Automated Apparatus for In-Line Inspection of Mass Produced Custom Parts

Prof. Glen Bright and Shaniel Davrajh
School of Mechanical Engineering, University of KwaZulu Natal,
Durban, South Africa
202500776@ukzn.ac.za

Abstract

The progression of industry, toward mass personalisation, initiates added complexities to the quality control and part inspection processes. Mass produced custom parts require varying, and sometimes unique inspection routines, with only certain features of a part requiring inspection. Inspection of these parts must occur at a higher frequency than batched production. This leads to an increase in the inspection time involved. There is a need for current inspection processes to undergo cost-effective modifications to facilitate flexible inspection of custom parts, whilst maintaining batched production rates. This paper details the modification of an existing Automated Visual Inspection System (AVIS), using Mechatronic Engineering as a design tool, to become more applicable and suited to a Reconfigurable Manufacturing Environment (RME). The AVIS was a constituent of a Computer Integrated Manufacturing (CIM) cell. The modified apparatus was able to perform part inspection at a faster rate than was achieved by the previous design.

1 Introduction

Industrial manufacturing is globally gearing toward mass producing custom products. The degree of competitiveness of modern production environments can be seen as a function of the ability of a process to reconfigure itself to handle varying product requirements, associated with mass customisation. The strategies adopted to increase the competitiveness of a manufacturing process are Product Design for Mass Customisation (PDMC), and Mass Customisation Manufacturing (MCM) [Qiao et al, 2006]. The concept of PDMC allows the customer to select a design configuration from a range of choices, at various stages of the manufacturing process. With MCM, a production line is designed to provide quick and flexible response to unanticipated changes in manufacturing trends. CIM cells are suited to emulate an RME, displaying the characteristics of an MCM system.

Non-contact quality control and part inspection are important procedures for mass producing custom products, as they ensure that the products lie within specified design tolerances. Although no value is added to the product during this stage of manufacturing, the importance of quality control and part inspection cannot be overemphasised. These processes are capable of relaying information about the nature and location of flaws in a production line, and materials used, aiding in the improvement of both product and process [Eganza and Bright, 2007].

Batched production facilitates the use of statistical inference as a quality control method. This method of inspection is not suited to inspecting customised parts. Current inspection processes need to therefore undergo necessary, cost-effective modifications to facilitate flexible inspection of custom parts, to maintain high quality standards whilst maintaining batched production rates.

The objectives of this project were to:

- Modify an existing AVIS, using Mechatronic Engineering as a design tool, to become more applicable and suited to an RME by incorporating intelligence to the system
- Research, design, develop and implement a more suitable sensor positioning system for in-line inspection
- Enhance the modularity of the previous inspection system
- Perform in-line inspection of custom parts at higher rates and frequencies than previous methods, in an existing CIM cell

Major considerations involved with the modified design were cost, modularization and standardization of the system.

2 Background

2.1 Quality control and part inspection

Mass produced products are required to be inspected during and after manufacture, in order to ensure that quality standards are adhered to [Birchon, 1975]. Quality control parameters in inspection routines include verifying part dimensions, assembly integrity, shape, surface finish, and colour. The production of batches of products allows the use of quality control based on the process of statistical inference, where only a small percentage of the batch of products is inspected. The inspection of these few sample products may lead to the possibility of two errors, namely consumer risk and producer risk.

Consumer risk is defined as the acceptance of a batch of defective parts, based on the outcome of the inspection of the samples being acceptable. Producer risk is where a batch of acceptable parts is rejected based on the result of the inspection of the samples being unacceptable. Consumer risk involves the possibility of a customer purchasing defective products. This leads to unwanted product recalls which often result in significant financial losses. Producer risk involves the possibility of significant wastage of materials, as well as time and financial losses, in the manufacturing process [Mayor J.R.S, 2000].

The difference between batched and customised production is that mass produced custom products require varying, and sometimes unique inspection routines, and so inspection of these parts must occur at a higher frequency than batched production. The increase in frequency of inspection results in an increase in the production time involved with the manufacturing process. Machine shops provide the necessary parts for assembly of engines and gearboxes. These parts are sometimes modified and customized for convenience.

2.2 Mechatronic Engineering approach

The Mechatronic engineering approach to the design of engineering systems can be currently viewed as the integration of Mechanical, Electrical/Electronic, Control, and Software engineering at all levels of the design process [Stadler, 1995]. The aim of this concept aims to provide the necessary structure and methodology by which optimised, efficient, and practical systems can be designed and developed (http://www.answers.com/mechatronics, 2007). This approach entails a system being conceptualised, then divided into subsystems. These subsystems are then further categorised into the core elements of Mechatronic Engineering.

3 Design

3.1 AVIS

The AVIS was designed to perform automated multi-faced part inspection using PC based technology and a single digital camera. The sensor was mounted on a C shaped track (as shown in Fig.1.), perpendicular to the direction of flow of products within the machine, achieving various sensor heights. A rotational part manipulation platform allowed for the part to rotate relative to the sensor, allowing for multi-faced access. The AVIS was able to produce 2D images of a product, which were used for design purposes.

The structural frame of the AVIS was designed to have high rigidity and vibration damping characteristics, thus minimising vibrations imparted to the sensor, during operation of the machine. This allowed the inaccuracies associated with the acquisition of images, to be reduced [Mayor J.R.S, 2000]. The AVIS was designed having a rectangular-volume base with a trapezoidal-volume upper-half, which was used as the inspection workspace. Fig.1. shows the mechanical structure designed for the AVIS, along with the sensor housed on the track.

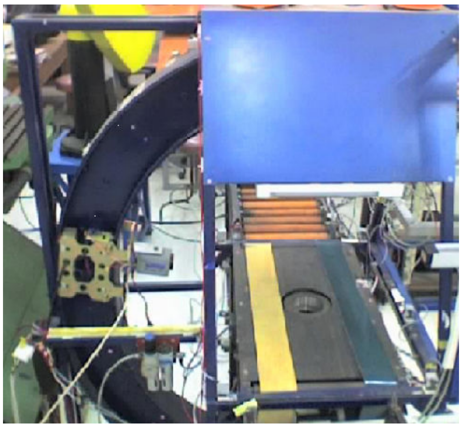

Fig.1. The AVIS [Mayor J.R.S, 2000].

The modified platform, referred to as the Non-Contact Automated Inspection System (NCAIS), differed from the AVIS, in that the part inspection process was performed during motion of the part. The machine therefore required intelligence to facilitate in-line inspection of specified regions of a mass produced custom product. The system was broken down into four subsystems namely: part identification system, sensor positioning system, part centralisation system, and the part accept/reject system [Bright et al, 2007].

3.2 Mechanical Design

The NCAIS used the mechanical frame as well as the materials handling system (conveyor) of the AVIS as an initial platform. The base of the NCAIS was *600mm x 800mm x 800mm* and was made of 25mm square mild steel tubing. The trapezoidal inspection volume (neglecting sensor and mechanical component volumes) was *550mm x 800mm x 600mm.* There were many sensor requirements that influenced the design of the mechanical structure, namely sensor position and orientation for:

- Collision free motion: avoidance of collisions between sensor and frame, or sensor and part during inspection.
- View angle: The angle between the incident beam from the light source and the surface normal of a point being measured. This should be less than the limit angle γ.
- Field of view: The range of data (area) that can be acquired by the sensor
- Depth of view: the distance from the area being inspected should be within a specified value [Eganza J and Bright G, 2007].

The multi degree of freedom sensor positioning system was designed using high tensile steel threaded bar instead of high precision leadscrews. Brass nuts were tapped and secured to a slider mechanism, mating onto the threaded bars which allowed for linear motion along the x and y axes. Stainless steel support rods were press fitted parallel to the threaded bar for support and resistance against torsion components which could have lead to inaccuracies in the sensor position. Rubber pads were placed between some mechanical components in order to reduce the amplitude of vibrations imparted to the sensor during the positioning process. Brackets for mounting the new mechanical structure onto the AVIS were made from Aluminium. Fig.2. below is a drawing of the apparatus, including the global co-ordinate system, drawn in Solid Edge V17.

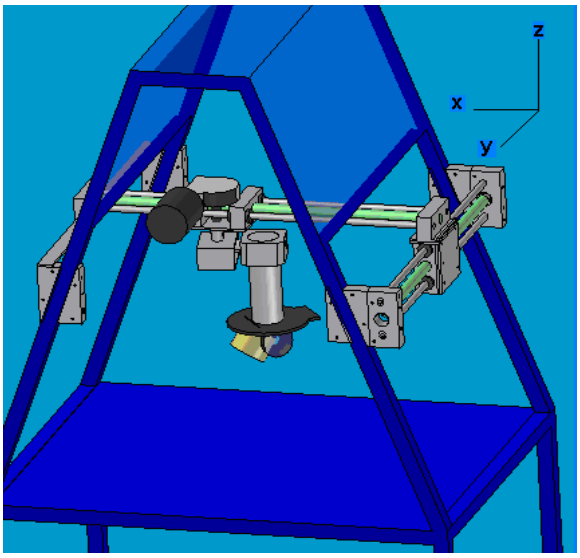

Fig.2. Illustration of NCAIS mechanical structure, drawn in Solid Edge V17.

The rectangular volume that was accessible for inspection by the sensor was 2*50mm x 450mm x 500mm.* The actuators selected in the design were 12 V DC motors and servos, in order to fulfil the torque requirements imposed on the system by the sensors and mechanical members of the structure. The part centralisation system used leadscrews, driven by DC motors in order to position the channelling guides.

Modelling and Simulation

The static loading on the mechanical members in the x and y directions was analysed using both analytical methods and a simulation package. The analytical solution for each direction (considered independently) excluded the use of support bars for simplicity and safety factor purposes (used as a worst case loading condition). This solution viewed the threaded bar as a beam with both ends having fixed constraints (no degrees of freedom, as shown in Fig.3.). The loading was then considered as two point loads (two contact points between load and bar), of equal magnitude W, with the maximum deflection at the mid-span.

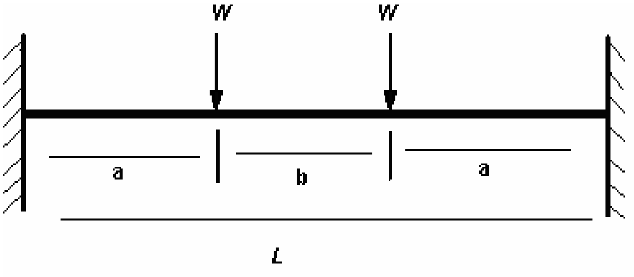

Fig.3. Static loading diagram

The corresponding equation for this loading condition is given by:

$$\text{Max deflection (at L/2)} = \frac{Pl^3}{6EI}\left(\frac{3^2}{4l^2} - \frac{a^3}{l^3}\right) \qquad (1)$$

where E (Young’s Modulus of Elasticity) and I (Moment of Inertia) are the material properties of the beam [Gere and Timoshenko, 1990].

A stress and deflection analysis for the loading conditions in the x and y directions were then simulated using Autodesk Inventor Professional V11, shown in Fig.4. The maximum equivalent stress calculated by the simulation was 35.82 MPa, with the maximum deflection being 0.216mm.

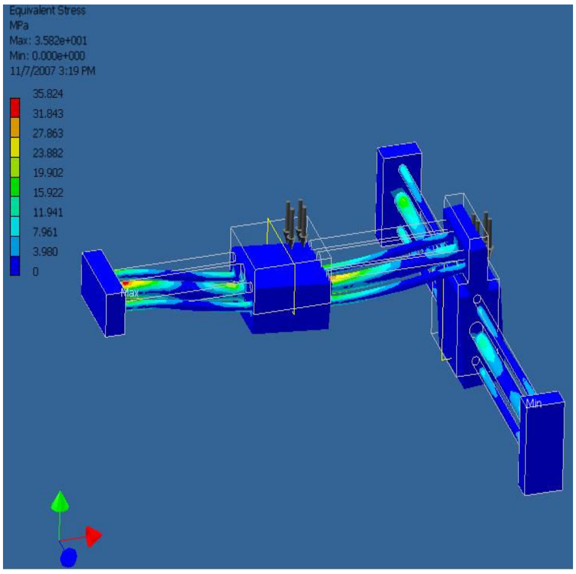

Fig.4. Simulated stress analysis

3.3 Electrical/Electronic Design

The circuitry implemented allowed for control and operation of the motors and sensors, as well as the signal conditioning required for the applications. A visual sensor, namely the DSE XH5096 USB camera, was used for image acquisition. Part identification was achieved by use of a stationary laser barcode scanner (shown in Fig.5.).

Fig.5. The PSC VS1200 barcode reader used for part identification

Once a barcode was scanned, it was compared to existing codes in a database, stored in the controlling PC. The orientation of the part was calculated by assuming predictable barcode positioning.

Camera Modelling

The model used for obtaining the position and orientation of the sensor in space was discussed by [Stadler, 1995] as shown in Fig.6. Frame O_o depicts a reference frame fixed in space. Frame C is the camera frame with its origin at some point on the camera. The sensor reference frame is denoted O. The co-ordinates of a pixel on the senor are P(x, y, 0), with length r. The camera has a panning motion (rotation θ about the Z_c axis) and a tilting motion (rotation α about X_c). An expression for relating the pixel P(x, y, 0) to a global frame can be stated as:

$$r_0 = C_m r \qquad (2)$$

where C_m is the camera transformation

The camera transformation for this model is:

$$C_m = \begin{bmatrix} -S\theta S\alpha & -C\theta & -S\theta C\alpha & aC\theta - bS\theta C\alpha + cS\theta S\alpha + a_0 \\ C\theta S\alpha & -S\theta & C\theta C\alpha & aS\theta + bC\theta C\alpha - cC\theta S\alpha + b_0 \\ -C\alpha & 0 & S\alpha & bS\alpha + cC\alpha + c_0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

where [a, b, c, 1] are the coordinates of the sensor relative to the camera frame and [a_o, b_o, c_o,1] are the co-ordinates of the camera relative to the global reference frame.

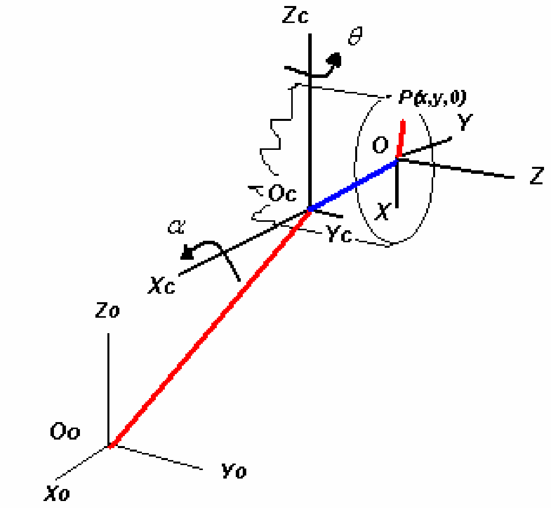

Fig.6. The Camera Model [Stadler, 1995]

Electronic Layout

Electronic speed control of the actuators, for the part centralisation and sensor positioning systems, was accomplished by use of a host PC and accompanying slave controllers. The Atmel MEGA 16 microcontroller was selected as the slave controller. Optical encoders were used for speed and position feedback. A single chip could have been used to control two motors in both the forward and reverse directions. It was decided to control each motor with a separate slave microcontroller. Fig.7. illustrates the physical layout of the components of the system.

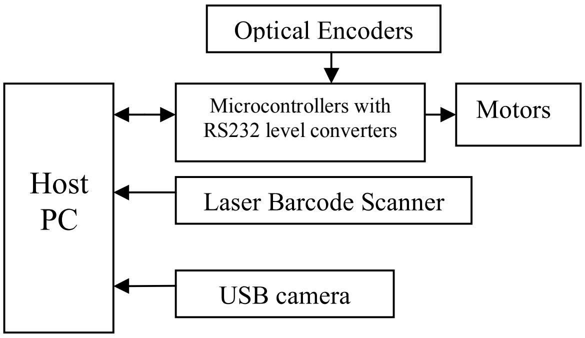

Fig.7. Physical layout of system

The use of a USB DAQ box was explored as an I/O analogue and digital interface board, in order to acquire data from the sensory circuits. In doing so, plug and play modularity to the system was established. Developed by Eagle technology, this board has an onboard sixteen bit counter that allows real time timing operations such as PID control (http://www.usbmicrodaq.com, 2007). The card is provided with instrument drivers for graphical programming languages such as Visual Basic 6.0.

The lighting design used the approach of ambient light suppression, in which the machine light source provides a light intensity much higher than the ambient light intensity. The lighting system selected was the Avago Technologies' Illumination and Colour Management feedback system (www.avagotech.com). The light sources were placed around the camera lens in a ring structure.

3.4 Software Design

The software design entailed motor control using feedback from the speed and position sensors, as well as image analysis on which the decision process was based. Software algorithms were made less complex by use of the DAQ box, and Visual Basic 6 was the initial programming language used, along with exploration of the image processing toolbox provided in MATLAB 7.1. Other languages such as C and C++ were explored using the WinAVR compiler, for motor control. A flowchart displaying the overall operating sequence of the NCAIS is shown in Fig.8.

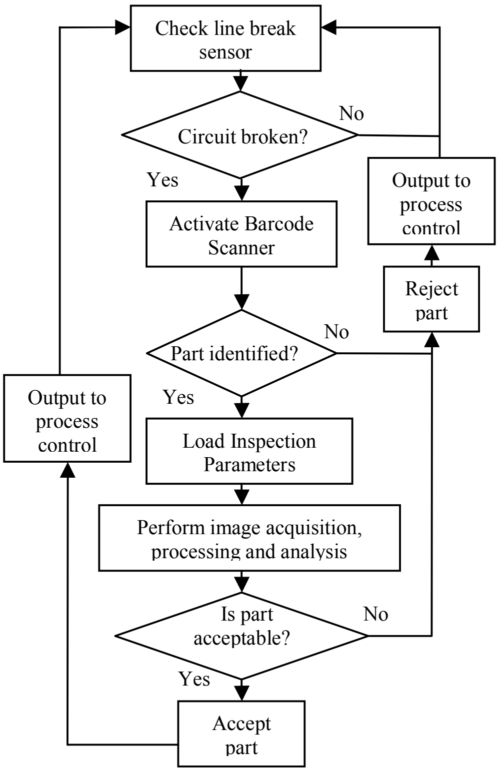

Fig.8. Flowchart displaying operating sequence of NCAIS [Bright G et al, 2007].

The use of Matlab was explored for image processing and analysing purposes. An image of a test part was acquired and then analysed as shown in Fig.9 (a), (b), and (c). This process was used for assembly analysis. Binary conversion of pixels occurred at predefined threshold values, depending on the part being inspected.

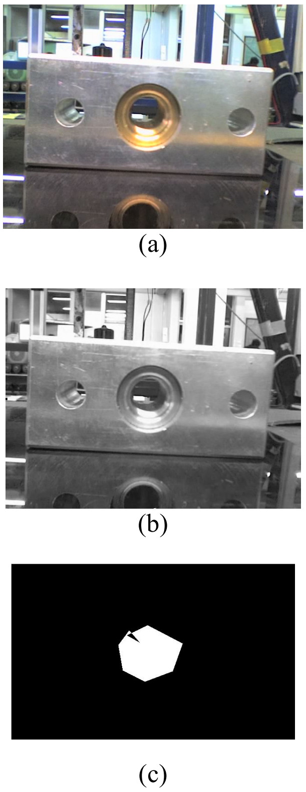

Fig.9. The various image processing tools explored in Matlab V 7.1. (a) Image read (b) convert to greyscale (c) Checking of ROI for assembly validation by means of binary conversion.

4 Results and Discussion

Operation and testing of the entire apparatus was performed, following assembly and testing of the subsystems. The mechanical structure of the part positioning system, as well as the sensor positioning system, performed effectively and reliably. The use of threaded bar lead to a significant cost reduction and some degree of inaccuracy in the sensor positioning. The region of interest being inspected was offset from the centre of the image as a result of these inaccuracies, as well as inaccuracies emanating from minor deflections in the structure. This was accommodated by the image processing software, as is found in MATLAB 7.1, by feature identification and extraction tools.

A characteristic in the design and operation of the AVIS was that the image acquisition process involved the undesired yet necessary stoppage of flow of products in a production line [Bright et al, 2007]. The NCAIS allowed for inspection of a moving part by allowing for a range of velocity differences between the part and the sensor, thus facilitating dynamic access to different regions of interest of that part. The time required for part inspection was reduced by eliminating unnecessary stoppage time, and inspecting only certain aspects (regions of interest) of a product. This made the NCAIS more suitable to RMEs.

The static loading conditions for the mechanical structure were simulated in Autodesk Inventor Professional V11. The simulation showed the maximum equivalent stress to be 35.82 MPa. This was well under the yield stress of the threaded bar (250 MPa) and the stainless steel (approximately 280 MPa). The simulated deflection was 0.216 mm which was insignificant in terms of structural integrity. These results verified that the stresses and deflections involved with the mechanical design were within the acceptable limits of the materials selected. The analytical solution of the loading on the members also confirmed that the material geometries and selection were acceptable. The analytical solution used the case of loading without support bars. This solution of this method would then be used as the worst case scenario for further mechanical development, even though the CAD simulation was more accurate for the system analysis.

A light source was placed around the camera, allowing for the direction of light toward the region of interest, on the part being inspected. The low cost lighting solution was able to maintain a variety of lighting conditions by means of dynamic RGB tuning and dynamic colour changing features of the system. The variations in lighting conditions (intensity and colour) allowed for higher contrast in the images acquired, according to the inspection requirements. This resulted in a more reliable image acquisition process as opposed to maintaining constant lighting conditions.

Inspection was performed on parts, typically found in a machine shop environment, using 2-D imaging techniques to determine dimensions of the part as well as to verify assemblies. Once an image was acquired, the steps of processing and analysing were performed along with feature extraction, and the results of the image obtained were compared to the predefined expected results. If a part did not fulfil the inspection specifications, then the possibilities of the cause of the defect were analysed. The location of a fault in the process or material being used could then be located more efficiently and quickly. This prevented further production of flawed products.

The use of the Atmel chips proved to be effective in terms of performance and cost. These chips offered Pulse Width Modulation (PWM) outputs, and when coupled with an appropriate transistor driver circuit, provided efficient and reliable speed and position motor control. The implementation of these controller circuits lead to an increase in the modularity and standardisation of the existing AVIS. Each motor had its own slave microcontroller. This allowed for standardisation of the code for motor control. The fault finding process was also simplified by use of separate controller circuits.

The current apparatus contains areas that are subject to improvement. The use of a laser will be explored in order to obtain a 3D model of the part being scanned. The use of 3D imaging will allow for inspection of free-form surfaces and will be able to perform other inspections that 2D methods are unable to. Various other image processing packages, such as OpenCV, will be researched and explored due to the many existing libraries of coding written in these languages for motor control and object identification. The use of transmissive methods (X-Ray, Echography, and MRI) may also be explored for imaging purposes, to diversify the operation of the machine. The barcode reader, used for the identification of the part, was stationary during the part identification process. The disadvantage of using this system is that the machine relies on a predicted part pose in order for successful operation, otherwise the part would be deemed unacceptable even though it may have been within the design constraints. It is probable that a more reliable method of scanning be implemented in the future. A possibility to achieve this task would be to mobilise the barcode scanner by use of a robotic arm. The scanning process however may also be used for object identification.

5 Conclusion

An existing AVIS was modified using the Mechatronic Engineering approach of system integration and optimisation. The system was first divided into subsystems and then further subdivided into the core elements of Mechatronic Engineering. Inspection in terms of dimensional and assembly validation of custom parts was performed, using visual methods. Intelligence was incorporated into the system by facilitating dynamic inspection of only key features that needed to be inspected. The apparatus was thus able to perform inspection of specified regions, at a faster rate than the AVIS. A sensory system was researched, adapted and implemented in the system. The implementation of the Atmel microcontrollers and the Avago lighting solution allowed for a low cost system to be developed. The Atmel chips also increased the modularity and standardisation of the previous design.

6 References

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