An automated hardware-software complex for detecting defects in electronic products

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The automated hardware-software complex (AHSC) for the detection and classification of defects in electronic products (EP), developed by specialists at JSC 'Central Design Office "Deyton"', is designed to reduce costs and improve the quality of products manufactured by enterprises in the radio-electronic industry. The AHSC features an open architecture and can be adapted to different microelectronic product lines and manufacturing processes used by manufacturers in Russia and Belarus. It includes mathematical, software, technical, informational, linguistic (language tools), methodological, and organizational support. The system detects defects in electronic products and helps identify limitations of traditional approaches to designing and controlling their manufacturing processes. The identification and classification of defects, along with their entry into a database (DB), makes it possible to analyze the defects and their causes step by step at various stages (operations) of EP production, and then, if possible, eliminate the causes.

Defects initially arise during the design and manufacture of EP, and are identified and eliminated, if possible, during the production process. This is achieved by modifying the design, the sequence of operations and the production technology, thereby increasing the yield of acceptable EP and labour productivity.

Defect detection using computer vision (CV) in the manufacture of EPs is an automated process in which high-resolution camera microscopes, software to check for defects in the visible spectrum and to analyze them in real time, and robotic components that select EP are used, ensuring high quality and efficiency of production processes. A defect is defined as any individual instance where the electronic product fails to meet the requirements set out in the relevant regulatory documentation.

A deviation is considered acceptable if the numerical value of a product parameter does not exceed the limits set out in the regulatory documentation. If the numerical value of a parameter goes beyond the established limits, this means that the electronic product has a defect.

The AHSC allows a distinction to be made between:

- critical deviations, the presence of which means that the EP cannot be used for its intended purpose, as it does not meet safety requirements;
- significant deviations, which affect the use of the EP for its intended purpose and its service life, but are not critical;
- minor deviations, which do not affect the use of the EP.

Critical and significant deviations constitute defects that require rejection of the affected products. Their detection therefore requires 100% inspection and, in some cases, repeated inspection. Minor deviations are considered defects but do not, on their own, warrant rejection; however, their cumulative effect may be equivalent to a significant or critical deviation.

The operation of AHSC on production lines is supported and supervised by specialists from the enterprises and JSC 'Central Design Office "Deyton"' in terms of improvement of new artificial intelligence technologies and the operation of robotics and mechatronics systems, as well as virtual reality.

At enterprises in the radio-electronic industry, appearance inspection of EP is essential for determining their quality, since their appearance affects the product's functionality. However, characteristics of electronic products such as miniaturisation, precision and high component density (in multi-crystal modules, hybrid microcircuits and microassemblies) pose a major challenge for manual inspection under a microscope, which re-

lies entirely on the inspector's eyesight and subjective judgement.

Therefore, to automate the appearance inspection of EP, defect detection based on image processing using artificial intelligence technologies has become essential. AHSC simulates the human eye's perception of defects using a camera microscope and makes decisions using computers and software, thereby implementing safe, effective, non-contact and non-destructive appearance inspection of EP.

The development of enterprises in the domestic radio-electronic industry requires the establishment of various quality control regimes, both in mixed-batch production and in individual small-batch production, using quality assessment systems for materials and products at all stages of the production process. Furthermore, it is necessary to use the potential for automating many traditional processes, such as post-production secondary sampling or quality tracking with separate checks for multi-type products combined within a single item. These production scenarios typically involve more complex processes, a higher degree of automation, stricter quality requirements and a greater need for flexible, systematic quality assessment software.

The complexity and diversity of the characteristics of EP defect images are primarily the result of interference from environmental factors and the unpredictability of the defects themselves. For traditional defect detection algorithms, even minor changes in the image can lead to failure at any stage of production and result in a batch of defective products.

Defects can range from minor issues that have a minimal impact on the EP to serious ones that render the EP unsuitable for use or make the process ineffective.

AHSC has been developed with reliable defect detection software based on image processing methods, including background removal, boundary approximation, and adaptation to EP with different component materials. It provides a non-contact method that guarantees no contamination or damage during inspection, effectively detecting visual distortions, surface irregularities and foreign objects.

AHSC uses a combination of traditional 2D and 3D methods of CV, supplemented by the skills of the product quality inspector. Traditional 2D computer vision has been used for automated quality control of electronic products for decades. It mainly consists of one or more camera-microscopes that capture an image and a computer that processes it and, using software, determines whether the inspected electronic product meets the specified quality requirements.

In recent years, 3D technology has added an additional dimension to the capabilities of computer vision. This type of detection is ideally suited for verifying the sizes and shapes of a wide range of defect types.

AHSC enables the resolution of tasks when a defect becomes difficult to describe, for example, for detecting defective surface abrasions on EPs, when the rejection of such defects requires identification and assessment by an experienced inspector. By learning from images of EP defect samples, AHSC simulates the work of experienced inspectors to achieve a more consistent and accurate inspection process.

Image quality is crucial to inspection accuracy and depends on illumination, exposure settings, and the optical characteristics of the camera-microscope. The AHSC preprocesses images of electronic product surfaces using 2D/3D computer vision. Traditional 2D/3D vision technology is used to identify potential defects in a specified area of the surface while avoiding the need to process the entire image with a neural network.

The selected areas are then passed to a neural network, trained on a large number of samples, which processes the image and assigns it a rating to determine whether it meets the established quality standard. If the assessment result is at the borderline level, AHSC performs post-processing using 2D/3D vision identifying specific, predefined types of defects or, for example, measuring their dimensions.

Often, the need for AHSC technologies increases as the complexity of the tasks grows. The best example is the inspection of EP for hard-to-detect defects, where it is difficult to specify the required area for inspection with sufficient accuracy to carry out the same inspection as an experienced inspector. When dealing with a large number of micro-areas on EP surfaces that need to be inspected for defects, processing the entire image using CV will often be very resource-intensive. This requires a hybrid vision approach, in which we can use 2D/3D vision to pre-process images and identify areas of the image containing

potential defects, so that only the relevant areas pass through the neural network.

Thus, hybrid vision makes sense when 2D/3D vision and machine learning (ML) can be combined to create a more reliable solution, and when more precise inspection of the surface quality of the EP is required to capture suitable images. This is often the case in industrial production environments, where the ability to detect defects is reduced (conveyor belt speed, lighting conditions, temperature, dusty production environments).

If the task is simply to 'count pixels' and measure dimensions or quantities to assess whether a part is within the specified tolerances, there is rarely a need to use machine learning. In such cases, traditional 2D/3D vision may be the only effective way of achieving the goal. When production volumes are low or consist of small batches of different products, 2D/3D vision is recommended as the most suitable method.

Defect measurement refers to quantitative measures used to assess and analyse the quality of electronic products, providing a standardised approach to identifying, tracking and analysing quality issues. AHSC automatically detects defective features and measures their dimensions using a camera-microscope and software. It records the measurement parameters for the same defect with some variations in position, mainly because we obtain different images.

This is caused by optical factors, uneven lighting and random noise. Therefore, various methods of measuring defects based on their size are used. The results show that such methods significantly improve the reliability and consistency of defect size measurements. If the modeling is carried out properly, the measurement methods can be applied to various types of defects.

The implementation of the AHSC provides the following benefits: a reduction in machine learning time through the refinement of technologies for sampling products with defects; the sorting of products with defects that do not constitute rejects, in order to assign them to a lower quality category; the creation of a global database of defects; programme analysis of the increase in the number of defects; formulation of proposals for changes to manufacturing processes; documentation (standardisation) and the use of acquired experience in further developments; detection of hidden defects (transparent particles); use of colour filters and mirrors; programming of lighting intensity; programming the movement speed of the camera-microscope (or product); ensuring the reliability of electronic and mechanical components; refining methods for certifying devices and refining procedure for validating quality inspection results for electronic component base (ECB) products; development of devices for automatic loading and unloading (sorting) of products; standardisation and simplification of electronic and mechanical components.

The AHSC software stack includes system and database software developed by RED SOFT. The complex also uses Java, Python and C#, together with computer vision, machine learning and neural-network technologies. Issues relating to the transition from convolutional to capsule neural networks, ensuring a better understanding of context and improving the accuracy of defect detection are being explored. The reported probability of defect detection by the AHSC is 90%.

The AHSC may be adapted for detecting external and internal defects in integrated circuit dies, semiconductor devices, microelectromechanical systems (MEMS), piezoelectric components, microassemblies, modules, and resistors. Potential applications also include incoming quality inspection and post-assembly defect detection.

In a production environment, manufacturers mainly use methods within the visible optical spectrum (optical radiation refers to electromagnetic radiation in the wavelength range from 100 nm to 1 mm; the terms 'light' and 'visible radiation' refer to the wavelength range of 360-830 nm, which is perceptible to the human eye) to detect product defects on assembly or production lines. These inspection methods use image processing and analysis to identify product nonconformities based on predefined criteria and are successfully applied to surface defect detection.

Visual inspection methods are also used to assess surface irregularities on products. Image acquisition is a crucial process in visual inspection. Traditionally, optical microscopy is used for surface inspection to obtain high-resolution images, although it has a limited field of view and is more suitable for a specific class of microelectronic products. It is possible to capture an image of the entire

product due to the large field of view; however, the resolution of the obtained images is much lower compared to the images obtained by examining the product segment by segment. The method, known as mesoscopy, aims to combine a wide field of view with the high-resolution capabilities of optical microscopy. In the AHSC, mesoscopy is used to acquire images for defect detection at a spatial sampling scale as fine as 3 μm per pixel. These defects are very small, so the images with very high resolution are required for analysis.

An important process in this context is threshold processing, which converts a colour or greyscale image into a binary one. The method allows you to create black-and-white binary images from greyscale or colour images by converting the intensity of all pixels into discrete values: one or zero. The threshold value reduces the intensity of pixels below a specified value to zero (black), whilst pixels above this value are assigned a value of one (white). Thresholding enables rapid image segmentation because of its simplicity and computational efficiency. The thresholding method is used by default for thresholding in software such as MATLAB. In this case, the segments in the image are classified. Foreign developers of defect detection software use the Minimum Error Thresholding (MET) method, which has been proven to be superior to other (around 40) thresholding methods.

Modified approaches using these methods have also been proposed, in which the median of the brightness histogram is used instead of the mean. It has been found that the median extension of the original MET method performs better than the original method for images with highly skewed and heavy-tailed brightness distribution. AHSC's developers investigated methods with median-based contrast correction for distinguishing defects by applying image-specific contrast adjustments, and then using the median-based Otsu's method for the thresholding process.

The AHSC incorporates specialised visual inspection techniques, including template matching, ORB (Oriented FAST and Rotated BRIEF), multi-view analysis, homography-based methods, and virtual-reality-based approaches.

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Defect measurement requires reliable tools and methodologies that ensure the accurate data collection, analysis and interpretation. By using these, enterprises can effectively monitor and evaluate quality indicators, identify trends and make informed decisions to ensure the production of high-quality microelectronic products.

The following results were obtained during the development of software and hardware tools for configuring AHSC's images to detect defects in the visible spectrum. The task of investigating image adjustment methods for CV was formalised. The most promising image adjustment methods for application in specific conditions were identified, selected and refined. Improvements have been proposed regarding the adjustment of images for CV. The image adjustment methods used in AHSC for the visible spectrum to detect defects in microelectronic products have proven to be effective; a precise tool for defect detection has been created, and data processing has been implemented, which optimises operating speed. The existing methods for formalising the task of image adjustment for CV have been modified to address more extensive defect detection tasks and will be applied in future work across various fields.

When using an automated hardware and software complex for detecting defects in microelectronic products with AI technologies, several key points must be taken into account to ensure the effective measurement, analysis and automated detection of defects. These include:

- establishing processes and mechanisms for detecting and recording defects, and ensuring their accurate registration and analysis;
- the severity levels of defects and their potential impact on product quality, safety or compliance with regulatory requirements;
- identifying and categorising defect types based on their appearance, which are relevant to the inspected product;
- defining the procedures and corrective actions required to eliminate identified defects and prevent their recurrence.

This will help to ensure the reliability, durability, functionality and performance of the product. The iterative process of measuring defects and analysing their nature is of great importance for organisations striving to deliver exceptional products that meet or exceed the expectations of customers and consumers. ◆