E-quality Control in Automotive Manufacturing—An Integrated Approach Using 3D Measurement and Photometric Stereo Reconstruction

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ABSTRACT

Intense pressures for quality control are experienced by automotive parts suppliers to stay tuned in competitiveness and to build a long-term relationship with automotive manufacturers. The automotive parts suppliers are urged to contribute towards enhancing the overall quality of national car. E-quality is a process through which inspection of the process and quality of the part produced is done online resulting in the improvement of the process and reduction in the amount of time consumed for the overall process. Automated quality control involves using a methodology to classify the parts based on the damages or the dimensions of the features on a part. However, achieving high classification accuracy is not an easy task, especially in area of quality control where small differences in damages or dimensions result in part fall into a different category. And also the traditional 2D vision is not as reliable as 3D measurement due to the limitations of the technology and the structure of a part. In this study, a novel approach which integrates photometric stereo reconstruction and 3D measurement for 3D inspection is presented. The data extracted from brake caliper and lever brake was used as case study to demonstrate the proposed methodology. Results show that the new methodology yielded superior results compared to the traditional inspection approach with very high classification accuracy. Moreover, the proposed approach is capable to archive 3D models of the parts and achieve rapid quality control. This paper forms the basis for solving many other similar problems that occur in many industries.

1. INTRODUCTION

The increase in competition among the production groups forced them to move towards shorter product life cycle, remote quality control, smaller products and network based production and distribution systems to stay in the competition. E-manufacturing is the process of integration of design, manufacturing, quality and business functions with integrated information networks. The competition in the manufacturing industry made them to place high emphasis on quality and reliability of the products. In other words, industry is striving towards achieving zero defect manufacturing, which requires the manufacturer to test each and every part produced. Especially, industries like those that produce brake wires for automobiles are forced to inspect each and every part as a defective product may result in an accident. In such scenarios, internet based inspection systems help perform quality inspection reliably, accurately and in very less time. E-quality is the process through which monitoring the process and inspection of the parts produced is performed online by integrating the machines into the information network. Ability to control the equipment remotely offers tremendous benefits. Designers located remotely can visualize their designs and carry out inspections remotely. Inspections settings can be adjusted according to the requirements.

This paper proposes a novel 3D E-quality control system that integrates photometric stereo reconstruction for classifying the parts into different categories. The 3D quality control system offers rapid quality control inspection of complex parts. The non-contact photometric scanner provides documented proof that manufacturers are meeting specifications by providing traceable data and accurate 3D models of complex parts, castings, stampings and more. And, the system is very easy to use. The 3D quality control system captures millions of data points in just minutes to represent the true and full geometry of the complex part. The systems then compare the scanned 3D models of

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produced parts to scanned 3D models of standard parts using 3D measurement based on ICP registration, cloud distance and color mapping to provide accurate and timely measurement feedback for quality control, helping provide proof that the produced products meet the required specification. The data extracted from brake caliper and lever brake was used as case study to demonstrate the proposed methodology. Results show that the new methodology yielded superior results compared to the traditional inspection approach with very high classification accuracy. Moreover, the proposed approach is capable to archive 3D models of the parts and achieve rapid quality control. This paper forms the basis for solving many other similar problems that occur in many industries.

2. LITERATURE REVIEW

2.1. E-QUALITY CONTROL

The traditional way of achieving and ensuring the quality standards is mainly via Statistical Process Control (SPC) procedures. However, in sequential manufacturing processes, product quality is influenced by many factors that involve causal relationship and interact with each other. Thus, it is very difficult to set up the best conditions of manufacturing specifications for SPC by executing the Design Of Experiments (DOE) in plants that have large equipment or sequential processes. The conventional SPC and six sigma techniques must respect several statistical assumptions such as normality of distribution of the variables, constant variance of the variables, etc. It is hard to meet all these assumptions in practice.

Current statistical approaches are difficult in analyzing qualitative information such as character the qualitative variable in several levels; and the uncertainty (i.e., variation) of vague observations is essentially non-statistical in nature, and hence these observations may not adequately support the random variation assumption inherent in statistical quality control methods. Moreover, the final solutions derived from standard statistical techniques may not be optimal because these methodologies are not able to learn from historical data. Based on the aforementioned deficiencies from current statistical approaches, a hybrid data mining approach which integrates rough set theory, fuzzy set theory, genetic algorithm and agent based technology is proposed. Comparing to standard statistical tools that use population based approach, the Rough Set Theory (RST) uses an individual, object-model based approach that makes a very good tool for analyzing quality control problems. Furthermore, Fuzzy Set Theory (FST) has demonstrated its ability in a number of applications, especially for the control of complex non-linear systems that may be difficult to model analytically. The Genetic Algorithm (GA) operates on a population solution rather than a single solution. To resolve the drawbacks of these statistical methodologies in quality control, the proposed approach expects to provide a way to optimize prediction for the lowest defective rate.

2.2. PLASTIC INJECTION

Plastic injection is a manufacturing process in which a thermoplastic is melted and injected by pressure into a mold cavity, cooling down and getting the shape of the mold cavity. Plastic injection has become a very useful technology for various industries like automotive, aerospace, and others. Molds are created with metal materials, usually either steel or aluminum, depending on material properties and specifications. When designing a part for plastic injection, it must be very carefully engineered to facilitate the injection and de-molding process. Part small and delicate features, material of the mold, material to be injected, capacity of the molding machine, are some of the important points to take into account when using this process.

When a part is manufactured this way, there are several defects that may come up during the process. Depending on the defect, the part may not meet its requirements and may not function as it was intended for. There may be little details easily fixable, but there may be other that will not work at all. Some of the cosmetic defects may include bubbles, cracking, discoloration, flashing, gouge, haze, scratching, among others.

One of the plastic components in a car that is molded is the inner handle cover. This part requires certain specifications for color, size, durability, and if these specifications are not met part needs to be scrapped. If part is undersize, it will not fit properly and will cause problems with the door handle. In the other hand, if it fits perfectly fine but the color is not the specified, it will work just fine but the appearance of the car interior will not be appropriate. It all depends on what kind of defect the part has to determine if it is usable or not.

2.3. PHOTOMETRIC STEREO RECONSTRUCTION

Photometric stereo reconstruction computes geographic surface using a fixed viewpoint observations under point lighting, assuming that the object is built with Lambertian material. However, materials usually are not exactly

Lambertian, therefore the estimated surface normal is inaccurate. As a result photometric stereo reconstruction has been extended to non-Lambertian materials, which can handle a wider range of material types. But they still rely on isotropic analytical Bidirectional Reflectance Distribution Function (BRDF) models that limit their generality.

To solve this problem, several approaches have been proposed that not using parametric BRDF models. Hertzmann and Seitz [1] estimate surface normal using a reference object similar material. This method doesn't rely on BRDF models, but it needs a reference object which is not available sometimes. Mallick et al. [2] transfer a general material to Lambertian material by removing the specular component, and then use the traditional photometric stereo reconstruction technique to obtain the surface normal. Other methods make use of general properties of surface reflectance to infer surface statistics. Zickler et al. [3] use Helmholtz reciprocity to recover depth and normal directions. Alldrin and Kriegman [4] utilize the symmetry about the view-normal plane in isotropic BRDF models. Lim and etc. [5] explore the possibility of using photometric stereo with images from multiple views, when correspondence between views is not initially known. A depth-map with respect to a view, picked from an arbitrary viewpoint as a reference image, serves as correspondences between frames. They compute the depth-map from a Delaunay triangulation of sparse 3D features located on the surface. Then they run a photometric stereo computation obtaining normal directions for each depth-map location which is integrated into the resulting depth-map to make it closer to the true surface than the original. Their approach presents high quality reconstructions and gives a theoretical argument justifying the convergence of the algorithm. Bernardini and etc. [6] combine the photometric stereo information with the 3D range scan data. The photometric information is simply used as a normal map texture for visualization purposes. Nehab and etc. [7] produce a very good initial approximation to the object surface using range scanning technology. Normal maps are estimated and then integrated to produce an improved, almost noiseless surface geometry.

3. The 3D E-QUALITY CONTROL SYSTEM

The 3D E-quality control system advances the basic research to address the aforementioned issues through the use of integration of cyber communication, virtual prototyping, photometric stereo reconstruction, robots, and machine vision system. The hardware consists of the state-of-the-art Cognex machine vision systems, YAMAHA robotics systems, and the photometric 3D scanning system in the Intelligent Systems Engineering Lab (ISEL). These equipment and systems provide the foundation for this project. The software consists of Intelligent Graphical User Interface (i.e., Application Program Interface) embedded with photometric stereo reconstruction and 3D measurement algorithms.

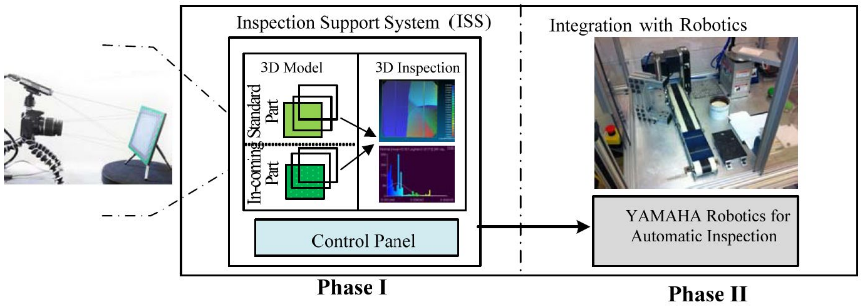


Figure 1. The Framework of the 3D e-Quality Control Systems (eQCSs).

Figure 1 outlines the overall framework for the 3D E-Quality Control Systems. In Phase I, the Inspection Support System (ISS) uses photometric stereo reconstruction to generate the high-resolution 2D images and accurate 3D models for inspection. The 3D scanning System based on the photometric stereo reconstruction is used to capture the high-resolution 2D images of the part from different angle with several light patterns. After these images have been produced, they are used to construct accurate 3D models which will be saved in the PC and compared with the standard 3D model later for the comparison is implemented, the contrast and difference between two parts will be identified. Finally, the inspection outcomes will be reported as Pass, Rework and Discard. In Phase II, the ISS is integrated with automatic inspection equipment (i.e., YAMAHA robotics) to perform fully automatic inspection through the Remote Quality Control Systems (RQCS). This paper focuses on phase I of the procedure mainly.

3.1. PHOTOMETRIC STEREO RECONSTRUCTION

To generate the accurate 3D model for inspection, the 3D scanning system uses photometric stereo reconstruction which uses a SLR camera plus a projector for scanning. The projector projects a sequence of four colored strip patterns and one uniform white pattern. In capturing, we take 8 photos for each gradient pattern under two linear polarization states, and 5 stereo photos for each structures light strip patterns, using Cannon 5D cameras in burst mode which requires just a few seconds to capture data at 12 megapixel resolution [2]. Because of noise and the limited resolution of the projector, the structured light scan introduces some high frequencies biasing and noise. We have to smooth the structured light scan surface using bilateral de-noising, and then create a surface normal map from the smoothed mesh and extract the high frequency details of the estimated normal using high-pass filtering [2] (see Figure 2).

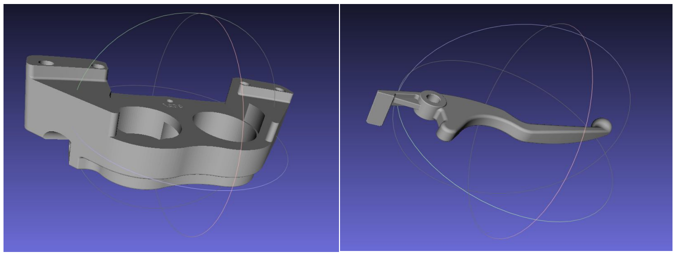


Figure 2. Scanned Geometry of a Car Brake Caliper and Lever Brake.

Finally, we optimize the mesh vertices to match this assembled normal map using an embossing process as in [3]. We obtain diffuse and specular normal from gradient illumination for objects whose reflectance is either diffuse or specular. For polarized patterns, individual linear polarizers are placed over each light. A linear polarizer is mounted on a servomotor in front the camera, which enable to polarizer to be rapidly flipped on its diagonal between horizontal and vertical orientations [2].

While using normal to improve geometry, we find the measured positions from a range-image. The pixel coordinates on the reference camera induce a natural parameterization of the corresponding surface. Accordingly, under perspective projection, the coordinates of a surface point can be written in terms of a depth function Z(x, y). In other words, given the pixel coordinates, the position of the corresponding surface point P(x, y) has only one degree of freedom, Z(x, y):

$$P(x,y) = \left[-\frac{x}{f_x}Z(x,y), -\frac{y}{f_y}Z(x,y), -\frac{x}{f_x}Z(x,y)\right]^T \tag{1}$$

where f_x and f_y are the camera focal lengths in pixels. Our problem is to find a depth function that conforms to the estimates we have for the position and normal of each point. To do so, we choose the depth function that minimizes the sum of two error terms: the position error E^p and the normal error E^n.

The position error is then defined as the sum of squared distances between the optimized positions and the measured positions:

$$\left|\left|P_i - P_j^m\right|\right|^2 = \mu_i^2(Z_i - Z_i^m)^2, where\ \mu_i^2 = (\frac{x_i}{f_x})^2 + (\frac{y_i}{f_y})^2 + 1 \tag{2}$$

Recall that the surface tangents T_x and T_y at a given pixel can be written as linear functions of the depth values and their partial derivatives:

$$T_x = \frac{\partial P}{\partial x} = \left[-\frac{1}{f_x}\left(x\frac{\partial Z}{\partial x} + Z\right), -\frac{1}{f_x}y\frac{\partial Z}{\partial x}, \frac{\partial Z}{\partial x}\right]^T \tag{3}$$

$$T_y = \frac{\partial P}{\partial y} = \left[-\frac{1}{f_x}x\frac{\partial Z}{\partial y}, -\frac{1}{f_y}\left(y\frac{\partial Z}{\partial y} + Z\right), \frac{\partial Z}{\partial y}\right]^T \tag{4}$$

Then the normal error is defined as

$$E^n = \sum_i [T_x(P_i)\cdot N_i^c]^2 + \left[T_y(P_i)\cdot N_i^c\right]^2 \tag{5}$$

The optimal surface is then given by

$$\arg\min_Z \gamma E^p + (1-\gamma)E^n \tag{6}$$

where the parameter $\gamma \in [0, 1]$ controls how much influence the positions and normals have in the optimization. The two error terms are measured in units of squared distance and therefore l is dimensionless.

3.2. 3D MEASUREMENT APPLICATION PROGRAMMING INTERFACE (API)

The implementation of remote access can be achieved through the Application Programming Interface (API). The objective of the API development is to provide a Graphical User Interface (GUI) to allow the user to establish and control communication lines with Web-enabled equipment, for example the RP machine remotely. Therefore, the API allows the user to view or measure or operate the part through Machine Vision Systems (MVS), a Web camera and "remote desktop" provided by Microsoft® Windows. The current 3D measurement API performs 3D inspection using point clouds to measure geometric elements like plane, cylinder, circle, sphere, boundaries, and so on. It extracts features directly from point clouds and gives feedbacks like standard deviation (average error), tolerance and distribution. Also it gets color mapping from surfaces or contours comparison and label edition on particular points for inspection. The inspector then can classify the part into Pass or Fail categories. The 2D inspection function can show the inspector the high-resolution images taken during the scanning process that are used to generate the accurate 3D model. The 2D inspection function can also lead the inspector to the MVS for traditional 2D inspection (see Figure 3 and Figure 4).

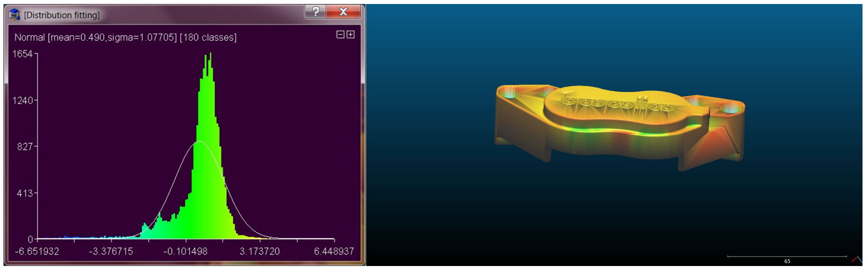
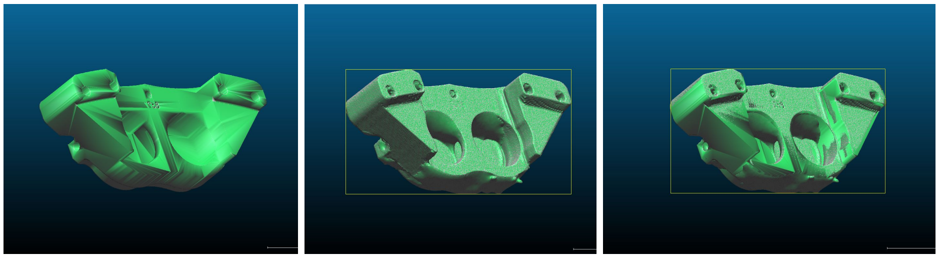


Figure 3. Distribution from 3D Measurement (Left) and Color Mapping of 3D Inspection (Right).

3.3. REGISTERATION OF 3D MEASUREMENT

Before doing 3D measurement, we need to register the two models to be compared. The first step is to scale the two models to make sure they are expressed in the same units. First, choose an accurate element, visible in the two models, such as edge, cornice, line or every other rectilinear element. Then, measure the distance, D_{max} between the two specific points on the model with the larger scale, and repeat the process on the other model and get the corresponding distance D_{min}. Eventually, compute the scaling factor $S_f=D_{max}/D_{min}$ and apply the it on the smaller model in the f_x, f_y and f_z fields of modify tool of the 3D measurement API. In the second step, we roughly register the two models with translate and rotation tool of the API, and then use the Iterative Closest Point (ICP) algorithm to precisely register and finish the superimposition of the two models (Figure 4).



(a) Scanned model (b) Standard model (c) Registered models

Figure 4. Register the Two Models before 3D Measurement Using the Iterative Closest Point (ICP) Algorithm.

The default way to compute distances between two point clouds is the "nearest neighbor distance". For each point of the compared cloud, the API searches the nearest point in the reference cloud and computes their (Euclidean) distance. If the reference point cloud is dense enough, approximating the distance from the compared cloud to the underlying surface represented by the reference cloud is acceptable. But if the reference cloud is not dense enough, the nearest neighbor distance is sometimes not precise enough. Therefore, the 3D measurement API takes an intermediate way to get a better approximation of the true distance to the reference surface. When the nearest point in the reference cloud is determined, the idea is to locally model the reference cloud surface by fitting a mathematical model, e.g. Delaunay triangulation, on the 'nearest' point and several of its neighbors. The distance from each point of the compared cloud to its nearest point in the reference cloud is replaced by the distance to this model (see Figure 5). This is statistically more precise and less dependent on the cloud sampling.

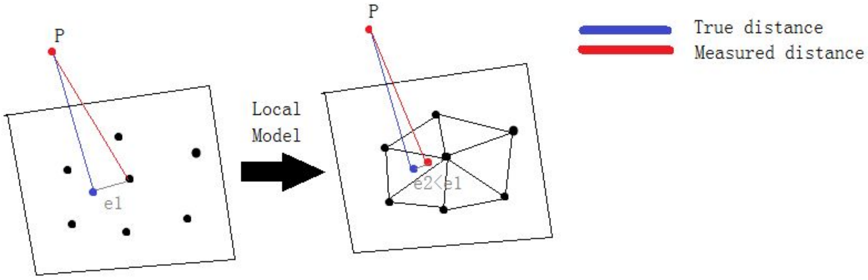


Figure 5. Compute Distances between Two Point Clouds Using Local Model.

4. CASE STUDY

The present case study refers to the occurrence of two common defects with plastic injection final parts and the change on dimensions after plastic injection. Plastic injection defects can lead to weakness and even failure by not accomplishing the minimum strength requirements. These requirements may be accomplished but in case aesthetic appearance becomes a main requirement, it may be affected by such defects. Shrinkage is an important aspect to consider during plastic injection due to its importance for the good fit and function of final products. Final inspection for this process consists of visual and first article inspection performed by the operator in charge. Coordinate Measurement Machines may also be used to assure dimension accuracy to final product. If defects are found, if possible, parts may be manually fixed, or in case it is not possible to fix it will be sent to scrap. Defects may happened randomly due to many factors, or they may occur concurrently, and need to be checked to make sure there is no other issues either with the mold, molding process, or materials being used. If dimensional accuracy is not accomplished, parts are simply scrapped.

Plastic injection is a manufacturing process in which a thermoplastic is melted and injected by pressure into a mold cavity, cooling down and getting the shape of the mold cavity. Plastic injection has become a very useful technology for various industries like automotive, aerospace, and others. Molds are created with metal materials, usually either steel or aluminum, depending on material properties and specifications. When designing a part for plastic injection, it must be very carefully engineered to facilitate the injection and de-molding process. Part small and delicate features, material of the mold, material to be injected, capacity of the molding machine, are some of the important points to take into account when using this process. These are some critical factors during injection molding (Figure 6): (1) Temperatures (plastic melting, barrel, nozzle and mold); (2) Plastic flow rate; (3) Plastic pressure AND (4) Plastic cooling time and rate.

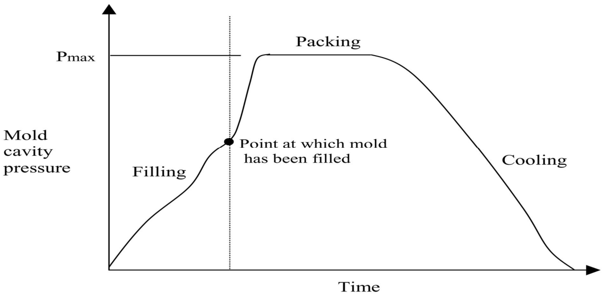
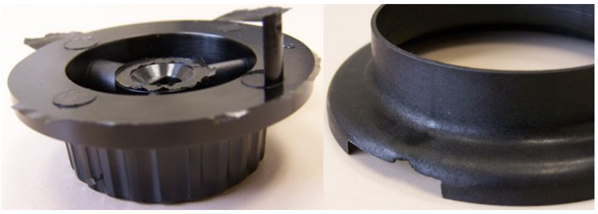


Figure 6. A Couple of Critical Factors during Injection Molding.

When a part is manufactured this way, there are several defects that may come up during the process. At this point all employees involved in the process are trained to spot these issues. This means that quality control is dependent on a human being been able to identify such defects. Depending on the defect, the part may not meet its requirements and may not function as it was intended for. There may be little details easily fixable, but there may be other that will not work at all. Some of the cosmetic defects may include bubbles, cracking, discoloration, flashing, gouge, haze, scratching, among others. A more complete list of defects and definitions could be developed. In this paper, cosmetic defects like flashing and short shots are focused on (see Figure 7).



Flashing Short Shot

Figure 7. Examples of Two Cosmetic Defects – (1) Flashing and (2) Short Shot.

Flashing occurs when there is a gap big enough for molten plastic to leak out of the cavity through the line of intersection between two halves of the mold. There are certain specifications that could be follow to avoid this imperfection, but most of the thermoset materials used in plastic injection will flash regardless of press and mold. Short shots refer to the situation when there is too little molten material been injected into the mold and the cavity does not fill properly. Rejected injection molded parts may cost a lot of money if there is not a good quality control plan established and if personnel don't have the right training to be able to capture defective parts on time. It is required to find any defects before shipping or using injected parts to be able to fix, rework, or simply scrap them.

There are certain points that need to be clarified to solve the problem of surface finish [16]. First there should be an examination of the precise location of the defect and find out when it actually was evident. Then we need to specify if the defect occurs with every shot or irregularly, if it is always on the same cavity or at the same place in the molding, if we can predict the defect and if it only happens with one machine or others. If we are capable to identify defects on time, we can make sure the proper measurements are taken to avoid major losses due to the lack of information.

To demonstrate the proposed methodologies for E-quality control in an industrial setup, automotive brake calipers that contain different types of defects are used for testing. This part requires certain specifications for color, size, durability, and if these specifications are not met part needs to be scrapped. If part is undersize, it will not fit properly and will cause problems. In the other hand, if it fits perfectly fine but the color is not the specified, it will work just fine but the appearance of the car interior will not be appropriate. It all depends on what kind of defect the part has to determine if it is usable or not.

4.1. DESIGN OF EXPERIMENTS

Six key dimensions: length (L), width (W), diameters of the two circles (D1, D2, D3, D4), and horizontal center-center distance between the circles (CCL1, CCL2), are shown in Figure 8. These pieces are machined with a +/- 0.25 mm tolerance limit. Pieces whose dimensions lay outside this range are rejected. Green surfaces are critical since it is in contact with breaking pad.

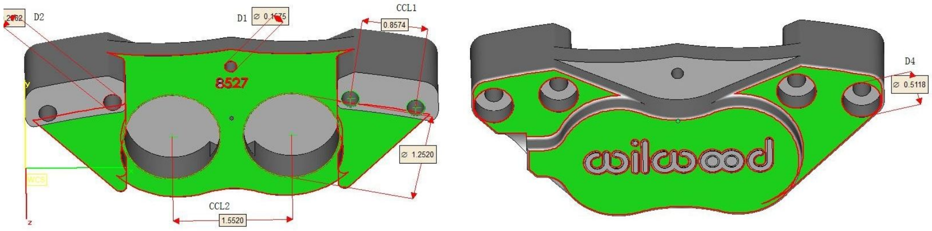


Figure 8. Six Key Dimensions for Brake Caliper Quality Control.

Twenty five pieces are made, with a few purposely machined out of tolerance limits on each dimension. Several pieces from each type are mixed up and fed through the conveyor belt for inspection. The flowchart for the testing is shown in the figure below (see Figure 9). Although this object does not pose any serious measurement challenge, it presents a moderate complexity for the requirement of our work (see Figure 10).

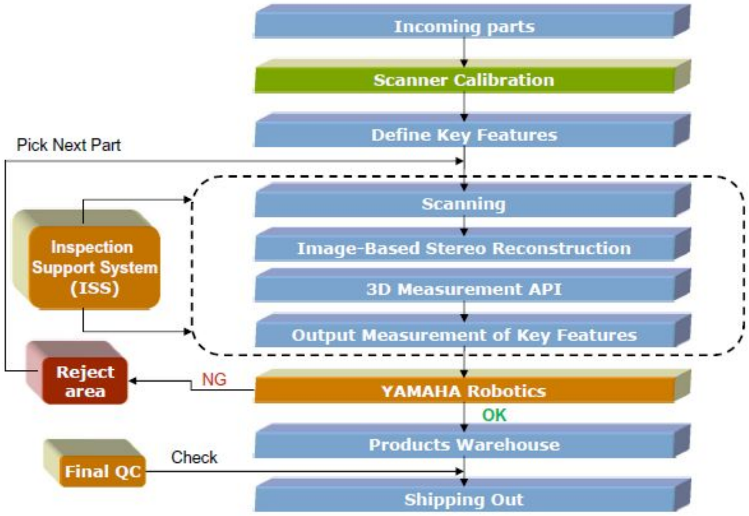


Figure 9. The Flow Chart of the Automotive Part Quality Control.

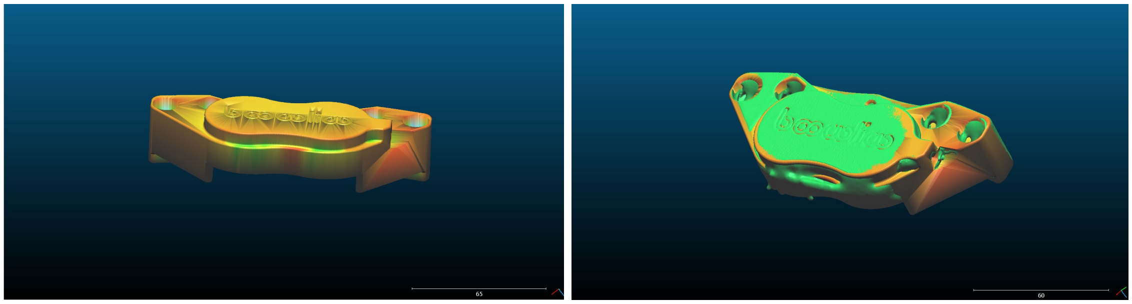


Figure 10. 3D measurement for 3D Inspection Using Color mapping.

4.2. CLASSIFIATION ANALYSIS

The following tables show the comparison of the classification analysis using 2D Machine Vision System, 3D Quality Control System and the efficiency test results. From Table 1 and Table 2, we can see that the 2D Machine Vision System can achieve accuracy of 0.84 and with precision of 0.895 while the 3D Quality Control System can achieve both accuracy and precision of 1compared with the actual efficiency test results.

Table 1. The confusion matrix of the 2D Machine Vision System (MVS) classification results.

	Predicted	
Actual Efficiency Test	Pass	Fail
Pass	17	2
Fail	2	4

Table 2. The confusion matrix of the 3D Quality Control System (QCS) classification results.

	Predicted	
Actual Efficiency Test	Pass	Fail
Pass	19	0
Fail	0	6

5. CONCLUSIONS

This paper presents a novel 3D E-quality control system that integrates photometric stereo reconstruction for classifying the parts into different categories. This 3D quality control system offers rapid quality control inspection of complex parts while the non-contact photometric scanner provides documented proof that manufacturers are meeting specifications by providing traceable data and accurate 3D models of complex parts, castings, stampings and more. The system captures millions of data points in just minutes to represent the true and full geometry of the complex part. The systems then compare the scanned 3D models to computer aided design (CAD) models to provide accurate and timely measurement feedback for quality control, helping provide proof that the produced products meet the required specification. The data extracted from brake caliper was used as case study to demonstrate the proposed methodology. Results show that the new methodology yielded superior results compared to the traditional brake caliper inspection approach with very high classification accuracy. The following conclusions were generated from this approach: (1) Measure the whole part, not just a few points, providing greater assurance that requirements have been met and improving overall quality. (2) Scan and store 3D models of your complex parts for future viewing, sharing, analysis and measurement. (3) Create accurate digital models of existing components for re-design or re-engineering purposes. (4) Help replicate complex parts, tooling or parts that are no longer in production.

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