T.2: Machine vision system for automation and quality assurance in fuel fabrication process

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Abstract
Laser Controls & Instrumentation Division (LCID) of RRCAT is involved in design and development of machine vision based inspection systems for quality assurance (QA) of nuclear fuel & fuel assembly components. These inspection systems are broadly categorized as machine vision based metrology systems, machine vision based OCR/OCV systems, machine vision based surface inspection system, etc. Metrology systems are classified further into various types depending on lighting arrangement used for illumination of component/part for which dimensions are being measured. These inspection systems can be further categorized based on 2D/3D measurement and technique involved in the inspection or measurement. This article showcases various customized machine vision based solutions deployed by LCID for constituent units of DAE to facilitate quality assurance and control (QAC) of nuclear fuel and fuel assembly components.

1. Introduction

Aerospace, defence and nuclear industry imposes special challenges to the manufacturing industry for their critical components and systems since they need reliable, consistent, uncompromised performance in an exceptionally harsh environmental condition without failing. This stringent requirement demands use of very special strategic materials. Sometimes special processes or fabrication procedures are needed, which leads to increase in overall cost. Many components or assemblies have complex geometry or shape in order to make it light weight or small in size or with larger surface area. Nuclear industry imposes a slightly additional burden on production of large quantity fuel assemblies for day to day consumption. The components and systems must be manufactured with very tight tolerance and must comply with strict quality assurance procedures. Being large quantity and radioactive in nature, significantly higher man-days are required to manufacture such high quality products. The quality assurance and control is a herculean task.

The components are traditionally qualified using standard industrial inspection procedures such as human based visual surface inspection, metrology laboratory, non-destructive testing (NDT)/NDE techniques, etc. Machine vision refers to a human like ability of a machine to see. Just like humans, the machine can be built with capability to capture visual information and make interpretations after decoding, analysis of the data. In last few decades, we have seen a revolution of semiconductor electronics technology, which is at the center of electronic sensors, imaging devices, actuators, etc. The phenomenal growth in the semiconductor industry has reduced the unit size of electronic devices in few nanometer range, which is shrinking further. This has greatly helped in miniaturizing devices and systems. The end result is highly packed core components like high resolution large area image detectors, multi core processors, large high speed memory, high density field programmable logic devices at relatively lower cost. Most of these core components are used as basic building blocks in design of a commercial machine vision system, which significantly boosted its performance and ability to perform in real time. There are many dangerous situations, where there is a risk of life such as high radiation, active fire, area full of explosives, etc. A vision capable robotic system comes to our rescue to handle such scenario. In addition to getting there, a robot can stream the live video and can take suitable actions via remote commands. In a nutshell, a machine vision based system provides an efficient, obedient and smart companion to the human community enhancing overall inspection capabilities.

2. Nuclear reactor fuel fabrication

Nuclear Fuel Complex (NFC), Hyderabad is an industrial manufacturing unit of the DAE, which caters to the fuel and structural requirements of nuclear power reactors in the country. NFC addresses the need of PHWR and BWR power reactors. It has a fuel production capacity of ~1500 Ton fuel bundles/year. In order to ensure the quality of its products, NFC has an ambitious program for automation of inspection task for fuel and fuel assembly components with the aim to manufacture high quality, high performance products at low cost. LCID participated in NFC's inspection campaign by contributing design and development of machine vision based systems for metrology and inspection to reduce the overall time and improve the quality by ensuring high accuracy measurements and precise visual inspection of various surfaces.

NFC manufactures some of these fuel bundle components in large quantities with the help of various Indian industry partners by providing technical infrastructure along with specially designed dies, tools, jigs, etc. With increasing production requirements, automated inspection has become inevitable. Automation further eliminates subjectivity and monotony associated with manual inspection.

3. Nuclear reactor fuel inspection:

NFC relies on human based inspection for visual and dimensional inspection. Various standard equipment such as digital profile projector / comparator, sophisticated coordinate measurement machine (CMM), etc. are presently used for inspection. These commercial equipment are very costly owing to their generic design suitable for inspection of wide range of components. The investment cost involved is highly prohibitive and unrealistic, since NFC needs many such equipment to cater quality assurance of wide variety of different components in large quantity. Moreover skilled manpower to use such high end equipment is also required to perform the inspection task. Due to complex shape and geometry, the manual inspection / metrology of various measurements may need further assistance of external tools. Thus, inspection based on commercially off-the-shelf (COTS) machines is highly time consuming and costly. Moreover, technical embargo on automated inspection system presents a hurdle on using COTS system for quality assurance of nuclear components and systems.

4. Machine vision systems for nuclear fuel cycle

NFC requested RRCAT to help in automation for quality assurance. LCID resorted to in-house customized design, development and fabrication of automated cost effective machine vision based visual and metrology systems for inspection of nuclear fuel, fuel assembly components and systems. LCID is leveraging high performance machine vision technology, which is a key to automation of industrial inspection at low cost with specific advantages of report generation, data analytics and its suitability of integration into existing manufacturing infrastructure for complete plant automation.

4.1 What is machine vision?

Machine vision refers to a human like ability of a machine to see. The intelligent machine can be built with capability to capture the visual information; decode, analyse it and make interpretations. The machine equipped with memory can store or hold the visual content (single shot still image of a scene or sequence of image frames; video). A built in computing element can then be programmed to read the visual content stored in memory, analyse it and make decision similar to human being. Thus, addition of vision capability along with computer to any machine empowers it to see, think and make judgement. Human eye and brain has exceptional capabilities. It can take miraculously perfect decisions in a fraction of a second. A computer however has limited memory. The power of software algorithms together with memory imitate human abilities, e.g., learning, thinking and analysis. This limited but powerful capability equips the machine vision system in taking near perfect and practically acceptable decisions.

One can easily add one or many more eyes (camera) as needed to capture the visual information of an object from a single or multiple views at once. Human vision is sensitive to a small section of electromagnetic spectrum, whereas a machine can see all the way from X-ray, infrared, ultraviolet, in addition to the spectrum visible to human eye. This makes machine vision based system more attractive. The machine does not have emotions nor a wondering mind to distract. Thus, it can focus very well and can do a repetitive job consistently round the clock, without compromising the performance. This ability sometimes scores over the humans in terms of consistency, quality and speed. Machines are designed to serve a dedicated purpose and hence their performance may degrade in an unexpected circumstance or situation unknown / unhandled by the machine designer.

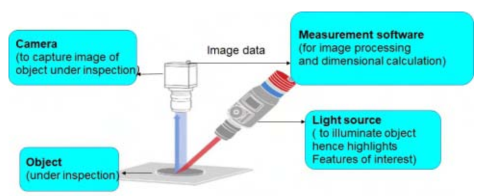


Fig. T.2.1: Block diagram of a machine vision system.

4.2 Machine vision system basics

A vision system is able to see the scene image formed due to light reflected from the scene. A light ray interacts with the objects that comes in its path and gets modified due to phenomenon of absorption, transmission or reflection. The extent of modification depends on the characteristics of the object. Technically, we can say that the light ray gets modulated due to the characteristic features of the objects in their path. The vision system uses this principle to favourably modify the incoming light so that the best image quality is obtained. Many optical elements such as lens, mirror, prism, filter, polarizer, etc. are used at the front end of the image sensor for this purpose. The primary objective of a lens is to map the desired scene area to the image sensor area. This mapping parameter is termed as magnification of a lens. Focal length and working distance are other important parameters, which decides the image quality. The lens also introduces some undesirable effects such as radial and pin cushioned distortions, abrasion errors, etc. The quality of the image also gets affected due to modification related to spatial spectral components. This effect is similar to selectively attenuating the higher frequency components of spatial spectra. This property of lens, which modulates the spatial resolution is termed as modulation transfer function (MTF). This results in blurring the area with sudden or frequent changes of special intensity values where we find higher/finer details (high density information content). Since the collected light reflected by object is the basis of image formation, we can influence the amount of reflected light by intentionally illuminating the object with preferential light source, so that desired features stand out, which can be clearly seen by a camera. The illumination can be applied from front side, e.g., co-axial, radial, low angle directional or from the back side. This results in selectively highlighting specific details in the image. The image capturing is the first stage of any machine vision system and utmost care must be taken to obtain complete information of the object with required details or features highlighted. Figure T.2.1 shows the major components of a machine vision system, viz., illumination (lighting), optics, image sensor, vision processing, and communications. The choice of these components and its arrangement is very crucial to obtain a high resolution, high quality image. The sensor in a machine vision camera converts this light into a digital image, which is then sent to the processor for analysis. Vision processing consists of algorithms that review the image and extract required information. The image processing pipe line merely identifies, highlights, extracts or separates the features for further analysis in order to make a decision. This image processing task is carried out by writing software based on standard or customized algorithms. The image size and efficiency of algorithmic implementation together with the CPU/GPU execution speed decides the time taken by machine vision system to declare the result. Finally, communication is typically accomplished by either discrete I/O signal or data sent over a serial connection to a device that is logging information or using it.

5. Machine vision imaging techniques

Machine vision is a non-destructive testing (NDT) method, widely used in manufacturing industry primarily for inspection of manufactured parts to assure quality. Different types of inspection is needed to ensure quality, e.g., surface inspection for detection of surface defects such as scratches, cracks, edge chipping, pitting, surface contamination, etc. 2D/3D metrology (dimensional inspection) is required to ensure compliance to specified design data. Sometimes volumetric inspection is required to identify defects such as deep cracks inside thick metal surfaces. In specific situation, destructive evaluation of few samples is needed to ensure material properties & integrity or prove the specific process.

The arrangement of imaging device and illumination results in different types of imaging systems such as shadowgraphy (back illumination) for 2D measurements, front illumination for surface quality inspection, pattern projection based triangulation for 3D measurements.

5.1 Shadowgraph technique for visual metrology

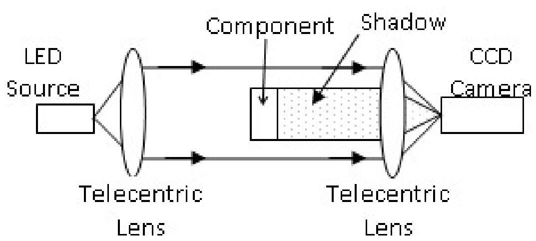


Fig. T.2.2: Shadowgraph technique for visual metrology.

Shadowgraphy is a one of the most popular methods used to do metrology with very high accuracy. This back lighting technique can enhance an image such that it negates some features and enhances others, by silhouetting a part, which obscures surface details to allow measurement of its edges. Figure T.2.2 shows shadowgraph technique for visual metrology. Back lighting enhances an object's outline, helps detect shapes and makes dimensional measurements more reliable for applications that need only external or edge measurements. A collimated back illumination coupled with telecentric optics for imaging is employed as it provides image with low distortion, constant magnification, well defined sharp edges eliminating edge position uncertainty and ensures suitability for more precise sub-pixel measurements. A profile projector is a commercial equipment, which projects a magnified shadow image (1X - 20X or more) of outer object profile on a screen. A pre-calibrated adjustable cursor can be moved on screen to record *x*-, *y*-position. This enables accurate measurement of object dimensions and matches various geometrical feature profiles (curves, holes, shapes, etc.) by overlaying standard templates on screen.

5.2 Front illumination for surface inspection

A machine vision system for inspection detects surface features such as defects, contaminants, irregularities, functional flaws in manufactured products.

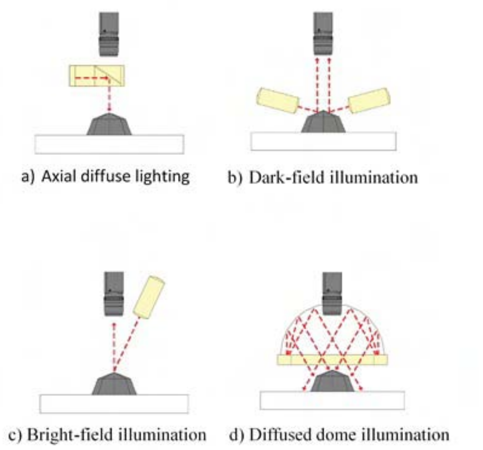


Fig. T.2.3: Front illumination imaging [1].

In the case of front illumination, the camera and light is located on the same side of the object. Figure T.2.3 shows front illumination imaging. 3D machine vision systems typically comprise of multiple cameras or one or more laser displacement sensors. Multi-camera 3D vision in robotic guidance applications provides the robot with part orientation information. These systems involve multiple cameras mounted at different locations and "triangulation" on an objective position in 3D space. A 3D machine vision system (Figure T.2.4) measures the planar (*x, y*) coordinates and height information (*z*) by projecting a collimated line pattern on object and acquiring the image of the object by area scan (2D) camera. Using a triangulation technique, a height map is generated from the displacement of the location of the patterns on an object. The object or camera must be moved to scan the entire product similar to line scanning. Applications typically include surface inspection and volume measurement, producing 3D results with a single camera.

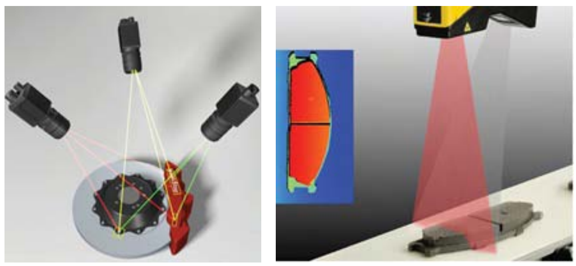


Fig. T.2.4: 3D machine vision system [1].

6. Image acquisition

Image acquisition being the most important step in machine vision system, utmost care must be taken to retain all the information with enhanced brightness, contrast, high resolution to obtain a high quality feature rich image.

1D imaging system using line scan camera: 1D vision systems scan one line at a time while the object moves. 1D vision analyses a digital signal one line at a time (see Figure T.2.5) instead of looking at a whole picture at once. This technique commonly detects and classifies defects on materials continuously moving on a conveyor belt.

2D imaging system using area scan camera: Most common inspection cameras perform area scans that involve capturing 2D snapshots in various resolutions provided by imaging sensor (Figure T.2.5). Another type of 2D machine vision–line scan builds a 2D high resolution image line by line. The line scan camera based system can unwrap cylindrical objects for inspection, add vision to space-constrained environments, meet high-resolution inspection requirements, and inspect objects in continuous motion.

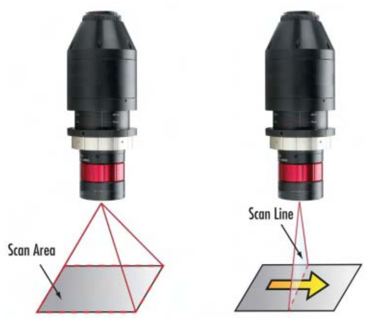


Fig. T.2.5: 1D (line scan) and 2D (area scan) imaging system.

7. Image processing techniques

Main objective of a machine vision system is to capture distinct object features or vital information in a high quality image. Various standard image processing algorithms are then applied in a particular sequence to reduce the overall data and retain only the features of interest, e.g., object shape, dimensions or surface irregularity. To extract the features various image processing operations such as noise removal, contrast and brightness enhancement, thresholding, morphological operations, edge detection, etc. are applied. This results into a processed image suitably highlighted with the desired features that enables precise computation of required parameters.

Photometric imaging: Photometric imaging technique weighs the intensity and power of light with respect to the sensitivity of the human eye. Imaging photometers consist of high resolution cameras with wide dynamic range allowing more subtle defect detection. It is designed to measure light intensity and luminance as it is perceived by the human eye. This technique closely simulates human perception of light by implementing software algorithms to interpret reflections or emissions of light captured in images to identify subtle anomalies leveraging light uniformity analysis and hence are highly capable of performing human-like error detection particularly for randomly-occurring defects such as dents, smudges, scratches, and other surface abrasions.

Computational imaging: Computational imaging is a technique that combines a sequence of images having different lighting or optical configuration.

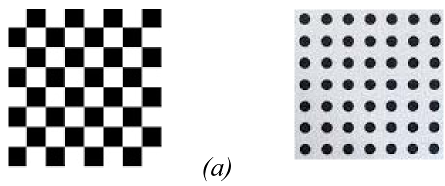
7.1 Machine vision algorithms

Machine vision algorithms consist of combination of sequence of standard image processing steps along with blob analysis, pattern matching, mathematical operations such as statistical data processing, sub-pixel processing, line/curve fitting and other data analysis operations based on geometry and trigonometry. The aim is to precisely compute various geometrical object features such as length, width, height, diameter, orientation, curvature, shapes, etc. to estimate the degree of matching with the specified object features.

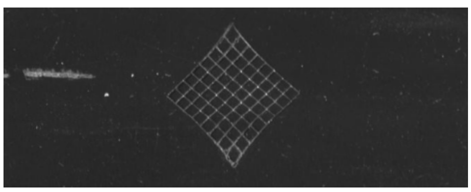
8. LCID inspection systems for visual and metrology

A machine vision based system consists of an imaging front end, a sample holding mechanism to precisely align the sample with respect to imaging optics and a computer pre-loaded with the customized software for processing, computation and display of the results and decisions. LCID has chosen to develop an in-house, customized solution and system for individual or a group of components rather than a generic single solution for entire range of components. This distributed design approach enables cost optimization on almost every critical optical, imaging and electronic hardware and ensures the system availability for the production house. The size of the object decides the field of view requirements of an imaging system. The size of the imaging sensor along with the individual pixel size, decides the system resolution. It is extremely challenging to obtain a very high resolution (few microns) over a very large field of view (hundreds of mm or more). To meet such extreme requirements, vision coupled with object motion in *x*-, *y*-, and z-direction is necessary. To illuminate a large object uniformly over its entire surface is equally challenging. To meet such demands, a compact high resolution imaging head, mounted on a precise movable platform is used to scan the entire object and then apply image stitching techniques to construct a large image fabric for further analysis. To achieve an accurate synchronized motion of the imaging system and the object, a careful design of mechanical system and electronic hardware is necessary.

The inspection systems need special calibration procedures to accurately estimate the acquired inspection features quantitatively. LCID uses industry standard calibration pattern, e.g., grid, chessboard pattern (Figure T.2.6(a)), customized secondary standards (Figure T.2.6(b)) or height length gauges (Figure T.2.6(c)) for calibrating 1D, 2D and 3D systems.



(a)



(b)

(c)

Fig. T.2.6: Calibration standards for visual systems- (a) chess board and circular grid calibration patterns, (b) unfolded image of custom engraved calibration pattern on a cylindrical black anodized tube sample and (c) standard gauge block set with 10 µm resolution.

LCID has developed a customized library of machine vision software algorithms for classification of surface defects for quantitative estimation of crack, pit and body chipping. A metrology toolbox is also designed and developed for measurement of object dimensions with precision of about few microns or tens of microns.

8.1 Inspection and metrology systems for PHWR fuel assembly components

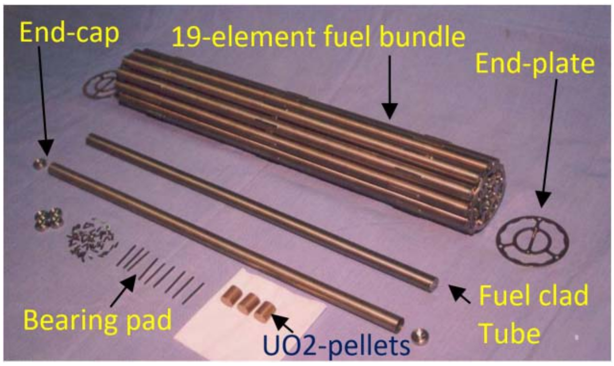
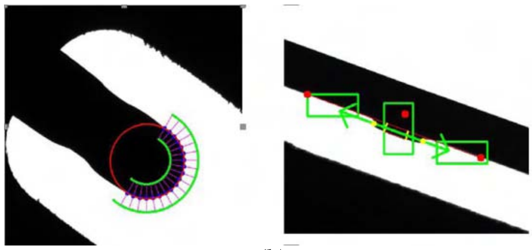


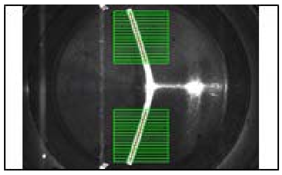
Fig. T.2.7: PHWR fuel bundle (19-element) along with various assembly components and fuel pellets.

Pressurised Heavy Water Reactor (PHWR) fuel bundle consists of a bundle of 19 / 37 element fuel pins welded together with the help of two end-plates as shown in Figure T.2.7. PHWR fuel assembly components such as end-plate, bearing pad, end cap, etc. has complex geometrical shape and critical dimensional requirements with tight tolerance. Conventional human based metrology using Vernier callipers, screw gauge and profile projector enables only single point measurements, whereas the machine vision based systems designed and developed by LCID provides multi-point measurement as illustrated in the following Figures T.2.8(a-c).

(a)



(b)



(c)

Fig. T.2.8: Multi-point dimension measurement algorithm- (a) end plate diameter measurement, (b) bearing pad semi-circular end profile and coin width and (c) conical angle of an end cap [2].

This especially designed multi-point sampling algorithm (Figure T.2.8(b)) precisely detects the edge defects and is able to measure the dimensions accurately. The surface irregularities or burr does not affect the measurements. Moreover, it is possible to report the actual average value along with minimum and maximum values. Multiple samples provide an opportunity to compute the RMS value of deviation from the mean values along the entire measurement periphery. These deviated surface values are used to highlight the area of the object and in few cases, the user can initiate a corrective action to modify the object in case, where the object dimensions exceed the prescribed limits.

An end cap (Figure T.2.7) is welded to a fuel clad tube filled with cylindrical uranium pellets to form a PHWR fuel pin. A set of three bearing pads is welded on the outer surface of PHWR fuel bundle, to maintain a gap for flow of coolant in the nuclear reactor. The coin width and circular profile of the bearing pad and conical angle, and groove depth of end cap are very critical parameters for welding quality. Similarly, a multi-point sampling algorithm along with circular edge fitting is developed for measurement of end-plate outer and inner dimeter as shown in Figure T.2.7. A structural illumination based on LED line projection system utilizing triangulation technique is designed to measure the end-cap groove depth and conical angle.

8.2 Automated PHWR fuel bundle inspection system

An automated PHWR fuel bundle inspection system (see Figure T.2.9) is developed to ensure the presence and correct location of all the bearing pads welded on the outer fuel pins and read the bundle inner diameter (ID) using optical character recognition (OCR) software. This system captures high resolution images (40 MP) of the entire peripheral fuel bundle surface to keep record of the visual surface quality. It generates and prints a bundle ID and its QR code on a specially designed tag attached to each fuel bundle.

In this way, it helps in tracking of fuel bundle till it is finally packed for dispatching to the reactor site. The system maintains a database of bundle inspection report for further tracking and accounting of the nuclear fuel. This system has already been commissioned at NFC and it is integrated in fuel production line.

Fig. T.2.9: PHWR fuel bundle surface inspection system.

8.3 PHWR fuel clad tube chamfer quality inspection system [3]

A system to inspect the clad tube chamfer quality is developed to measure the chamfer width and detect the quantifiable defects. The imaging field of view is chosen to capture entire image of the clad tube chamfer region at its end. The high resolution and high quality telecentric optics enables precise measurement of the chamfer width. The image processing software identifies chamfer region defects, which are displayed for the user (see Figure T.2.10).

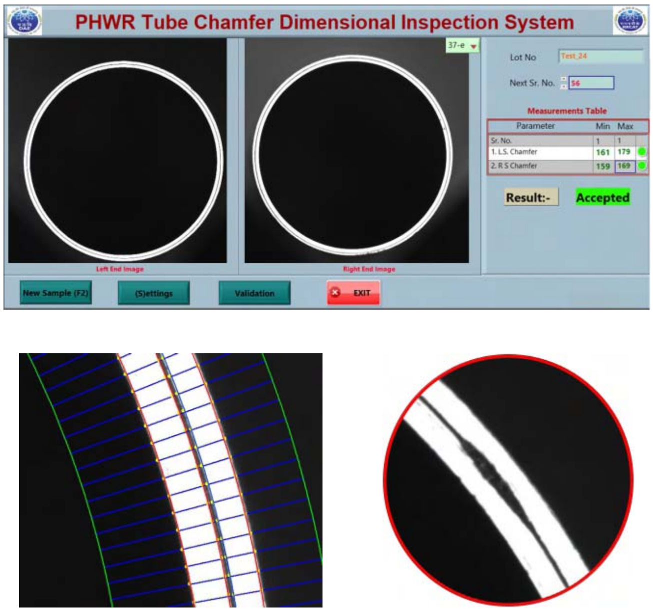
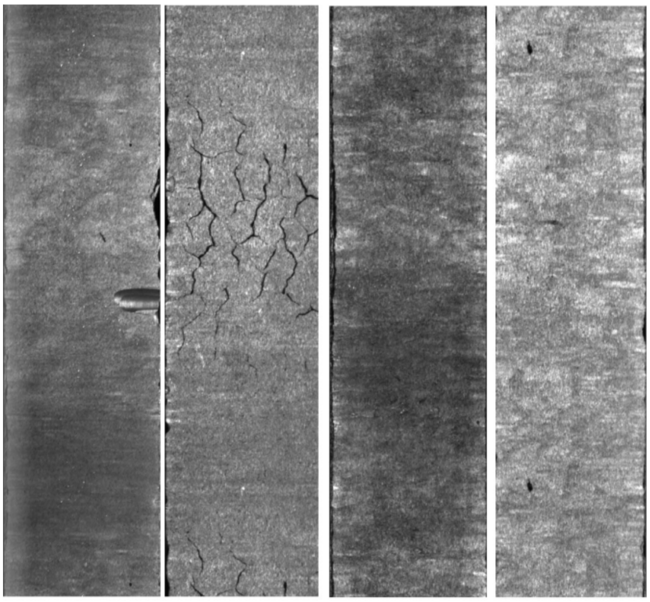


Fig. T.2.10: Fuel clad tube chamfer quality inspection system.

8.4 PHWR fuel pellet inspection system [4-14]

PHWR uses cylindrical UO_2 fuel pellets manufactured from uranium powder using sintering process. In order to ensure the integrity of these nuclear fuel pellets, it is essential to assure that they are free from surface and volume defects. A surface inspection system (Figure T.2.11(a)) has been developed for PHWR fuel pellets. This system uses a line scan industrial camera to acquire an image of stack of cylindrical pellets located on a set of rollers. An image processing software has been developed to separate the individual pellet image from the stack and analyse it for identification of various types of surface defects such as circumferential cracks, surface crack with its orientation, body and edge chips and pit (Figure T.2.11(b)). Numerous customized algorithms have been designed and developed for defect classification and provide information for quantitative analysis. The software measures defect dimensions and provides accept / reject decision based on pre-defined criteria. This industrial grade system complies with the Nuclear Power Corporation of India Limited (NPCIL) visual inspection standard.

(a)



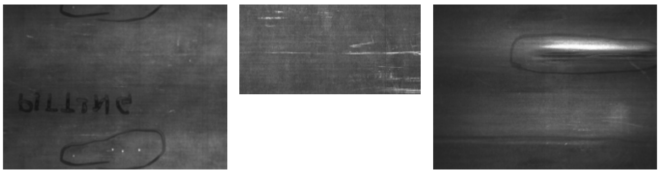
Edge & body chip *Cracks* *End capping* *Accepted, no defect*

(b)

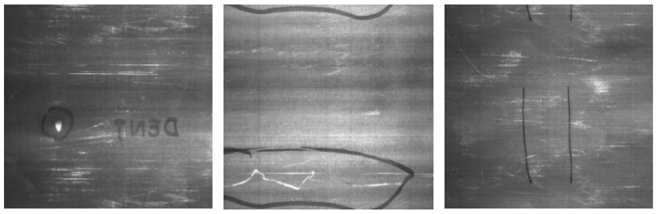
Fig. T.2.11: PHWR fuel pellet inspection system- (a) PHWR fuel pellet inspection system and (b) unfolded UO_2 pellet surface image depicting defects.

8.5 PHWR fuel clad tube surface inspection system

Another surface inspection system has been developed for PHWR clad tube to identify various surface anomalies such as dent, scratches, cut marks, pitting, etc. This system uses multiple line scan camera for acquiring an unfolded image of ~ 510 mm length of fuel clad tube rotated on a set of parallel rollers. Clad tube wall thickness is only ~ 380 µm, hence, it is necessary to ensure that there is no surface defect with a depth more than 38 µm. Though the imaging system is not able to measure the actual depth of the defect, the defect information gets translated into intensity value (dark or bright depending on type of illumination) due to surface irregularity. The difference between the intensity of the tube surface and defect is used to develop algorithms to identify defective area. Various other image features are extracted and utilized to further develop defect classification algorithms (Figure T.2.12).



(a) *(b)* *(c)*



(d) *(e)* *(f)*

Fig. T.2.12: PHWR clad tube surface defects- (a) pit, (b) scratches, (c) grinding mark, (d) dent, (e) handling marks and (f) tool mark.

8.6 PHWR fuel element end profile inspection system

Machine vision based PHWR fuel element end profile inspection system has been commissioned for inspection of end profile of welded 37-element PHWR fuel element (Figure T.2.13). Fuel pellets are loaded in clad tube of fuel element and profile end caps are welded on both ends for sealing. This system measures nine dimensions of both end profile weld joints simultaneously within ~ 15 seconds. For inspection, element is rotated and two similar imaging systems acquire the images of end profile at angular resolution of ~1° simultaneously. Inspection software processes 180 images of each weld joint and computes different dimensions of end profile.

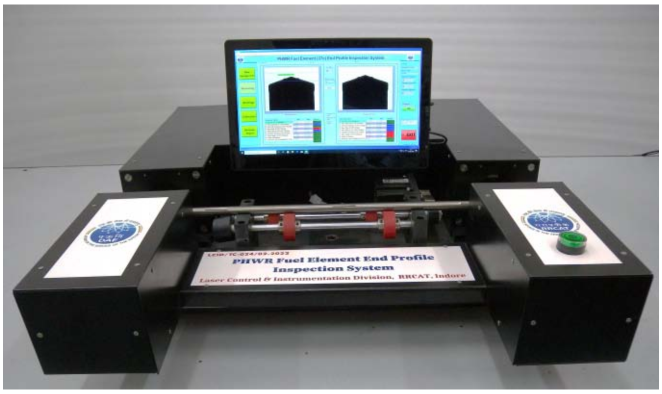


Fig. T.2.13: PHWR fuel element end profile inspection system.

Measurement results are then compared with specified limits of various dimensions and accept / reject result is generated. This system has optical resolution of 10 µm and repeatability <10 µm. It offers multi-point, fast and reliable inspection of end profile as compared to manual inspection, where multi-point inspection is very time consuming and tiring affair.

8.7 PHWR fuel punch inspection and metrology system

A machine vision based automated metrology system based on hybrid design combining the shadowgraph imaging and structured light 3D imaging (see Figure T.2.14) has been developed for measurement of 10 vital dimensions of six variants of PHWR fuel punches used in fuel pellet fabrication process. A punch holder mounted on a motorized linear translation stage is designed to precisely align the punch sample of any size with respect to the two imaging systems. This system has optical resolution of 5 µm and repeatability of < 5 µm.

Fig. T.2.14: PHWR fuel punch inspection and metrology system.

9. Inspection system for measurement of irradiated samples

A metrology system to measure the dimensions of irradiated samples (Figure T.2.15) has been delivered to Post Irradiation Examination Division (PIED), BARC for studying the effect of nuclear radiation on material properties.

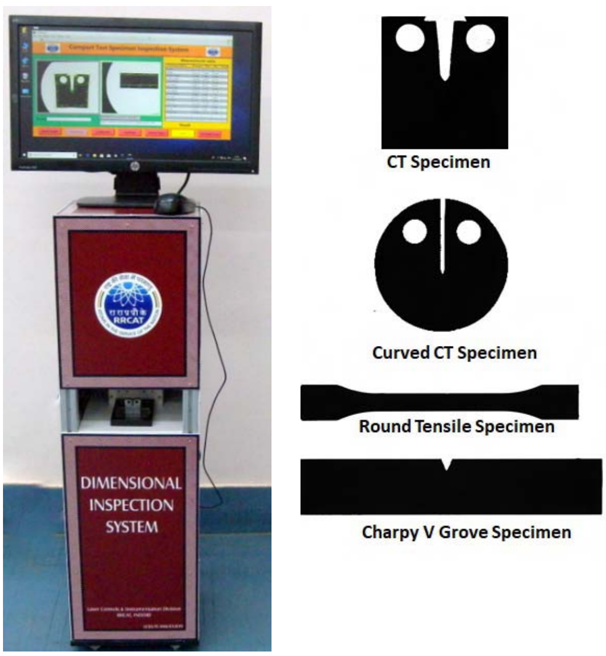


Fig. T.2.15: Inspection system for measurement of irradiated samples.

10. Metrology systems for Fast Breeder Reactor fuel assembly components

Sodium cooled Fast Breeder Reactor (FBR) constitutes the second stage of India's three-stage nuclear program. It contains Uranium-Plutonium mixed carbide pellets as fuel and liquid sodium as coolant. A fuel bundle consists of multiple fuel pins enclosed in a hexagonal wrapper. A spacer wire is wrapped in helical shape around the fuel pin to insure isolation between adjacent fuel pins. This helical wire is held firmly at the end by crimping and spot welding on the top plug. To fix the spacer wires firmly, a slot with depth of 1.2 mm, and width of 0.8 mm is engraved on the top plug. This slot has an angle of 12°. In case, any of these slot parameters exceed specified tolerance, there is a possibility of flaring of wire while crimping, which leads to rejection of fuel pin at a later stage of production.

Metrology systems have been developed for FBR fuel and its assembly components such as various types of end plugs and fuel pellets.

10.1 Inspection system for Fast Breeder Test Reactor top and bottom plugs [15]

A metrology system for quality assurance of Fast Breeder Test Reactor (FBTR) fuel (top & bottom) end plugs is installed and commissioned at Radio Metallurgy Division (RMD), NFG, BARC. This system measures precise dimensions of eleven different dimensions of the 'top plug' and seventeen dimensions for the 'bottom plug' with an accuracy of ±10 µm (see Figure T.2.16).

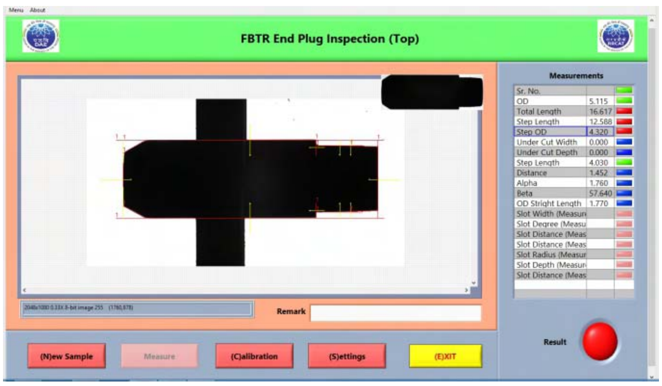


Fig. T.2.16: Inspection software for FBTR metrology system displaying shadowgraph image.

10.2 Slot depth, slot width and slot angle measurement system for top plug of FBTR fuel pin [16]

A metrology system to measure the FBTR fuel pin top plug slot angle, depth and width has been commissioned at RMD, BARC. An image of the top plug [Figure T.2.17] illuminated with the pattern is captured using a digital camera mounted vertically above the plug holder. The projected strips assume the shape of the underlying object. Any surface discontinuity, e.g., slot, modifies (distorts) the pattern as per the surface geometry of the object. The extent of distortion is a measure of surface discontinuity. These changes in the pattern are detected by the system.

Using the triangulation technique, the slot depth is measured from the displacement of the reflected pattern's location on the top plug. The software processes and analyses the acquired pattern image and measures the slot angle and slot width.

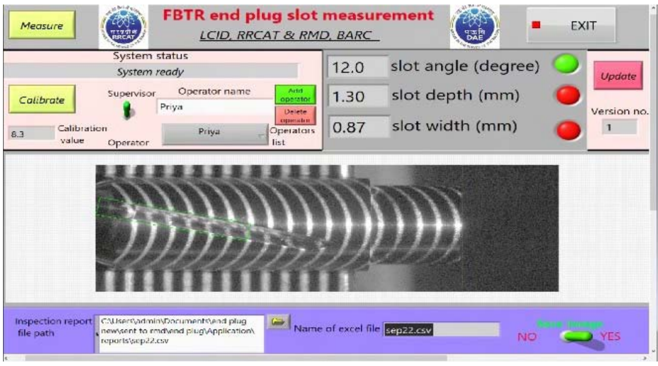


Fig. T.2.17: FBTR fuel pin top plug slot depth, width and angle measurement.

10.3 Machine vision based FBTR weld metallography system [17]

Top plugs are welded to SS 316 stainless steel clad tube using TIG welding. Fuel tubes are welded by TIG weld for bottom plug (inactive operation) and top plug (active operation). Due to the thickness variations of the end plug and the fuel clad tube, obtaining defect free weld joint is a challenging task from weldability point of view. Conventional techniques like microscope are used to evaluate weld quality based on measuring all the weld pool parameters as well as micro structural defects present in a weld pool. These end plug weld evaluation is carried out as per ASTM metallography standard practices. To assist the operator with this task, a machine vision based system (Figure T.2.18) has been developed to capture a weld zone image for measuring the required weld pool parameters and report generation with acceptance or rejection of weld sample as per FBTR weld metallography practice mandated for FBTR fuel pin production. This system provides measurements of weld pool parameters like maximum penetration, penetration at junction, tube thickness and weld pool width. Microstructural defects like porosity, inclusion, cracks, lack of penetration, undercut and microstructure can be seen (Figure T.2.19) by changing the lenses of the same system on single sample.

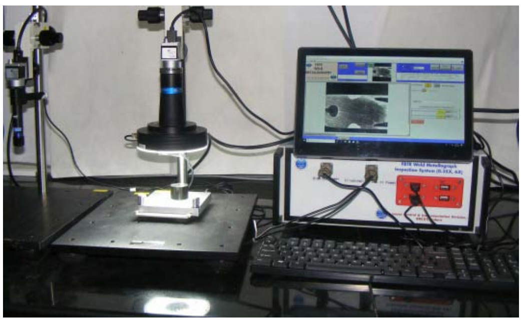


Fig. T.2.18: Machine vision based FBTR weld metallography system with two imaging stations.

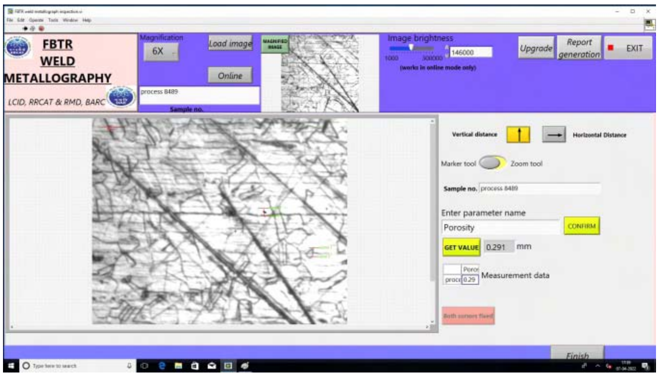


Fig. T.2.19: Machine vision based FBTR weld metallography system GUI.

11. XGAR inspection software [18,19]

An Inspection system for the evaluation of X-ray Gamma Auto Radiograph (XGAR) of Fast Breeder Test Reactor (FBTR) fuel pins is developed. A typical fuel pin used in FBTR consists of an active stack length of ~ 320 ± 1.5 mm with insulation pellets on both ends of active stack length. There are SS components such as plenum tube and pellet support disc on one side and a spring along with spring support on the other side of the active stack. All these components are encapsulated within a SS tube to form FBTR fuel pin. After welding of end plug at both ends, this pin is inspected for correctness of loaded components and measurement of stack length. To inspect this fuel pin, XGAR image of a set of ten pins is obtained on X-ray film. A digitized 16-bit image (Figure T.2.20) of the XGAR film is generated using an optical scanner.

Fig. T.2.20: A digitized image of the XGAR film

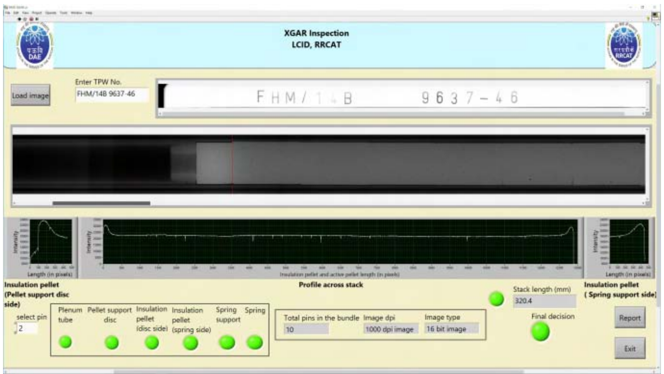


Fig. T.2.21: Screenshot of the XGAR inspection software.

The inspection software (Figure T.2.21) processes the XGAR film image to detect the number of fuel pins and separates out each pin image from the image of cluster of pins. Image processing algorithms have been developed to analyse extracted image of individual fuel pin for presence of various components and their correct sequence.The software further computes the active pellet stack length for each fuel pin, which is an important parameter.

The software then generates an accept / reject decision depending on whether all the components are present in correct sequence and the active stack length is within the tolerance.

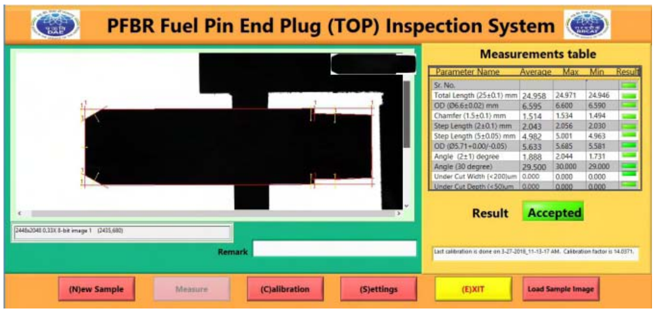
12. Inspection system for radioactive FBTR fuel pellets located inside a glove-box [20]

Fig.T.2.22: Inspection system for radioactive FBTR fuel pellets located inside a glove-box.

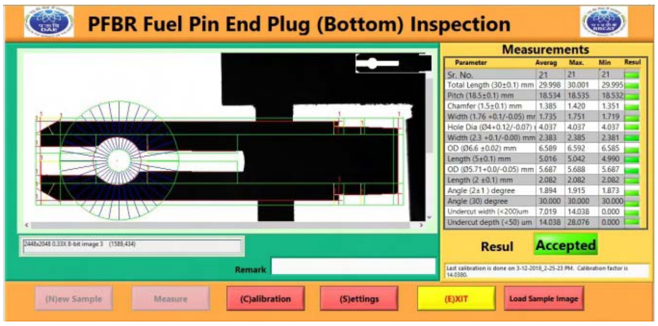
A machine vision based metrology system has been commissioned at RMD, BARC (see Figure T.2.22) for measurement of FBTR fuel pellet dimensions and computation of linear mass with the help of a weighing balance placed inside the glove box. To minimize the radiation exposure and eliminate deposition of radioactive dust onto the optics of the camera and illumination system, this first of its kind imaging system is specially designed with the entire machine vision system located outside the glove box. This greatly simplifies the system maintenance. This system has an integrated foot switch for complete operation and audio voice message alert to indicate rejection of pellets. This innovative design enables the system camera to capture the pellet images looking through the transparent glass wall of the glove box on pressing the foot switch. The on board computer acquires the weight of the pellet and computes the linear mass.

13. End plug metrology systems for FBR [21]

FBR uses various types of fuel bundles. The fuel pins used for these bundles also vary in size and type of end-plugs. Metrology systems have been commissioned at Advanced Fuel Fabrication Facility (AFFF), BARC, Tarapur for inspection of different types of fuel pin end-plugs such as end plugs for blanket assembly (Figure T.2.23(a)), PFBR top and bottom plug (Figure T.2.23(b)), spring support (Figure T.2.23(c)), cobalt plug (Figure T.2.23(d)), etc.. These end plugs are welded at the end of fuel clad tubes.



(a)



(b)

(c)

(d)

Fig. T.2.23: Metrology system for FBR fuel pin end-plugs- (a) PFBR Blanket pin inspection software, (b) PFBR bottom plug inspection software, (c) PFBR spring support inspection software and (d) cobalt plug inspection system.

14. Conclusion

Machine vision for nuclear fuel cycle provides an elegant option to perform metrology and inspection of various fuel and fuel accessory components and fuel assemblies. This accurate, non-contact, fast, 24x7 industrial grade inspection solution is highly suitable for integration into existing production cycle, replacing the human based inspection, which is highly subjective. Moreover, the machine vision based system provides high quality data for further analysis and quality control. LCID has implemented numerous state of the art metrology and inspection systems based on machine vision technology leveraging the technological benefits for Indian nuclear fuel production cycle. Many machine vision based systems have replaced the human based inspection procedures leading to automation of various quality assurance tasks. This not only helps in augmenting the fuel production throughput but also minimizes the radiation exposure.

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