 mm by considering the sensor error, then Euclidean motion whose error value of minimization routines reach the threshold value was stopped. The final transformation parameters for the local registration procedure were obtained. In the test, the subsequent fine registration obtained fast (in less than 5 s) and accurate convergence according to the initial estimate.

Another set of tests was made on the different accurate of positioning control in order to verify the influence of the alignment procedures:-

- Manual placement- no positioning mechanism
- Servo driven mechanism- pulse based positioning control
- Stepper driven mechanism- encoded positioning control.

The test results demonstrated a good effectiveness of positioning mechanism. Fig. 8b shows the reconstruction results for three settings. It is found the one with stepper control is the best, multi-view data is well aligned with the known position. While the manual one is the worst suffer from rotation and translation error, the servo control one has the rotational error. In short, the stepper control has the best convergence in registration because of better positioning control, the one without aid of the fixture finds the wrong pose, or even diverges. Moreover, it is shown that ICP algorithms tend to have problems dealing with too many points are chosen from featureless regions of the data.

5. ALGORITHMS

Registration is a task to reliably estimate the geometric transformation such that two data can be precisely aligned. The process can be described by three components: a transformation which relates the target and source data, a similarity measure which measures the similarity between target and source data, and an optimization which determines the optimal transformation parameters as a function of the similarity measure.

5.1. Coordinate –based Transformation

Initial alignment of multi-view data is able to compute using coordinate-based transformation, by considering the data sets as implicitly connected by common arbitrary axis. The process takes place in two stages: i) locate common arbitrary axis ii) inverse arbitrary axis rotation.

5.1.1. Locate common arbitrary axis

Essentially, a least square error cylindrical surface fitting is worked out for an arbitrary axis ($\vec{P}_c$, $\hat{a}$) i.e., (Fig. 9)$\|(\vec{P}-\vec{P}_c)-(\vec{P}-\vec{P}_c)\cdot\hat{a}\hat{a}\| = r$

Acquired data: n sampled surface points from cylindrical reference object, $\vec{P}_i(x_i, y_i, z_i)$, $i = 1, \cdots, n$

Arbitrary axis: Axial point,$\vec{P}_c(x_c, y_c, z_c)$ axis direction, $\hat{a}(a_x, a_y, a_z)$

Fitting cylindrical surface:$\|(\vec{P}-\vec{P}_c)-(\vec{P}-\vec{P}_c)\cdot\hat{a}\hat{a}\| = r$

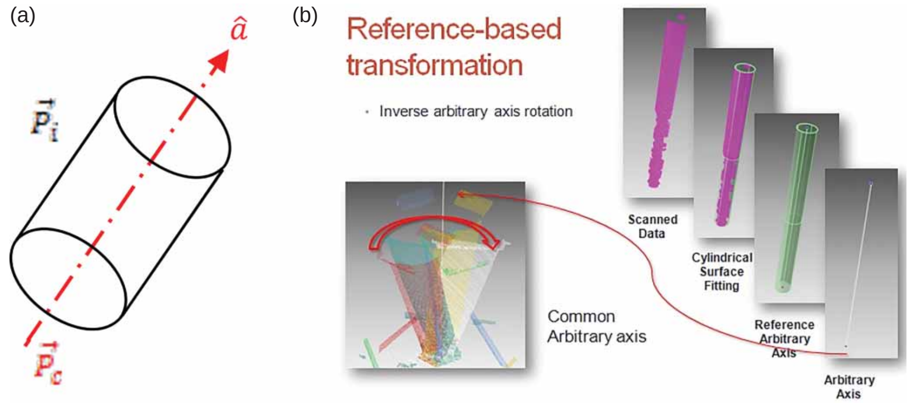

Fig. 9: Reference-based transformation: (a) Common arbitrary axis, (b) Rotation about arbitrary axis.

Cartesian coordinate form:

$$\begin{aligned}&\{(x-x_c)-[(x-x_c)a_x+(y-y_c)a_y+(z-z_c)a_z]a_x\}^2\\&\quad+\{(y-y_c)-[(x-x_c)a_x+(y-y_c)a_y\\&\quad+(z-z_c)a_z]a_y\}^2+\{(z-z_c)-[(x-x_c)a_x\\&\quad+(y-y_c)a_y+(z-z_c)a_z]a_z\}^2-r^2=0\end{aligned}$$

Simplify using $a_x^2+a_y^2+a_z^2=1$,

$$\begin{aligned}&(x-x_c)^2(1-a_x^2)+(y-y_c)^2(1-a_y^2)+(z-z_c)^2(1-a_z^2)\\&\quad-2(x-x_c)(y-y_c)a_xa_y-2(y-y_c)(z-z_c)a_ya_z\\&\quad-2(z-z_c)(x-x_c)a_za_x-r^2=0\end{aligned}$$

With fitting errors, e_i:

$$\begin{aligned}&x_i^2-2x_ix_c+x_c^2-(x_i^2-2x_ix_c+x_c^2)a_x^2+y_i^2-2y_iy_c\\&\quad+y_c^2+z_c^2-(y_i^2-2y_iy_c+y_c^2)a_y^2+z_i^2-2z_iz_c\\&\quad-(z_i^2-2z_iz_c+z_c^2)a_z^2-2(x_iy_i-y_ix_c-x_iy_c\\&\quad+x_cy_c)a_xa_y-2(y_iz_i-z_iy_c-y_iz_c+y_cz_c)a_ya_z\\&\quad-2(z_ix_i-x_iz_c-z_ix_c+z_cx_c)a_za_x-r^2=e_i,\\&\qquad i=1,\cdots,n\end{aligned}$$

$$\begin{bmatrix}-2x_i\\1\\2x_i\\-1\\-2y_i\\1\\2y_i\\-1\\-2z_i\\1\\2z_i\\-1\\2y_i\\2x_i{-}2\\2z_i\\2y_i\\-2\\2x_i\\2z_i\\-2\\-1\end{bmatrix}^T\begin{bmatrix}x_c\\x_c^2\\x_ca_x^2\\x_c^2a_x^2\\y_c\\y_c^2\\y_ca_y^2\\y_c^2a_y^2\\z_c\\z_c^2\\z_ca_z^2\\z_c^2a_z^2\\x_ca_xa_y\\y_ca_xa_y\\x_cy_ca_xa_y\\y_ca_ya_z\\z_ca_ya_z\\y_cz_ca_ya_z\\z_ca_za_x\\x_ca_za_x\\z_cx_ca_za_x\\r^2\end{bmatrix}+x_i^2+y_i^2+z_i^2$$

$$-2(x_iy_i-y_iz_i-z_ix_i)=e_i$$

$$X_{nx22}\,B_{22x1}+D_{nx1}=E_{nx1}$$

Therefore,

$$B=-(X^TX)^{-1}X^TD=-X^+D$$

Or

$$\vec{P}_c=\begin{bmatrix}x_c & y_c & z_c\end{bmatrix}^T=\begin{bmatrix}B_1 & B_5 & B_9\end{bmatrix}^T$$

$$\hat{a}=\begin{bmatrix}a_x & a_y & a_z\end{bmatrix}^T=\begin{bmatrix}\sqrt{B_3/B_1} & \sqrt{B_7/B_5} & \sqrt{B_{11}}/B_9\end{bmatrix}^T$$

$$r=\sqrt{B_{22}}$$

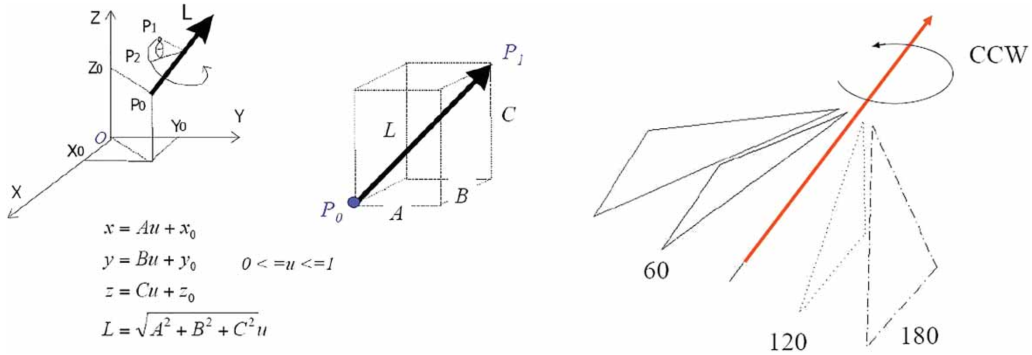

Fig. 10: Inverse arbitrary axis rotation.

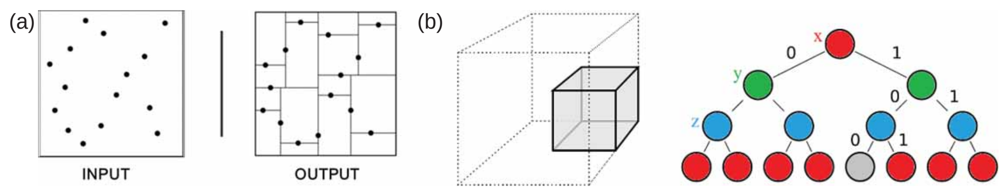

Fig. 11: (a) Data storage, (b) K-d tree (k = 3) with Morton code.

Axial points:

$$\vec{P}_{c0}(x_{c0}, y_{c0}, z_{c0}) = \vec{P}_c(x_c, y_c, z_c)$$
$$\vec{P}_{c1}(x_{c1}, y_{c1}, z_{c1}) = \vec{P}_c(x_c, y_c, z_c) + \hat{a}(a_x, a_y, a_z)$$

5.1.2. *Inverse arbitrary axis rotation*

After having located the axial points and the arbitrary axis of rotation, the initial alignment can then be done by an inverse calculation of the respective angular position of each measurement into the common reference based on the movement parameters of the positioning mechanical device.

The following steps are performed for transformation and rotation of a point about the axis (Fig. 10).

1. Translate so that rotational axis passes through origin (x_0, y_0 ,z_0).
2. Rotate so that the rotational axis is aligned with one of the principal coordinate axes, say z-axis.
3. Perform rotation of object about coordinate axis by required angle.
4. Perform inverse rotation of step 2.
5. Perform inverse translation of step1.

Simplify with substituting for the respective angles to obtain the following matrices:

$$R_{arb} = TrR_xR_yR_z(\Delta\theta_j)R_y^{-1}R_x^{-1}Tr^{-1}$$

This is followed by inverse arbitrary axis rotation of controlled angular increment, i.e.,

$$R_{arb} = T(\vec{P}_c)R_x(\vec{P}_c, \hat{a})R_y(\vec{P}_c, \hat{a})R_z(\Delta\theta_j) \times R_y^{-1}(\vec{P}_c, \hat{a})R_x^{-1}(\vec{P}_c, \hat{a})T^{-1}(\vec{P}_c)$$

5.2. K-d Tree for Fine Registration

The goal of fine registration is to obtain the most accurate solution as possible. Providing a close initial pose, the registration is often refined in an iteration-based optimization process [6, 9].

In this work, ICP approach is applied to refine the initial alignment results by minimising the distance between two sets of blade data (P and M), where are defined as $P = \{\overrightarrow{P_i}\}$ for $i = 1, \ldots N_p$ and $M = \{\overrightarrow{M_i}\}$ for $i = 1, \ldots N_m$ where P_i and $M_i \in Rn$, where $n = 3$ and $m > p$.

In each iteration step, the algorithm selects the nearest neighbors as correspondences and calculates the transformation. Iterations in ICP are summarized as the following steps:

Step 1. Search the closest neighbor points M_K from the reference data set M to a given floating data P_K of the floating data set P , i.e. $d(P_K, M_K) = \min\{d(PK, M)\}$

Step 2. Compute the transformation which comprises a rotation matrix R and a translation matrix T by using quaternion algebra [27].
The quaternion is a 4D vector denoted as $q = [q_0 , q_1 , q_2 , q_3]$ and is used to represent the 3D rotation, which is of practical

importance to us. The norm of a quaternion N(q) is conventionally the sum of the squares of the four components. The 3×3 rotation matrix generated by a unitQuaternion is given as

$$R = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2(q_1 q_2 - q_0 q_3) & 2(q_1 q_3 + q_0 q_2) \\ 2(q_1 q_2 + q_0 q_3) & (q_0^2 + q_2^2 - q_2^2 - q_3^2) & 2(q_1 q_3 - q_0 q_1) \\ 2(q_1 q_3 - q_0 q_2) & 2(q_2 q_3 + q_0 q_1) & q_0^2 + q_3^2 - q_1^2 - q_2^2 \end{bmatrix}$$

Step 3. Calculate the mean square error of the objective function.

$$e(R, T) = \frac{1}{N_p} \sum_{i=1}^{N_p} \|m_i - R(p_i) - T\|^2$$

Step 4. Apply R and T to P . If the stop criterions are reached, then the algorithm stops. Otherwise it goes to the second step.

Step 5. Find the best transform parameters of R and T with the minimum $e(R, T)$.

The final transformation parameters for the local registration procedure are obtained by iterating the point correspondence and error minimization routines until the results converge to a user-defined criterion.

The most time-consuming operation of the ICP is to establish corresponding points which requires iterating lookup of closest points over the entire dataset. As shown in Fig. 11a, the input data are situated in random order, the key of efficient implementation is the fast computation of nearest neighbors. [2,8,17].

To accelerate the search process, this paper applies K-d tree, a systematic data storage method. Point cloud being captured is stored in a k-d tree, where $k = 3$, one of k dimensions is used as a key to split the complete space, and the key is stored in a node to generate a binary node tree. The root node contains the complete bin regions, and the leaf nodes contain a sub-bin region.

The matching between query points and image points can be performed later via nearest neighbor search of the k-d tree. (Fig. 11b). As such, to a query point Pi, the key of Pi is compared with the keys in nodes of Q to find the most matched leaf node qb. All points in the node bin region of q_b are computed to find the closest point.

6. CONCLUSIONS

A low cost turbine blade inspection system has been developed and tested. The blade being mounted on the rig allows full coverage capture in multiple views by the 3D laser scanner. The integrated implementation of regression for arbitrary axis calibration, arbitrary axis rotation for auto-registration and k-d tree for sorted point cloud storage free us from the shortcoming of the traditional method which requires time-consuming nonlinear optimization routines.

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REFERENCES

[1] Arya, S.; Mount, D. M.; Netanyahu, N.S.; Silverman, R.; Wu, A.Y.: An optimal algorithms for approximate nearest neighbor searching in fixed dimensions, Journal of the ACM, 45(6), 1998, 891–923. http://dx.doi.org/10.1145/293347.293348

[2] ASME Y14.5M-2009: Dimensioning and tolerancing, The American Society of Mechanical Engineers, New York, 2009

[3] Bentley, J. L.: Multidimensional binary search trees used for associative searching, Communications of the ACM, 18(9), 1975, 509–517. http://dx.doi.org/10.1145/361002.361007

[4] Besl, P.J.; McKay, N.D.: A method for registration of 3D shapes, IEEE Transactions on Pattern Analysis and Machine Intelligence, 14(2), 1992, 239–256. http://dx.doi.org/10.1109/34.121791

[5] Cardew-Hall, M.; Cosmas, J.; Ristic, M.: Automated proof inspection of turbine blades, International Journal of Advanced Manufacturing Technology, 3(2), 1988, 67–88. http://dx.doi.org/10.1007/BF02601613

[6] Chen, Y.; Medioni, G.: Object modeling by registration of multiple range images, Image Vision Computing, 10(3), 1992, 145–155. http://dx.doi.org/10.1016/0262-8856(92)90066-C

[7] Chen, L.; Lin, G.: Reverse engineering in the design of turbine blades – a case study in applying the MAMDP, Robotics and Computer-Integrated Manufacturing, 16(2), 2000, 3161–3167.

[8] Chua, C. J. R.; Point signatures: a new representation for 3d object recognition, International Journal of Computer Vision, 25(1), 1997, 63–85. http://dx.doi.org/10.1023/A:1007981719186

[9] Faugeras, O. D.; Hebert, M.: The representation, recognition, and locating of 3-D objects, Int J Robot Res, 5(3), 1986,

27–52. http://dx.doi.org/10.1177/027836498600500302
[10] Feldmar, J.; Ayache, N.: Rigid, Affine and Locally Affine Registration of Free-form Surfaces, Tech. Rep., Technical Report of INRIA, Sophia Antipolis, France, 1994.
[11] Hsu, T.; Lai, J.; Ueng, W.E.; Hwang, J.Z.: An iterative coordinate setup algorithm for airfoil blade inspection, International Journal of Advanced Manufacturing Technology, 26(7–8) 2005, 797–807. http://dx.doi.org/10.1007/s00170-003-2040-0
[12] Hsu, T.; Lai, J.; Ueng, W. E.: On the development of airfoil section inspection and analysis technique, International Journal of Advanced Manufacturing Technology, 30, 2006, 129–140. http://dx.doi.org/10.1007/s00170-005-0046-5
[13] Hsu, T.; Lai, J.; Ueng, W.E.; Hwang, J. Z.: A coordinate setup algorithm based on six points principle for airfoil blades inspection, Journal of the Chinese Society of Mechanical Engineers, 25(4), 2004, 353–361.
[14] Huang, X.; Gu, P.; Zernicke, R.: Localisation and comparison of two free-form surfaces, Computer-Aided Design, 28(12), 1996, 1017–1022. http://dx.doi.org/10.1016/0010-4485(96)00011-5
[15] Johnson, A.E.: Spin-images: A Representation for 3-d Surface Matching, Ph.D. Thesis, Carnegie Mellon University, USA, 1997.
[16] Kakde, H. M.: Range searching using kd tree, 2005: 1–12. http://www.cs.utah.edu/~lifeifei/cs6931/kdtree.pdf
[17] Katz, R.; Srivatsan, V.; Patil, L.: Closed-loop machining cell for turbine blades, International Journal of Advanced Manufacturing Technology, 55, 2011, 869–881. http://dx.doi.org/10.1007/s00170-010-3138-9
[18] Lai, J.Y.; Chen, K.J.: Localization of parts with irregular shape for CMM inspection, International Journal of Advanced Manufacturing Technology, 32, 2007, 1188–200. http://dx.doi.org/10.1007/s00170-006-0430-9
[19] Lai, J.Y.; Ueng, W. D.; Yao, C. Y.: Registration and Data Merging for Multiple Sets of Scan Data, International Journal of Advanced Manufacturing Technology, 15, 1999, 54–63. http://dx.doi.org/10.1007/s001700050039
[20] Li, Y.; Gu, P.: Inspection of free-form shaped parts, Journal of Robotics and Computer-Integrated Manufacturing, 21(3), 2005, 421–30. http://dx.doi.org/10.1016/j.rcim.2004.11.015
[21] Lin, A. C.; Chang, H. C.: Automatic 3D measuring system for optical scanning of axial fan blades, International Journal of Advanced Manufacturing Technology, 57, 2011, 701–717. http://dx.doi.org/10.1007/s00170-011-3329-z
[22] Lu, B.; Ou, H.; Armstrong, C.G., et al.: 3D die shape optimization for net-shape forging of aerofoil blades, Materials & Design, 30(7), 2009, 2490–2500. http://dx.doi.org/10.1016/j.matdes.2008.10.007
[23] Makema, E.; Ou, H.; Armstrong, C.: A virtual inspection framework for precision manufacturing of aerofoil components, Computer-Aided Design, 44, 2012, 858–874. http://dx.doi.org/10.1016/j.cad.2012.04.002
[24] Masuda, T.; Yokoya, N.: A robust method for registration and segmentation of multiple range images, Computer Vision and Image Understanding, 61(3), 1995, 295–307. http://dx.doi.org/10.1006/cviu.1995.1024
[25] Menq, C.H.; Yau, H.T.; Lai, G.Y.: Automated precision measurement of surface profile in CAD-directed inspection, IEEE Transactions on Robotics and Automation, 8(2), 1992, 268–278. http://dx.doi.org/10.1109/70.134279
[26] Mohaghegh, K.; Sadeghi, H.; Abdullah, A.: Reverse engineering of turbine blades based on design intent, International Journal of Advanced Manufacturing Technology, 32, 2007, 1009–1020. http://dx.doi.org/10.1007/s00170-006-0406-9
[27] Mukundan, R.: Quaternions: from classical mechanics to computer graphics and beyond, Proceedings of the 7th Asian Technology Conference in Mathematics, 2002
[28] Gelfand, N.; Ikemoto, L.: Geometrically stable sampling for the ICP algorithm, Proceedings of the fourth international conference on 3-D digital imaging and modeling (3DIM), 2003, 1991–1998.
[29] Park, S-Y.; Subbarao, M.: An accurate and fast point-to-plane registration technique, Pattern Recognition Letters, 24(16), 2003, 2967–76. http://dx.doi.org/10.1016/S0167-8655(03)00157-0
[30] Reber, E. E.; Michell, R. L.; Carter, C. J.: A review of industrial capabilities to measure free-form surfaces, Nat. Phy. Lab., Middlesex, UK, NPL. Rep. DEPC_EM 014, Jan. 2007.
[31] Savio, E.; Chiffre, L.; Schmitt, R.: Metrology of freeform shaped parts, CIRP Annals-Manufacturing Technology, 56(2), 2007, 810–835. http://dx.doi.org/10.1016/j.cirp.2007.10.008
[32] Wald, I.; Havran, V.: On building fast kd-trees for ray tracing, and on doing that in O(NlogN), IEEE Symposium on Interactive Ray Tracing, 2006, 61–69. http://dx.doi.org/10.1109/RT.2006.280216
[33] Yilmaz, O.; Gindy, N.; Gao, J.: A repair and overhaul methodology for aeroengine components, Robotics and Computer-Integrated Manufacturing, 26, 2010, 190–201. http://dx.doi.org/10.1016/j.rcim.2009.07.001

[34] Zheng, J.; Li, Z.: Worn area modeling for automating the repair of turbine blades, International Journal of Advanced Manufacturing Technology, 29, 2006, 1062–1067. http://dx.doi.org/10.1007/s00170-003-1990-6

[35] Zhu, L.; Barhak, J.: Efficient registration for precision inspection of free-form surfaces. International Journal of Advanced Manufacturing Technology, 32, 2007, 505–515. http://dx.doi.org/10.1007/s00170-005-0370-9