Utilizing Computing Power to Simplify the Inspection Process of Complex Shapes

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1. Introduction

The exponential increase of computing power, predicted by Moore's law [1], influences modern inspection capabilities. The availability of computing power allows the design and implementation of affordable sensing devices employing numerical analysis to generate measurement results. In particular, modern laser sensors [2] benefit from computing power by providing rapid and accurate range measurements. In consequence, modern non-contact CMMs are capable of collecting large amounts of accurate data.

However, the current availability of computing power allows enhancing and further simplifying the inspection process. The contribution of computing power to the inspection process may be clarified by comparison to the process of checking-out of a store. The checkout process is similar to the inspection process of parts since products are evaluated and each one is assigned a number. In the checkout process this number is the product's price while in inspection it is a measurement or a deviation from the nominal condition. Another analogy is that feedback information collected in the checkout process can be used to manage the inventory levels in a store, while feedback information collected during inspection can be used to control the accuracy of the manufacturing process. Technology has considerably contributed to both processes by changing the supporting devices and methodologies throughout the years. Table 1 summarizes those changes and lists the advantages gained by such technological progress.

Technology applied for Inspection of manufactured parts	**Technology applied for checking-out of a store**	**Advantage contributed by the technology**
Gages and precision equipment	Abacus, pen and paper	Accurate results
Coordinate measuring machines (CMMs)	Cash register	An automated procedure with increased precision made possible by the introduction of computing
Non-contact laser sensors	Barcode reader	An advanced acquisition method with increased scanning rate
Computational alignment algorithms	Omnidirectional barcode reader	The ability to disregard the objects orientation during inspection

Table1 – Technological advances and their effect on the checking-out process and the process of inspecting manufactured parts.

As revealed in table 1, computing power enabled automating both processes by gradually removing human interaction factors from the process and by this improving the repeatability and the speed of each process. For the checking-out process, the first improvement attributed to computing power resulted in increased speed and a reduced chance of human error by transferring calculation operations from the brain to the cash register. In the inspection process, computing power contributed to development of CMMs that could repeatedly follow a predefined inspection plan and automatically perform accurate measurements. The next improvement in both processes enabled acquiring data with no contact with the object and it is related to both computing power and sensor technology. In the case of the barcode reader, it virtually removed the possibility of human error and increased the speed of the checkout process considerably. The introduction of non-contact laser sensors contributed to the inspection process by increasing the rate of data acquisition.

Further improvement in the checking-out process came with the modification of the barcode reader to be omnidirectional in nature. With this technology, scanning the barcode on the product became so fast and simple that in many cases the customer could perform the cashier's duty. Instead of searching for the barcode and scanning it with a hand held device from a certain direction, the cashier can now pass the product through the reader that automatically reads the barcode information with little regard to product orientation. With this technology the user need not be aware of the location of the barcode on the product nor be concerned with the direction and position of the product during scanning. These benefits offered by the omnidirectional barcode reader for the checkout process have not been fully realized in the inspection process. Nevertheless, similar simplification of the inspection process can be achieved by employing computational alignment algorithms in conjunction with non-contact sensor technology when complex shapes are inspected.

2. Computational alignment for inspection of complex shapes

Such simplification of the inspection process lies in alteration of the part alignment phase. The purpose of part alignment is to establish a common reference coordinate system for the designed model and the measured points. Collected 3D measurement points are represented in the machine coordinate system while the part design defines the part coordinate system. In order to calculate the deviation of a 3D measured point from the nominal shape those two coordinate systems have to be aligned.

The traditional alignment process is essentially a calibration process where known features or locators [3] are used to establish the reference coordinate system. However, when parts with complex geometry are involved, it is possible to perform alignment using computational methods. The complexity of the object's shape itself can provide sufficient feature characteristics by which coordinate system correspondence can be established. This computational alignment method is referred to in the literature as registration of coordinate systems [4-8]. During registration, a transformation between the coordinate systems is calculated by best fitting measured 3D points to the nominal shape. The use of a computational approach for alignment offers several advantages from the process point of view:

1) Rigorous definition of datums in the design phase for the sake of inspection is not essential when employing a computational alignment approach. The CAD model itself defines the nominal shape by which the coordinate systems are registered. This significantly simplifies the design procedure especially when it is difficult to assign a datum or when modern manufacturing techniques such as rapid prototyping [9,10] are involved where definition of a datum is unnecessary.
2) Data acquisition and part alignment can be separated into two different unrelated processes where part alignment follows the physical measurement process. Thus, measurements can be acquired without concern of part orientation and position. Such free-orientation inspection can be highly beneficial as it can eliminate the need for a fixture to hold the part during inspection. In turn, fixtureless inspection allows further simplification and enhancement of the quality control process by removing the need to design, manufacture and use the fixture.
3) Inspection planning for non-contact measurement equipment can be simplified in many cases to reduce user interaction. The need to make contact with a specific point on the object can be replaced with generic scanning patterns enhanced with algorithms predicting the best vantage [11,12] and with methods to compensate for sensor limitations in real time.

Other benefits from employing a computational approach for part alignment present themselves at the level of the inspection equipment. Such benefits may include: 1) simpler calibration procedure; 2) systematic error compensation at the post-processing stage [13]; 3) improved part exposure during inspection as there are less occlusion opportunities by a fixture.

Computational alignment may not always be applicable as it requires intense processing and large amounts of inspection data that adequately describe the shape to be registered. Furthermore, it cannot easily handle repetitive shapes, as the shape itself provides the information required for alignment. Nevertheless, the advantages offered by computational alignment are substantial and worth pursuing, especially when considering the constant increase in computing power.

3. Registration methodologies

This increase in computing power permits overcoming the computational hurdle associated with matching large amounts of inspected data to a complex shape. Utilizing computational power for alignment is common in Reverse Engineering applications. Alignment solutions are essential for assembling point clouds acquired from different views of an object. In Reverse Engineering, many times an object is scanned from several different directions as demonstrated in figure 1b. Each scanned point cloud is represented in its own coordinate system and is referred to as a range image. Later, range images are registered and assembled together to represent the measured shape from all around. The registration process in Reverse Engineering applications is difficult as each range image is registered in relation to other images with no knowledge of the scanned object.

When applied to inspection purposes, however, the alignment problem is simpler as the shape of the inspected object is known, yet requirements are more demanding, such as in the case of measurement accuracy. In contrast to Reverse Engineering, when registration is employed for inspection, the known geometry of the inspected part, represented by a CAD model, is used as the nominal shape to which points can be registered. Only recently, such computational part alignment, through registration algorithms, was introduced for inspection purposes [14-16]. These methods, however, do no address the advantages to the inspection process gained from computational alignment.

A computational alignment approach suitable for inspection purposes involves two main stages:
1) **Initial pose estimation**: In this stage, an initial transformation solution is determined where the measured points and the nominal shape are roughly aligned. The solution need not be accurate but close enough for the next stage. Examples of such alignment methods can be found in [7,17].
2) **Solution refinement**: In this stage the previously obtained solution is refined using the Iterate Closest Point (ICP) algorithm [4-6]. The ICP algorithm iteratively minimizes the distance function between a cloud of points and a predefined shape.

After registration has been preformed, the distances between the registered point cloud and the object can be calculated to reflect the deviation of each point from its nominal position. The results could be visualized in 3D using a color scale corresponding to the distances as shown in figure 1d.

4. Results

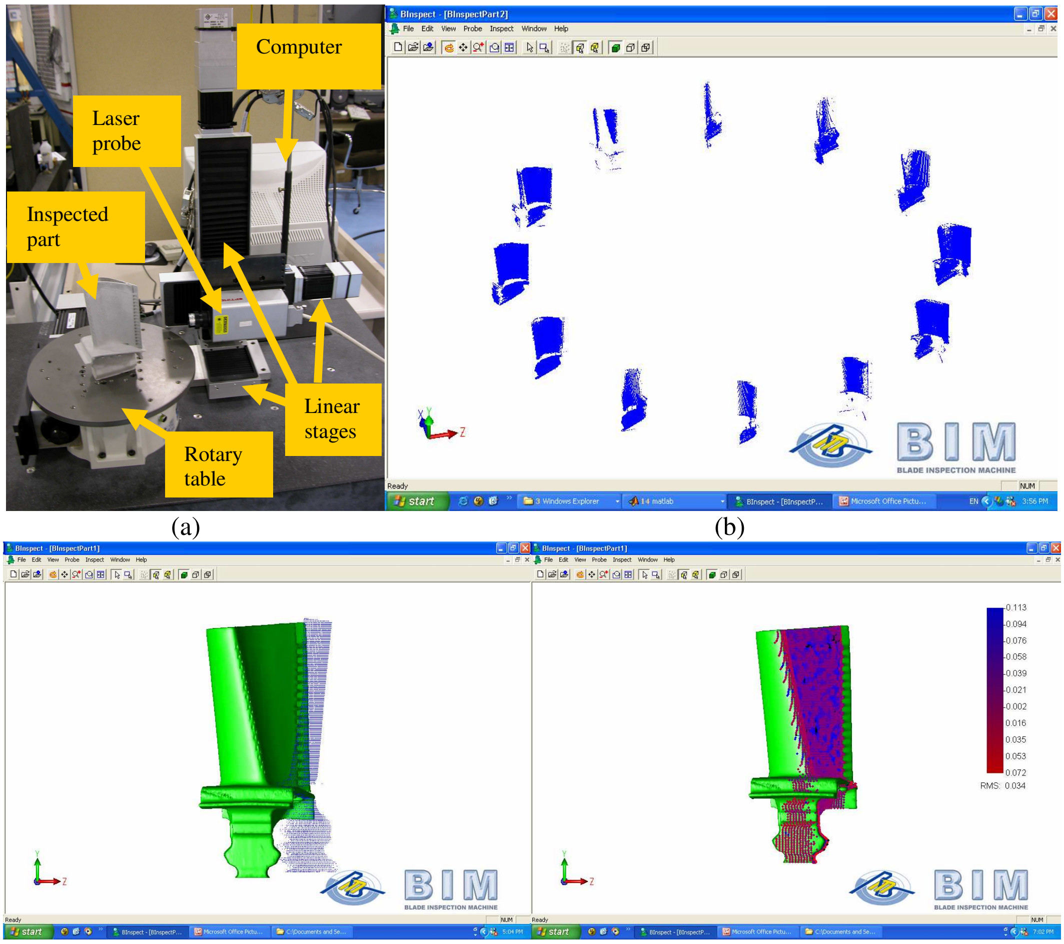
Computational alignment is especially applicable when complex shapes, such as the shape of a turbine blade are to be inspected. Measurement of turbine blades using Reverse Engineering techniques and non-contact sensors has already been suggested in [19]. Non-contact inspection of turbine blades provides many advantages over current methods employing contact probes, especially when computational alignment is used. For this reason the shape of a turbine blade was selected as an example to demonstrate the alignment methodology.

A turbine blade shape was manufactured using Rapid Prototyping from an STL model. In this manufacturing process, defining a datum was unnecessary. Thus, there was no predefined coordinate system by which to align the part during inspection. Instead, the STL model itself was used as a reference to determine the manufacturing quality. The part was inspected while it was held by its own weight with no fixture. Figure 1 summarizes the inspection process that was preformed using the Blade Inspection Machine (BIM) that was developed for the purpose of accurate inspection of complex shapes. The BIM employs a non-contact laser probe mounted on three linear stages and it has a rotary table on which the part can be mounted. With the BIM, the part was inspected from several vantages to acquire all-around information from the inspected part as demonstrated on figure 1b. No special pre-alignment procedure was required during the acquisition process. Part alignment and analysis were preformed after the data acquisition was complete.

Figure 1c shows a scanned range image and a model in their original coordinates prior to alignment. The initial pose estimation stage was preformed, in this case, by the user. Figure 2 shows the progress of the ICP algorithm on two regions of the model, visualizing the closing gap between the points and the part with each iteration. The alignment process is complete with the convergence of the ICP algorithm. After registration, the deviation of the manufactured part from the nominal model can be calculated for each measured point. The distance information can be coded into color and displayed as seen in figure 1d. In this example, part alignment was preformed in the virtual world after inspection rather than in the physical world prior to inspection. This demonstrates the ability to decouple the data acquisition and the alignment processes. This is an important advantage as the alignment procedure can be repeated without repeating the inspection process, making the entire procedure less prone to errors.

5. Conclusions

The increase in computing power opens new possibilities to enhance inspection capabilities. Computing power has already contributed to development of accurate measurement equipment. However, the potential of employing computing power for inspection purposes has not been fully realized. The inspection process can be simplified significantly by computational alignment. The advantages gained from performing part alignment virtually instead of physically are considerable, especially when complex shapes and modern manufacturing techniques are used. Further research into computational alignment algorithms, especially initial pose estimation algorithms, will result in a faster and a less restricting inspection process.



(a) (b)

(c) (d)

Figure 1 – The part inspection process: (a) The Blade Inspection Machine (BIM) and the rapid prototyped part mounted on the BIM; (b) a screen shot of the clouds of points acquired from twelve vantages all around the part as displayed in the BIM software. (c) The cloud of points acquired by the BIM in machine coordinates and the model in part coordinates. (d) The final registered cloud of points compared to the model. Deviations are portrayed using a color scale.

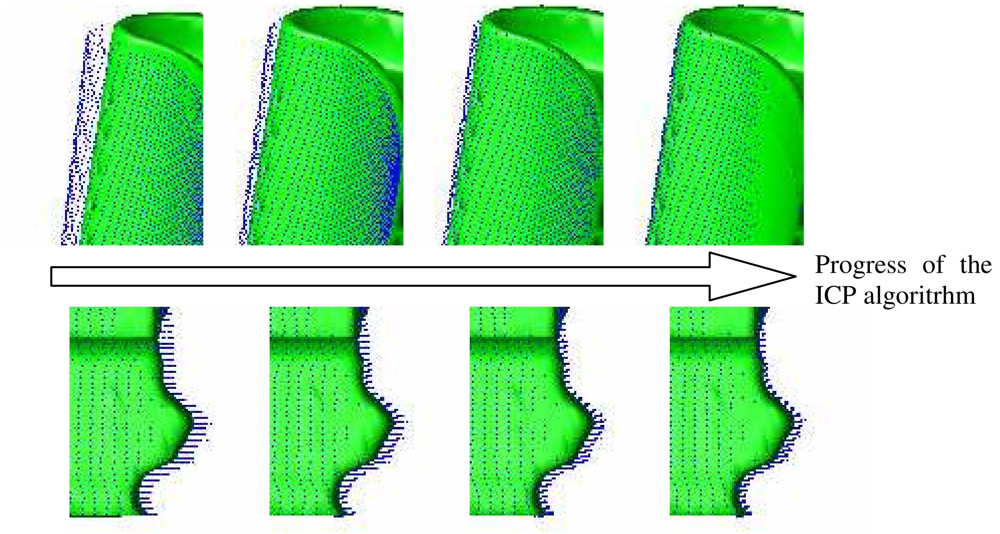


Figure 2 – Progress of the ICP algorithm. The top and bottom rows show two different regions on the model. The results of the first iterations of the ICP algorithm are displayed left to right. The leftmost pictures correspond to the initially estimated pose of the point cloud. It can be seen how the cloud of points gets closer to the model with each iteration.

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