Vision-based Assembly and Inspection System for Golf Club Heads

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A B S T R A C T

Golf club head production is started by creating metallic films and forming blank casts, which then undergo complex and sophisticated assembly procedures, morphological inspection and strength testing. Not only chemicals used in these processes often threaten the health of operators, but also most of this backend processing involves manual assembly and welding, demanding substantial amounts of manpower. In light of these pitfalls, this paper proposes a Vision-based Assembly and Inspection System for Golf Club Heads (VAIS-GCH) to mitigate the time-consuming and labor-intensive golf club head production process. Two cameras are coordinated to capture top-view image of the striking plate, and top- and side-views of the casting body for visual processing. After the barycenter shift and shifting angle of the striking plate are determined, a robot arm is then directed to suction up the striking plate from the conveyor belt, adjust it to the canonical orientation, and move the yet-to-be assembled striking plate to the top of the casting body. The 3D spatial positions of the casting body, namely, the XYZ shifting angles of the coupling opening, are detected by comparing the top- and side-view images captured with pre-stored 3D golf club head template to facilitate the coupling of the striking plate and casting body. The side-view camera monitors the insertion depth of the striking plate during the coupling process to make sure the surface of the striking plate levels with the casting body. The loft angle, formed by the line perpendicular to the tangent of the bottom of casting body and the tangent of the striking surface, is tested to confirm whether specifications are satisfied. Through the coordination of two cameras, the accuracy and efficiency of the golf club head assembly are increased significantly. The alignment error is smaller than 0.8 mm and the assembly and inspection process takes less than 2 s.

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1. Introduction

Products in traditional 3D (Dangerous, Dirty and Difficult) industries typically consist of assembling multiple metal parts through screws, welding, and adhesives. A substantial amount of manual work and human-operated machinery are often indispensable in most production processes. Demands on the technical level of manpower are high; yet yields are only 60–80%, leading to high costs and unstable quality. This is especially true for the manufacturing of golf clubs. Targeting on various player age groups, the models of golf clubs are diverse in terms of flying direction and distance after ball striking. Yet the quantity manufactured for each specification tends to be small with relatively high unit profit and short product life cycle. Traditionally, manufacture of golf club heads are completed manually by performing fixture production, welding, and testing steps to ensure production quality. Following preliminary assembly, loft angles of golf club heads are examined by applying rulers. Human visual inspection is then conducted to verify whether products conform to customer specifications. This is a laborious process with low efficiency, and human errors are common. Golf club manufacturers routinely adjust the assembling procedures and inspection criteria in response to different specifications demanded by various models within a rather short product cycle. This practice inevitably leads to increasing human operating errors. Take the fabrication of a high-end titanium golf club head for example, the head is composed of a casting body, manufactured by die-casting, and a striking plate, finished by forge and EDM wire cut. The error regarding the outline of the striking plate fabricated is negligibly small due to the high precision of the wire cut machine employed.
However, the casting body may be warped due to anisotropic shrinkage during cooling down. The distortion of casting body makes the pre-taught welding path no longer fit for the real shape of weld seam, resulting a drop of 8–10% in yielding rate. In light of the high cost of the titanium, the integration of robotic arm with vision means becomes imperative to circumvent this problem.

Robotic arms are often employed for automated processes in industrial applications. For example, spot welding is first performed by robots in automobile industry because the simple joint space interpolation involved. For seam weld, a smooth curve in Cartesian space should be generated from prescribed positions. This is fulfilled by a laborious teaching and complex coordinate transformations. An adequate robotic moving path should include velocity and acceleration information important to tasks such as seam welding, spray painting and assembly, etc. This requirement cannot be fulfilled simply by manual teaching. Offline programming through a CAD system is often resorted to alleviating the path planning problems [1–4]. When the shape of a coupling workpiece is distorted, the robot should be able to dynamically adapt to the new outline of the weld seam. Recent development of machine vision technology is employed to inspect the welding surface, and to adjust the robot path during welding [5–7]. Features are identified after image capture and utilized to calculate corresponding 3D space coordinates and angles of rotation for fast, dynamic planning of smooth paths. This allows mechanical arms to reach the correct position accurately.

Robotic arms combined with machine vision were employed to construct an automatic golf club head welding system [8]. The image of golf club head that had undergone preliminary welding was processed by Sobel and Laplace filters for boundary separation. Mobile paths and shifting angles were then computed to guide the robotic arms to perform automatic welding operation. In this setup, the critical stages before and after preliminary welding, e.g., coupling of striking plate and casting body, and loft angle inspection, still demand human operation, nullifying a fully automatic golf club head manufacturing process. Although robotic arms were employed to expedite 3D object’s grasp and movement, these applications did not demand space coupling and component coupling in high precision. The aforementioned technological transition is further hindered by the 3D space curved surface construction encountered in most metal parts, which are far more complex than simple planar objects. This causes difficulty in performing high-precision automated coupling, welding, and assembly. Therefore, the vision-based 3D correspondence and coupling for spatial objects has become a key issue in developing intelligent automatic equipment [9–13]. Also, a nondestructive inspection approach is required for the mass production of components for industrial applications, such as the automobile, shipbuilding, and aerospace industries where high inspection rate is required [14–19].

This paper presents a Vision-based Assembly and Inspection System for Golf Club Heads (VAIS-GCH) to resolve these deficiencies. This system is equipped with two cameras, one mounted on a robotic arm to capture top-view images of the striking plate and casting body, and the other a stationary camera positioned laterally to the casting body to provide the corresponding side view. Images captured at different stages of assembly are further processed for 3D alignment between the striking plate and casting body. The camera on the moving robotic arm captures the striking plate image, conveyed through an assembly line, from the top to derive the barycenter position and shifting angle of the striking plate. The robotic arm then suction up the striking plate from the barycenter and compensates the angle shifted to a preset canonical orientation. After moving the robotic arm with the striking plate to the top of the casting body, both the camera on the robotic arm and the stationary one take a top-view and side-view image of the casting body, respectively. The top-view image of the casting body is utilized to calculate the barycenter of the casting body. The pre-stored 3D golf club head template is then compared to derive the XYZ-plane shifting angles of the casting body within a fixture structure. The robotic arm then inserts the striking plate into the opening of casting body based on the 3D spatial position derived. During the coupling process, the stationary camera monitors the insertion depth to make certain the top surface of the striking plate levels with that of the casting body. The side view after coupling of striking plate and casting body is then analyzed to determine whether the loft angle, formed by the line perpendicular to the tangent of the bottom of casting body and the tangent of the striking surface, meets the specification. This can greatly improve coupling precision between the striking plate and casting body, thereby increasing production and inspection efficiency to expedite fast transitions between different models and assembly lines.

2. VAIS-GCH system

2.1. Environmental settings

The VAIS-GCH system is composed of five main parts: a circular LED light source, two CCD cameras, a robotic arm, a casting body, and a fixture, as shown in Fig. 1. The striking plate is placed in arbitrary location and orientation on the assembly line, while the casting body is positioned within a fixture with possible 3D spatial variations. The circular LED and a CCD camera, with a resolution of 2592 × 1944, are mounted on the robotic arm. This translates to an image resolution of approximately 0.5 mm/pixel. This camera provides top view of both the striking plate and casting body during different assembly stages. Another stationary CCD camera with a resolution of 1024 × 768 is installed laterally at the side of casting body to capture the corresponding side-view image during coupling of the striking plate and casting body, and examination of loft angle after preliminary welding. The resolutions of these two cameras are different, since the insertion of striking plate into the casting body demands higher precision and is

Fig. 1. Major system components: an LED light source, moving and stationary cameras, robotic arm, suction head, striking plate, casting body and fixture. The moving camera, mounted on the robotic arm, provides top-view images of striking plate and casting body, while the stationary camera captures side-view of casting body.
vital to the success of our approach. Both cameras are geometrically calibrated first [20]. A suction head is located at the tip of the robotic arm for suctioning up the striking plates traveling along the conveyor belt. It can move back and forth between the striking plate and the casting body confined within a fixture. The images captured are analyzed by a computer and the robotic arm is controlled based on the parameters derived during various stages of assembly and inspection. The world coordinate system is adopted for the robot arm. The features identified from images taken by two cameras are converted from the camera coordinate to world coordinate to instruct the robot arm to take appropriate action.

2.2. VAIS-GCH system flow

The VAIS-GCH system can be divided into striking plate suction, striking plate and casting body coupling, and the loft angle detection stages, as shown in Fig. 2. During the striking plate suction stage, the barycenter and shifting angle of the striking plate are derived. The information is fed to robotic arm to position the suction head precisely to the barycenter, suction up the striking plate and compensate the shifting angle to a canonical orientation. Next, the robotic arm moves to the top of the casting body, along with the stationary camera placed laterally, to capture corresponding top- and side-view images. By maximizing the overlapping area between a pre-stored 3D golf club head template, and the top- and side-view images, the XYZ-plane shifting angles of the casting body within a fixture structure are calculated. Based on the spatial deviations detected, the robotic arm can adjust the striking plate to the matching position to precisely insert the striking plate into the coupling hole of the casting body. At the same time, the stationary camera, placed laterally to the side of casting body, monitors the coupling process to make sure the surfaces of the striking plate and casting body level with each other. Once the upper surface of the striking plate coincides with that of the coupling hole of the casting body, an appropriate insertion depth is reached. A second robotic arm might perform the preliminary welding and the whole process proceeds to the loft angle detection stage. The side-

![Fig. 2. VAIS-GCH system flow.](image-url)
view image of the golf club head is captured by the stationary image to further identify the bottom and the striking surface of the club head. Once determined, the loft angle, formed by the line perpendicular to the tangent of the bottom of casting body and the tangent of the striking surface, is tested to confirm whether specification is satisfied.

2.2.1. Striking plate suction stage

When the striking plate suction stage is initiated, the robotic arm moves to the top of the striking plate on the conveyor belt. Since the position of the conveyor belt is a known a priori, directing the robotic arm to move vertically above the conveyor belt can be assured. The camera mounted captures the striking plate image, as shown in Fig. 3(a). The segmentation of the grey-level image acquired is performed by applying Otsu’s binarization algorithm first to transform into the corresponding black-and-white image [21], as shown in Fig. 3(b). The striking plate corresponds to the object with the largest area in the binary image. The connected component labeling (CCL) is utilized next to separate the striking plate in the foreground from the background [22].

After the striking plate is identified, the corresponding spatial information, namely, barycenter position and angle shift, has to be determined next. In order to maintain stable balance during the suction-up of the striking plate from the conveyor belt, the suction position of the robotic arm shall preferably correspond to the barycenter. Assuming the density of the striking plate is uniformly distributed, the striking plate barycenter position \((x_c, y_c)\) can be obtained by averaging the \(x\) and \(y\) coordinates of the subject image, as shown in Fig. 3(c).

To determine the angle shift of the striking plate placed on a conveyor belt, a minimum circumscribed rectangle surrounding the striking plate must first be derived. The minimum circumscribed rectangle and image centerlines are used to derive the striking plate shifting angle \(\theta\). The minimum circumscribed rectangle is directly related to the striking plate boundaries. Boundaries occur at neighboring pixels with different values and are often located through the Sobel filter [23].

A convex hull is a set where any connection of two points in the convex hull graph does not pass through the graph exterior. A necessary condition for the minimum circumscribed rectangle requires that one of its sides overlaps with the polygon formed by the convex hull [24]. After all boundary points are processed by performing convex hull calculation [25], the recorded convex hull collection or congregation points are further utilized to calculate the minimum circumscribed rectangle defining the striking plate range. The steps for the calculation of the minimum circumscribed rectangle are listed below:

(a) The sideline formed by the first point \(P_0\) and the second point \(P_1\) sequence recorded from the convex hull stack is the first edge. This is viewed as the bottommost edge. The leftmost, rightmost, and topmost edge points for this sideline are sought in the convex hull to obtain the initial minimum area.

(b) Continue from the second edge \((P_1, P_2)\). Seeking the leftmost edge point requires only beginning to search from back point of the second edge. The rightmost and topmost points are similar.

(c) Calculate the surrounded area for this sideline. If it is smaller than the area of the previous sideline, update the minimum area recorded and store all points located temporarily.

![Fig. 3.](image)

Striking plate suction stage: (a) the robotic arm carrying the camera mounted moves to the top of the striking plate and captures the corresponding top-view image. (b) Binarized striking plate image with threshold 110. (c) Striking plate object after binarization, CCL, and boundary extraction, are performed. The convex hull derived is utilized to calculate the shifting angle and barycenter position. (d) The robotic arm then suctions up the striking plate from the barycenter and compensates the angle shifted to a preset canonical orientation.
(d) Let $i$ represent implementation to the convex hull $ith$ edge. Continue to the final point according to the $P_{i-1}$ and $P_i$ sequence, and Steps (a) and (b).

(e) The convex hull minimum bounding rectangle is obtained with the five points correspond to the minimum area recorded.

The minimum circumscribed rectangle is used to obtain the shifting angle $\theta$, as shown in Fig. 3(c). The suction head of the robotic arm is then positioned on the barycenter, suctions up the shifting angle striking plate is adjusted to a pre-set canonical spatial orientation, as shown in Fig. 3(d). The robotic arm, carrying the striking plate, will move to the top of the casting body to perform the coupling between these two components.

2.2.2. Striking plate and casting body coupling stage

During the coupling of the striking plate and casting body, not only the barycenter of the striking plate and casting body shall coincide with each other, but also the placement angle of the striking plate must match with that of the opening of the casting body. When the striking plate is inserted into the coupling opening of the casting body, the stationary camera placed laterally keeps monitoring the insertion depth until the surface of the striking plate levels with the top of the casting body. The coordination of two cameras placed on top and laterally guarantees the above requirements are met.

The casting body to be coupled is placed in a fixture structure. Minor spatial variations along $XYZ$ coordinate axes are often incurred during the course of placement of the casting body into the fixture structure. To facilitate the coupling operation, the $3D$ spatial shift, namely, the $XYZ$ plane shifting angles $\theta_x, \theta_y$, and $\theta_z$ of the casting body in the fixture must be detected first to allow the striking plate being inserted into the coupling hole precisely, as shown in Fig. 4. An image captured by a single camera can only render relevant $2D$ information. The registration of top- and side-view images acquired by coordinating two cameras is indispensable in deriving and compensating $3D$ spatial deviation of the casting body.

The robotic arm, carrying the striking plate, moves to the top of the casting body. The camera mounted on the robotic arm captures the corresponding top-view image, as shown in Fig. 5(a). In Fig. 5(b), the image is pre-processed by applying Otsu’s binarization algorithm to transform into a binary image. The peripheral groove along the opening is highly sensitive to the illumination and placement angles of the casting body, resulting in undesirable discontinuities or protrusion along the perimeter. In light of this observation, morphological CLOSE [26] and active contouring [27] are applied to cascade the broken parts due to binary operation, as shown in Fig. 5(c). After the edge along the peripheral groove is identified, the coupling hole can be segmented from the rest of the casting body.

The casting body to be coupled is placed in a fixture structure. Minor spatial variations along $XYZ$ coordinate axes are often incurred during the course of placement of the casting body into the fixture structure. This $3D$ spatial deviations, namely, the $XYZ$-plane shifting angles $\theta_x, \theta_y$, and $\theta_z$ of the casting body in the fixture, must be detected first to guarantee precise coupling between striking plate and casting body. In Fig. 6, a model template of casting body is obtained from a database. The model template is subjected to $3D$ adjustment along $XYZ$ coordinate axes within a search space. For every spatial orientation, the tilted template is projected onto both the $XY$ and $XZ$ plane. The $2D$ $XY$-plane projection formed is compared with the top-view image obtained through the camera mounted on robotic arm, while the $XZ$-plane projection with the side-view images from the stationary lateral camera, as shown in Fig. 5(e) and (f). The total overlapping area between the $XY$-, $XZ$-projected templates and the top-, side-view images captured indicates the degree of similarity between the template tilted and the casting body. The search space for the $XZ$-plane shifting angles $\theta_x, \theta_y$, and $\theta_z$ is limited to be $\pm 10^\circ$, respectively. An exhaustive search is performed within this rather limited range. No local minimum is encountered during various sessions of the test. The shifting angles $\theta_x, \theta_y$, and $\theta_z$ corresponding to the maximum overlapping area represent the correct amount of deviations for the casting body in the fixture $T(\theta_1, \theta_2, \theta_3)$. The convex hull minimum bounding rectangle is obtained with the $fi$-th edge. At the end of this stage, the robotic arm shall move the striking plate upwards to ensure the loft angle $\phi$ of the golf club head assembled is detected and tested to confirm whether specification is satisfied.

2.2.3. Loft angle detection stage

After completing the coupling of the striking plate and casting body, the loft angle $\phi$ of the golf club head must be tested to determine whether the specification demanded is conformed. To calculate the loft angle $\phi$, both the bottom horizon of the casting body and the centerline of the striking plate must first be derived. The side-view image of the golf club head is acquired by the camera placed laterally, as shown in Fig. 8(a). Binarization and boundary extraction of the casting body and striking plate boundaries are performed. The
Fig. 5. Striking plate and casting body coupling stage: (a) top-view image. (b) Pre-processed by applying Otsu’s binarization algorithm. Note the discontinuities along peripheral grooves are highlighted. (c) Morphological CLOSE and active contouring are applied to cascade the discontinuous segments together. (d) Binarization, closing, CCL, and boundary extraction are performed to derive the barycenter and shifting angle of the opening of the casting body. (e) and (f) The shifting angles $\theta_x$, $\theta_y$, and $\theta_z$ of the casting body are detected by simultaneously maximizing the overlapping area between a pre-stored 3D golf club head template (in wire frame), and the top- and side-view images, respectively. (g) The side-view image is monitored to identify the gap between the upper surfaces of the striking plate and coupling hole of the casting body. (h) Based on the spatial deviations detected, the robotic arm can accurately adjust the striking plate to precisely insert the striking plate into the coupling hole of the casting body.
tangent \( \vec{PQ} \), passing through the outermost point \( P \) on the casting body bottom boundary, corresponds to the horizon. The tangent \( \vec{OQ} \), passing through the center point \( O \) of the striking plate, intersects \( \vec{PQ} \) at point \( Q \). The loft angle corresponds to the angle formed by the tangent \( \vec{OQ} \) and the line \( \vec{QR} \) passing through \( Q \) and perpendicular to \( \vec{PQ} \), as shown in Fig. 8(b). Whether the derived loft angle \( \phi \) conforms to the preset golf club head specifications is subject to further examination. If so, the system continues to process the next coupling operation between the striking plate and casting body. If not, help

Fig. 6. The model template of the casting body in the database is projected to the XY- and XZ-plane, respectively, for comparing with the overlapping area between the top- and side-view images captured.

Fig. 7. (a) Calculation of casting body side image coupling depth \( d \). (b) Too shallow, as the apical surface of the striking plate is visible. (c) Too deep, as the apical surface of the striking plate is invisible from the lateral view.
from a human operator will be sought to determine if the physical dimensions of the striking plate and casting body are within tolerance.

3. Experimental study

In order to test the reliability of the VAIS-GCH system developed, the calibration data, insertion depth and loft angle are tested for the striking plate suction, striking plate and casting body coupling, and the loft angle detection stages, respectively.

3.1. The consistency of calibration data derived during the striking plate suction stage

Two sets of test are performed, aiming at deriving the positioning accuracy of the robotic arm and the reliability of the algorithm developed, respectively. For the first set of experiment, two striking plates are employed. For each striking plate, the camera mounted on the robotic arm travels to the top of the striking plate, takes a top-view image, and then moves to the top of the casting body. The whole cycle is repeated for 20 rounds. The shifting angles and barycenters of the images acquired are listed and compared, as listed in Table 1. The robotic arm is fixed at the top of the striking plate in the second test. After taking 20 top-view images, the shifting angles and barycenters of the images acquired are derived to compare the reliability of the algorithm developed in Table 2. The distribution of striking plates 1 and 2 are more disperse than that of striking plate 3. The results obtained indicate that the major source of errors in determining the shifting angles and barycenters of the striking plate is rooted from the positioning inaccuracy of the robotic arm.

3.2. The consistency of XYZ-plane shifting angles of the casting body derived during the coupling stage

Two casting bodies are employed. For each casting body, the camera mounted on the robotic arm travels to the top of the casting body, takes a top-view image and then moves back to the top of the striking plate. The whole cycle is repeated for 20 rounds. The shifting angles and barycenters of the images acquired are listed and compared, as listed in Table 3. The distribution of striking plates 1 and 2 are more disperse than that of striking plate 3. The results obtained indicate that the major source of errors in determining the shifting angles and barycenters of the striking plate is rooted from the positioning inaccuracy of the robotic arm. A deviation of 1° in shifting angle is considered as acceptable and within tolerance according to our study, as shown in Fig. 9.

3.3. The accuracy of coupling depth derived during the coupling stage

The casting body remains stationary in the fixture structure. Twenty side-view images are acquired through the camera placed laterally. The proper insertion depth is calculated and compared, as listed in Table 4.

4. Conclusions and future work

VAIS-GCH provides spatial coupling and detection for 3D objects. Barycenter position and the shifting angle are used to suction up and correct the striking plate to the canonical orientation. Rotation...
in 3D space is performed according to the 3D shifting angles of the casting body. The barycenter of the striking plate is moved to alight with that of the casting body. After identifying the top surfaces of both striking plate and casting body, the appropriate coupling depth can be derived. The correctness of the loft angle can be detected automatically. The utilization of two coordinated cameras can provide reliable 3D assembly and inspection information. The inclusion of a second robotic arm to perform the welding of striking plate and casting body can form a fully automatic golf club head production process.

Acknowledgments

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References


Table 4
The insertion depth derived from the 20 lateral images of two casting bodies and the corresponding striking plates acquired.

<table>
<thead>
<tr>
<th>Coupling depth d</th>
<th>Side-view 1</th>
<th>Side-view 2</th>
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<td>198.0 pixels</td>
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<td>$\sigma$</td>
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<td>$d_{\text{max}}$</td>
<td>224 pixels</td>
<td>201 pixels</td>
</tr>
</tbody>
</table>

Fig. 9. The XYZ-plane shifting angles of the casting body derived for 20 top-view images: (a) casting body 1 and (b) casting body 2.


