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(57) Abstract:

The present invention relates to an AI-enabled image-based quality inspection system for real-time inspection of manufactured articles. The system includes an inspection zone, image acquisition assembly, adaptive illumination module, edge inspection controller, machine-learning inference engine, defect decision module, operator feedback interface, and production-line control interface. The adaptive illumination module varies lighting conditions to improve visibility of defects under different product surfaces and inspection requirements. Captured images are processed locally by the edge inspection controller, and the machine-learning inference engine detects defects such as cracks, scratches, dents, contamination, missing components, colour mismatch, dimensional deviation, printing errors, coating defects, and misalignment. The defect decision module generates a pass, fail, hold, re-inspection or grade decision with defect localization, severity score and confidence value. The production-line interface actuates rejection, sorting, alarm or process-control equipment. The system further supports traceability, operator feedback, model drift monitoring, and retraining data generation for continuous improvement. Accompanied Drawing [FIGS. 1-2]

FORM 2

THE PATENTS ACT, 1970

(39 of 1970)

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The Patent Rules, 2003

COMPLETE SPECIFICATION

(See section 10 and rule 13)

TITLE OF THE INVENTION

"AI-ENABLED IMAGE-BASED QUALITY INSPECTION SYSTEM WITH ADAPTIVE OPTICAL CAPTURE AND REAL-TIME DEFECT CLASSIFICATION"

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The following specification particularly describes the nature of the invention and the manner in which it is performed:

FIELD OF THE INVENTION

[001] The present invention relates to industrial quality inspection systems and, more particularly, to an AI-enabled image-based quality inspection system configured to capture visual data of manufactured articles, perform machine-learning based defect identification, classify quality deviations in real time, and generate actionable inspection outputs for production-line control, rejection, sorting, grading, traceability, and process correction.

BACKGROUND OF THE INVENTION

[002] Quality inspection is a critical stage in manufacturing industries such as electronics, automotive components, pharmaceuticals, food processing, textiles, packaging, precision machining, semiconductor assembly, and consumer goods production. Conventional inspection techniques often depend upon manual visual checking, fixed optical comparators, template matching, or rule-based vision systems. Although such techniques may be useful for limited and repetitive inspection tasks, they are generally unsuitable where defects are small, irregular, partially visible, texture-dependent, lighting-sensitive, or subject to variation between batches.

[003] Manual inspection is affected by fatigue, subjective judgement, inconsistent attention, operator skill variation, and limited ability to detect micro-level surface defects over prolonged production cycles. In high-speed manufacturing lines, products may move rapidly across conveyors or rotary fixtures, making human inspection insufficient for continuous and accurate monitoring. Such limitations increase the possibility of defective products reaching customers or compliant products being incorrectly rejected due to human error.

[004] Existing machine vision systems commonly use fixed cameras and predefined image-processing rules such as edge detection, colour thresholding, brightness comparison, contour matching, or dimensional template checking. These systems generally require controlled lighting, constant product orientation, uniform background, and stable surface appearance. Any deviation in illumination, camera angle, product colour, material texture, or manufacturing tolerance may result in false rejection or missed defect detection.

[005] In many manufacturing environments, the same inspection station must handle multiple product variants, different surface finishes, varying dimensions, and different defect categories. Traditional rule-based inspection systems require manual reconfiguration for each variant and may not generalize to new defect types. Such reconfiguration causes production downtime, requires expert calibration, and reduces operational flexibility.

[006] Image-based machine learning has improved the possibility of identifying complex visual patterns; however, many available implementations remain limited to offline analysis or cloud-based inference. Such arrangements may introduce latency, data security concerns, network dependency, and delayed response to production faults. In a real-time industrial line, a defect decision must be generated within a short time window so that a rejection actuator, diverter, robotic picker, or process controller can respond before the article leaves the inspection zone.

[007] Another difficulty is that defects may appear differently under different lighting conditions. For example, scratches, dents, cracks, coating gaps, soldering irregularities, contamination, deformation, misalignment, printing errors, colour mismatch, surface pits, and missing components may become visible only under particular light angles, exposure levels, or spectral conditions. A fixed-light vision system may therefore fail to capture sufficient defect evidence.

[008] Existing AI inspection systems also face the problem of model drift. A model trained on earlier image data may become less reliable when a new raw material lot, tool wear condition, lighting aging, camera contamination, or product variant is introduced. Without a structured feedback mechanism, the system may continue to produce inaccurate decisions without alerting the operator that the inspection confidence has degraded.

[009] There is also a need for inspection systems that provide explainable results rather than merely producing a pass or fail output. In industrial quality control, operators and auditors often require information regarding the defect location, defect category, defect severity, image evidence, batch identity, time stamp, and machine condition associated with the defect. Mere binary classification does not provide sufficient traceability for corrective action, supplier analysis, warranty review, or regulatory compliance.

[010] A further limitation of known systems is poor integration with production equipment. A useful quality inspection system should not only detect a defect but should also communicate with line controllers, programmable logic controllers, robotic handling systems, rejection gates, alarms, manufacturing execution systems, and quality dashboards. This integration allows immediate process correction, automatic segregation of defective articles, and creation of inspection records for each product unit.

[011] Therefore, there remains a need for an improved AI-driven quality inspection system that combines adaptive optical image capture, edge-based machine learning inference, defect localization, severity scoring, confidence monitoring, operator feedback, and real-time production-line control in a hardware-integrated inspection architecture. The present invention addresses these needs by providing a practical and technically enabled inspection system suitable for high-speed and variable manufacturing environments.

SUMMARY OF THE INVENTION

[012] The present invention provides an AI-enabled image-based quality inspection system for automatically inspecting manufactured articles moving through an inspection zone. The system includes an image acquisition assembly, an adaptive illumination module, an edge inspection controller, a machine-learning inference engine, a defect decision module, an operator feedback interface, and a production-line control interface. The system captures one or more images of each article, analyses the images using trained machine-learning models, identifies quality defects, and generates a real-time inspection decision.

[013] In one aspect, the image acquisition assembly includes one or more industrial cameras positioned to capture images from selected inspection angles. The adaptive illumination module changes lighting intensity, direction, wavelength, exposure coordination, or lighting sequence based on the product type, surface condition, or inspection recipe. This enables the system to reveal defects that may not be visible under a single fixed lighting condition.

[014] In another aspect, the edge inspection controller processes the captured images locally at or near the inspection station. The controller performs pre-processing, region-of-interest extraction, normalization, feature embedding, defect localization, classification, and severity estimation. Local processing reduces inspection latency and allows the system to operate even when remote connectivity is limited.

[015] In another aspect, the machine-learning inference engine is configured to detect surface defects, structural defects, assembly defects, dimensional irregularities, contamination, colour mismatch, printing errors, cracks, scratches, dents, missing parts, and other visual non-conformities. The inference engine may use convolutional neural networks, transformer-based visual models, hybrid vision models, anomaly detection networks, or a combination of trained classification and segmentation models.

[016] In another aspect, the system generates an explainable inspection output including a pass status, fail status, defect class, defect location map, severity score, confidence value, product identifier, image record, time stamp, and recommended action. The production-line control interface may actuate a rejection gate, stop a conveyor, trigger an alarm, instruct a robotic sorter, or transmit inspection data to a manufacturing execution system. The system may further update inspection thresholds or retraining queues based on operator confirmation and historical defect trends.

BRIEF DESCRIPTION OF THE DRAWINGS

[017] The accompanying drawings illustrate exemplary embodiments of the present invention and are intended to assist in understanding the structure and working of the AI-enabled quality inspection system. The drawings are schematic in nature and do not limit the scope of the invention, since equivalent hardware arrangements, camera placements, controller configurations, and inspection workflows may be adopted without departing from the inventive concept.

[018] Figure 1 illustrates a simplified block diagram of the AI-enabled image-based quality inspection system, showing the arrangement of an inspection zone, industrial camera assembly, adaptive illumination module, edge inspection controller, machine-learning inference engine, defect decision module, operator interface, production-line controller, and rejection or sorting actuator.

[019] Figure 2 illustrates a simplified operational flow of the quality inspection process, showing product identification, adaptive image capture, image pre-processing, defect detection, defect localization, severity scoring, confidence verification, inspection decision generation, production-line action, data logging, and feedback-based model improvement.

DETAILED DESCRIPTION OF THE INVENTION

System Architecture

[020] The present invention provides a hardware-integrated AI-driven quality inspection system configured to inspect a manufactured article during production or post-production handling. The system may be installed along a conveyor line, rotary indexing table, robotic handling station, packaging line, assembly line, or batch inspection fixture. The term “article” as used herein may include a product, component, sub-assembly, package, label, surface, container, printed element, machined part, electronic board, pharmaceutical unit, textile section, moulded part, food item, or any other object requiring visual quality inspection.

[021] The system includes an inspection zone through which the article is presented in a defined orientation or in a dynamically tracked position. The inspection zone may be provided with a product presence sensor, encoder, proximity sensor, trigger sensor, optical sensor, RFID reader, barcode reader, or machine signal input. The trigger input coordinates image capture with the position and speed of the article so that the required region is imaged within an inspection window.

Image Acquisition Assembly

[022] The image acquisition assembly includes at least one camera positioned to capture image data of the article. In preferred embodiments, the assembly includes multiple cameras positioned at front, top, side, angular, or underside views depending upon the required inspection features. The cameras may include area scan cameras, line scan cameras, high-speed cameras, monochrome cameras, colour cameras, depth cameras, infrared cameras, ultraviolet cameras, or hyperspectral imaging devices.

[023] The cameras may be mounted on fixed brackets, adjustable rails, robotic arms, or enclosed inspection housings. Each camera may be calibrated with respect to field of view, focal distance, exposure, lens distortion, pixel-to-dimensional conversion, and inspection region. The calibration data may be stored in an inspection recipe associated with a product type or batch code.

Adaptive Optical Capture

[024] The adaptive illumination module is configured to control one or more lighting units surrounding the inspection zone. The lighting units may include ring lights, dome lights, bar lights, coaxial lights, backlights, low-angle lights, structured lights, infrared lights, ultraviolet lights, polarized lights, or wavelength-specific lights. The illumination module may alter brightness, pulse duration, direction, colour temperature, wavelength, or lighting sequence according to the product surface and inspection objective.

[025] In one embodiment, the system captures multiple images of the same article under different lighting conditions. For example, a first image may be captured under diffuse light for colour and printing inspection, a second image under low-angle light for scratch detection, and a third image under backlight for dimensional or contour inspection. The edge inspection controller may combine or compare the multiple images to increase defect visibility.

[026] The adaptive optical capture mechanism provides a technical advantage because defects that are not visible under ordinary lighting may become detectable when the illumination angle, intensity, or spectral band is adjusted.

This improves inspection reliability for reflective, transparent, textured, coated, curved, or dark surfaces.

Edge Inspection Controller

[027] The edge inspection controller is a computing unit located at or near the inspection station. The controller may include one or more processors, graphics processing units, neural processing units, field programmable gate arrays, memory units, image acquisition ports, communication interfaces, and industrial input-output modules. The controller receives image data from the camera assembly and performs real-time processing without depending entirely upon cloud computation.

[028] The edge inspection controller executes an inspection pipeline including image validation, exposure correction, geometric alignment, background suppression, region-of-interest extraction, noise reduction, colour normalization, image scaling, and defect candidate identification. The controller may reject unusable images caused by blur, obstruction, improper exposure, or missing product presence and may trigger re-capture when the inspection window permits.

Machine-Learning Inference Engine

[029] The machine-learning inference engine is configured to analyse the processed image data and identify visual defects. The inference engine may include one or more trained models for classification, object detection, segmentation, anomaly detection, or feature comparison. The model may be trained using labelled images of acceptable articles and defective articles, and may further use synthetic defect images, augmented training images, or operator-verified production images.

[030] The inference engine may generate a defect signature embedding representing the visual characteristics of a detected defect. The embedding may be compared with stored reference embeddings corresponding to known defect types. This allows the system to classify defects such as cracks, scratches, dents, missing components, contamination, colour variation, wrong assembly, dimensional deviation, printing misalignment, sealing defects, coating discontinuity, burn marks, solder bridges, or foreign particles.

[031] In another embodiment, the inference engine includes an anomaly detection model trained primarily on acceptable articles. When an inspected article deviates from learned acceptable appearance, the system generates an anomaly score and highlights the region causing the deviation. This is useful where defective samples are rare or where new defect categories may arise during production.

Defect Decision Module

[032] The defect decision module receives outputs from the machine-learning inference engine and generates a quality decision. The decision may include a pass result, fail result, re-inspection result, hold result, or grade classification. The module may consider defect class, defect size, location, severity, confidence score, product variant, customer specification, and inspection rule thresholds.

[033] In one embodiment, the decision module applies different acceptance thresholds for different regions of the article. For example, a minor surface mark may be acceptable in a non-visible region but unacceptable in a sealing region, electrical contact region, medical-contact region, printed code region, or safety-critical area. The system may therefore apply region-specific quality criteria.

[034] The decision module may further generate a defect heat map or localization overlay to show the exact image region responsible for the quality decision. The heat map or overlay may be displayed on an operator interface and stored along with the inspection record. This improves explainability and enables a technician to verify whether the AI decision corresponds to an actual manufacturing defect.

Production-Line Control Interface

[035] The production-line control interface communicates the inspection decision to industrial equipment. The interface may communicate with a programmable logic controller, conveyor controller, robotic arm, pneumatic rejection gate, diverter, marking device, alarm device, packaging machine, sorting bin, or manufacturing execution system. Communication may occur through wired or wireless industrial protocols, digital input-output channels, Ethernet, serial communication, fieldbus, or application programming interfaces.

[036] Upon detecting a defective article, the system may generate a reject signal at a calculated time based on conveyor speed and article position. The reject signal may activate a pneumatic pusher, air jet, robotic picker, diverter arm, or stop mechanism. For repeated defects or abnormal defect frequency, the system may generate a process warning or stop command to prevent further defective production.

Operator Feedback and Continuous Improvement

[037] The operator feedback interface allows an authorized user to review inspection images, confirm or override AI decisions, assign defect labels, adjust inspection recipes, and approve retraining data. The confirmed inspection data may be stored in a retraining queue for periodic model improvement. The system may track false positives, false negatives, confidence trends, and newly appearing defect patterns.

[038] The system may include model drift monitoring. When the confidence distribution, image quality profile, defect frequency, or product appearance deviates from a stored baseline, the system may alert the operator that recalibration, lighting adjustment, camera cleaning, recipe review, or model update may be required. This prevents silent degradation of inspection performance.

Data Logging and Traceability

[039] Each inspection event may be stored with an article identifier, batch number, image record, inspection time, defect category, defect score, decision result, operator action, machine identifier, and production status. The stored data may be used for audit, quality certification, supplier feedback, process optimization, warranty investigation, and compliance reporting.

Technical Advantages

[040] The invention provides several technical advantages over conventional inspection arrangements. It improves defect detection accuracy by combining adaptive optical capture with image-based machine learning. It reduces latency through edge inference. It improves flexibility by supporting multiple product variants through inspection recipes. It improves explainability by generating defect localization outputs. It improves production efficiency by directly controlling rejection or sorting equipment. It improves long-term reliability by monitoring model drift and incorporating operator-confirmed feedback.

Industrial Applicability

[041] The present invention is industrially applicable in manufacturing and processing environments requiring fast, repeatable, and traceable visual quality inspection. The system may be used for inspection of electronic assemblies, automotive parts, pharmaceutical packaging, medical devices, food packages, textile defects, printed labels, moulded articles, machined components, semiconductor packages, battery cells, consumer products, and other articles where image-based defect analysis is required.

We Claim:

1. An AI-enabled image-based quality inspection system comprising an inspection zone for receiving a manufactured article, an image acquisition assembly configured to capture image data of the manufactured article, an adaptive illumination module configured to vary optical illumination during image capture, an edge inspection controller configured to process the image data, a machine-learning inference engine configured to identify a visual quality defect from the processed image data, a defect decision module configured to generate an inspection decision based on defect class, defect location, severity value and confidence value, and a production-line control interface configured to transmit the inspection decision to an industrial actuator or production controller.
2. The system as claimed in claim 1, wherein the image acquisition assembly comprises one or more industrial cameras selected from area scan cameras, line scan cameras, colour cameras, monochrome cameras, depth cameras, infrared cameras, ultraviolet cameras, or hyperspectral imaging devices.
3. The system as claimed in claim 1, wherein the adaptive illumination module is configured to control at least one of lighting intensity, lighting direction, pulse duration, wavelength, colour temperature, exposure coordination, or sequential lighting pattern for improving visibility of surface or structural defects.
4. The system as claimed in claim 1, wherein the edge inspection controller is configured to perform image validation, exposure correction, geometric alignment, region-of-interest extraction, background suppression, normalization, noise reduction, and image scaling before defect inference.
5. The system as claimed in claim 1, wherein the machine-learning inference engine comprises at least one trained visual model configured for classification,

object detection, segmentation, anomaly detection, feature embedding comparison, or a combination thereof.

6. The system as claimed in claim 1, wherein the machine-learning inference engine is configured to detect at least one defect selected from cracks, scratches, dents, contamination, missing components, colour mismatch, dimensional deviation, printing error, coating discontinuity, sealing defect, soldering defect, foreign particles, deformation, or misalignment.
7. The system as claimed in claim 1, wherein the defect decision module is configured to apply region-specific quality thresholds such that a defect detected in a critical region of the manufactured article is assessed differently from a defect detected in a non-critical region.
8. The system as claimed in claim 1, wherein the defect decision module generates an explainable inspection output comprising a defect localization map, heat map, defect category, severity score, confidence score, product identifier, time stamp, and pass, fail, hold, re-inspection or grade decision.
9. The system as claimed in claim 1, wherein the production-line control interface is configured to actuate a rejection gate, diverter, air jet, robotic picker, conveyor stop, alarm, marking unit, sorting mechanism, or manufacturing execution system based on the inspection decision.
10. The system as claimed in claim 1, further comprising an operator feedback interface configured to receive operator confirmation or correction of the inspection decision, store verified inspection data, monitor model drift, and generate a retraining queue for improving the machine-learning inference engine.

Dated this 05th day of May 2026

Signature: K.R. [signature]

Applicant(s)

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ABSTRACT

AI-ENABLED IMAGE-BASED QUALITY INSPECTION SYSTEM WITH ADAPTIVE OPTICAL CAPTURE AND REAL-TIME DEFECT CLASSIFICATION

[042] The present invention relates to an AI-enabled image-based quality inspection system for real-time inspection of manufactured articles. The system includes an inspection zone, image acquisition assembly, adaptive illumination module, edge inspection controller, machine-learning inference engine, defect decision module, operator feedback interface, and production-line control interface. The adaptive illumination module varies lighting conditions to improve visibility of defects under different product surfaces and inspection requirements. Captured images are processed locally by the edge inspection controller, and the machine-learning inference engine detects defects such as cracks, scratches, dents, contamination, missing components, colour mismatch, dimensional deviation, printing errors, coating defects, and misalignment. The defect decision module generates a pass, fail, hold, re-inspection or grade decision with defect localization, severity score and confidence value. The production-line interface actuates rejection, sorting, alarm or process-control equipment. The system further supports traceability, operator feedback, model drift monitoring, and retraining data generation for continuous improvement.

Accompanied Drawing **[FIGS. 1-2]**

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