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AI and Machine Vision in Food Processing

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Abstract

As a global and vital part of modern life, the food process industry continues to evolve and develop, adopting newly developed tools and technologies to improve efficiency and ensure food safety while minimizing environmental impact and striving towards sustainability. Food processing is essential for preparing and preserving food for an ever-growing population. Artificial intelligence and machine vision technologies have emerged as promising tools in the food process industry, offering opportunities for enhanced quality control, increased productivity, and improved traceability. This article discusses the implementation of artificial intelligence and machine vision in the field of food process engineering, showcasing how these technologies can optimize processes, improve quality control, and contribute to sustainability in food production.

Keywords: *Artificial intelligence, machine vision, food processing, Artificial neural networks.*

1. Introduction

The food industry plays a crucial role in supplying the ever-growing global population with safe and nutritious food. The human population has reached 8 billion people on November 15. 2022 and World Population Prospects 2022 published by the United Nations Department of Economic and Social Affairs predicts that by 2058 there will be 10 billion people on the planet [1]. With climate changes resulting in extreme weather, the food industry will be tested to find novel foods and technologies to satisfy the increased demand for food. Traditionally, food processing has relied heavily on thermal processing techniques such as pasteurization and canning to ensure food safety and extend shelf life. However, these processes require lots of energy and can result in nutrient loss and changes in the sensory properties of food products. Moreover, traditional food processing methods may not be sufficient to meet the growing demand for diverse and convenient food products [2]. To reduce energy consumption, and environmental footprint and increase efficiency and sustainability as well as food quality and shelf-life, the food industry is turning toward novel food processing technologies employing high hydrostatic pressure, pulsed electric fields, irradiation, ultrasonication, cold plasma, hydrodynamic cavitation, microwaves, radio frequency heating, ohmic heating, ozone treatment and supercritical fluids such as carbon dioxide and water [3].

Artificial intelligence (AI), a term that was used first by John McCarthy in 1955, in his proposal for a summer research project on the concept of thinking machines, which was held at Dartmouth College in 1956 gathering leading minds in computer science and cognitive psychology, to create a machine capable of performing tasks that would typically require human intelligence [4]. Researchers have underestimated the complexity of such tasks and progress in the field was slower than expected, resulting in the "AI winter" from the late 1960s to the late 1990s. During this period, AI research and development faced significant challenges and funding was reduced. However, during the late 1980s and early 1990s, there was a resurgence in AI research and development, boosted by the growing processing power of digital computers and progress in computer science. In recent years, there has been significant progress in AI research, driven by advancements in machine learning and various related disciplines. These advancements have opened up new possibilities for the food industry, particularly in the field of food processing [5][6]. The purpose of this paper is to outline the various applications of AI and machine vision technologies in the food processing industry.

2. Artificial Intelligence

The field of artificial intelligence has evolved within computer science, concentrating on the creation of systems that can carry out functions traditionally associated with human intelligence. This involves various skills such as solving problems, identifying patterns, comprehending natural language, and acquiring knowledge through experience. Artificial neural networks (ANN) serve as the cornerstone of artificial intelligence, functioning as computational models that draw inspiration from the architecture and operations of the human brain [7]. ANNs are made from interconnected artificial neurons organized in layers (**Fig. 1a.**). Input layer which receives raw input data, where each neuron corresponds to one of the features of input data. Hidden layers of neurons (one or more), are located between input and output layers on ANN. The neurons in this layer receive inputs from the preceding layer through weighted connections, utilizing an activation function to generate outputs that are transmitted to the subsequent layer (Fig. 1b.). The output layer, which is the last layer of the artificial neural network (ANN), generates the network's output. Each neuron in this layer corresponds to a specific class or value that the ANN aims to recognize or forecast.

Each neuron within these layers has associated weights and biases that are adjusted during the training process. The neuron's activation function defines how it reacts to the sum of the weighted inputs. Common activation functions include the sigmoid, tanh, ReLU, and softmax [8].

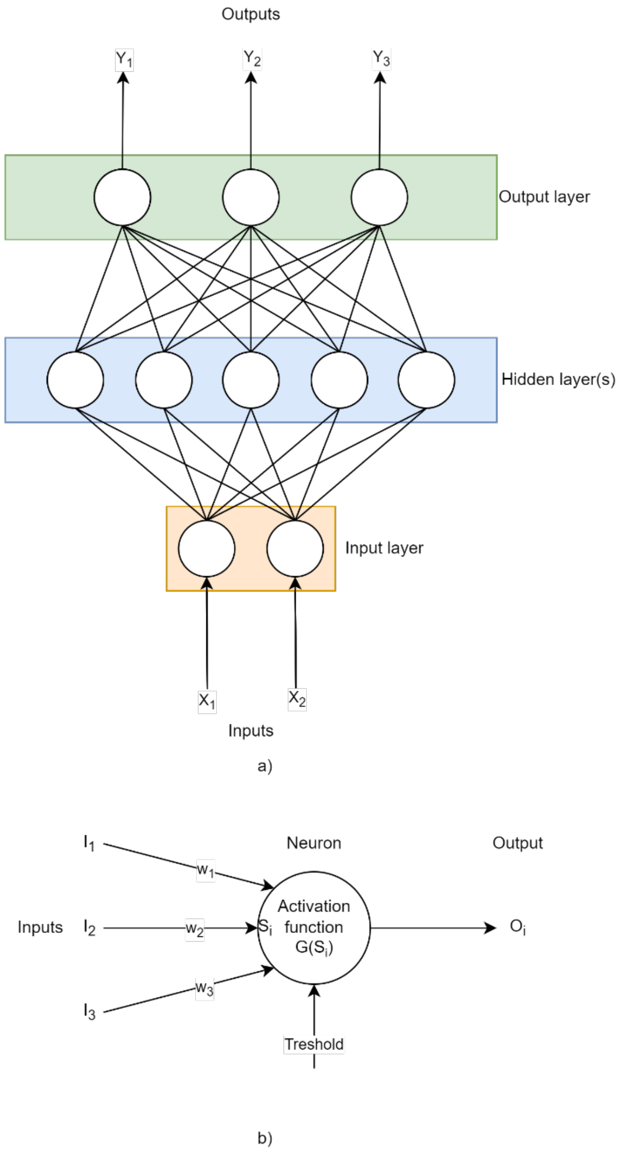

Fig. 1. Generalized structure of ANN (a) and artificial neuron (b)

Neuronal connections facilitate the transfer of output from one neuron to become the input for another neuron. The strength and sign of these connections are determined by the weights, which are adjusted during the training phase so that the network can learn to make accurate predictions or decisions. This training usually involves a process known as backpropagation, where the error between the predicted output and the actual output is computed and used to update the weights of the network through an optimization algorithm such as gradient descent [9][10].

The structure and design of an ANN play a crucial role in its ability to learn and perform tasks accurately.

Typically, AI systems are categorized into two types weak or strong AI [11][12]. Weak AI, or narrow AI refers to AI systems that are designed and trained for a specific task, such as image recognition or speech recognition. Conversely, strong AI, also known as general AI, refers to a machine that possesses the capability to utilize intelligence across a wide range of problems, rather than being limited to addressing a single specific issue. This variant of AI can grasp, learn, and implement knowledge in various areas, yet it has not been completely realized and is still the focus of continuous research. The field of AI includes a range of subfields that target different components of human intelligence, with the key ones being:

- Machine learning relies on algorithms to enable machines to learn from data and make predictions. Learning can be done with supervised, unsupervised, or reinforcement learning techniques. Recently, deep learning techniques that utilize deep neural networks—characterized by multiple hidden layers—have surfaced as effective tools for modelling intricate patterns within data. [13].
- Computer vision systems have a goal to enable machines to perceive and understand visual information such as images or videos. These systems use image processing algorithms to extract meaningful features from the visual input and can be applied in various tasks such as object recognition, image classification, and machine vision [14][15]. These systems have wide applications in various industries.
- The field of robotics emphasizes the design and development of machines that can physically interact with their environment. These machines are equipped with sensors, actuators, and algorithms that allow them to perceive their surroundings, make decisions, and carry out tasks autonomously [16][17].
- Natural language processing aims to enable machines to understand and generate human language. This field involves the development of algorithms and models that can process and analyse text, speech, and other forms of language data [18][19].
- Expert systems are AI systems that emulate the decision-making ability of human experts in a specific domain. These systems use knowledge representation and reasoning techniques to provide solutions and recommendations based on their expertise [20].

AI aims not only to simulate intelligence but also to extend human capabilities by processing large amounts of data at a speed that far exceeds what humans can do. AI applications are diverse and span multiple industries, including healthcare, transportation, finance, manufacturing and, as your document discusses, food processing.

3. Machine Vision Systems

Machine vision systems are being incorporated in various industries, including the food industry, typically in conjunction with machine learning or ANN to enhance automation and improve quality controlMachine vision systems typically consist of two main components: the acquisition of images and the processing of those images. The acquisition phase involves various sensor types designed to capture images of food products [21] complemented by suitable lighting sources. The image processing phase involves applying different methods, ranging from statistical to machine learning and deep learning models to effectively analyse and interpret the captured images.

Machine vision systems use various types of sensors to capture images for analysis. The choice of sensor depends on the specific requirements of the application, such as resolution, speed, sensitivity, and environmental conditions. Several kinds of sensors are frequently employed in machine vision systems:

- Charge-Coupled Device Sensors: These sensors are known for their high-quality images and excellent light sensitivity. CCD sensors are commonly used in applications requiring precise measurements, inspection, and high-resolution imaging [22].
- Complementary Metal-Oxide-Semiconductor Sensors: CMOS sensors are generally more cost-effective and consume less power compared to CCD sensors. They are capable of faster processing speeds and are used in applications where high frame rates and integration with on-chip processing circuits are required [22].
- Infrared Sensors: These sensors capture images based on infrared light, which is not visible to the human eye. They are useful for applications in low-light conditions or where temperature differentiation is important [23].
- X-ray Sensors: Used for inspection purposes where penetrative imaging is necessary, such as detecting flaws inside metal parts or inspecting packaged goods for contaminants [24][25].
- Thermal Imaging Sensors: Capture images based on the heat emitted by objects. They are used in applications ranging from medical diagnostics to industrial inspection where temperature variations need to be monitored [26][27][28].
- Line Scan Sensors: Instead of capturing a whole image at once, these sensors capture data line by line to create an image. Line scan cameras are suitable for inspecting objects moving at high speeds on a production line, such as webs of materials or cylindrical parts [29].
- Time-of-Flight Sensors: These use the time it takes for light to travel to an object and back to calculate distance. ToF cameras are useful in 3D imaging and can help with object recognition, volume measurement, and collision avoidance in robotic applications [30][31][32].
- 3D Sensors: Utilize various technologies, such as laser triangulation or stereovision, to create three-dimensional images of objects. They are used in complex inspection tasks where depth information is critical [33][34].
- Ultraviolet Sensors: UV cameras can capture images using ultraviolet light, which can be used to highlight certain features that are not visible with standard lighting conditions [35].
- Multispectral and Hyperspectral Sensors: Capture image data at specific frequencies across the electromagnetic spectrum. These sensors can detect chemical composition or moisture content and are used in applications such as agricultural monitoring [36][37][38].

The importance of lighting in machine vision cannot be overstated, as it plays a critical role in the effectiveness of the imaging system. Proper lighting is essential for capturing high-quality images that are needed for accurate analysis. The choice of light source will depend on the specific requirements of the application [39]. Several pivotal outcomes can be attained by implementing efficacious illumination within machine vision systems, underscoring its significance:

- Feature Enhancement: Lighting can be configured to emphasize specific features on the subject being imaged, such as edges, colours, or textures, which are critical for accurate detection and measurement.
- Consistency: Consistent lighting ensures that images are captured with uniform brightness and contrast, which is essential for reliable comparison and analysis, especially in applications where precise measurements or consistent quality checks are required.
- Contrast: Proper lighting enhances the contrast between the object and its background, facilitating easier identification and processing by the vision system.
- Image Clarity: Good lighting reduces shadows and glare that can obscure details and degrade the quality of the image. With clear images, machine vision systems can detect defects, sort products, and guide robots with greater precision.
- Speed and Efficiency: Adequate lighting allows for faster shutter speeds, which is crucial for imaging fast-moving objects on production lines without motion blur, thus improving the throughput and efficiency of industrial processes.
- Reduction of Noise: Optimal lighting conditions enable the camera to operate with lower ISO settings and shorter exposure times, reducing the amount of noise in the captured image and increasing the signal-to-noise ratio.
- Safety and Non-destructive Inspection: In some applications, the correct lighting can allow for the safe and non-destructive inspection of products, such as using X-ray or infrared light to inspect packaged goods without opening them.
- Flexibility: By manipulating lighting conditions, a machine vision system can be adapted to different tasks and environments, making the system more versatile and capable of handling a wide range of inspection duties.

In summary, lighting in machine vision is pivotal in ensuring that the system performs as expected. It affects virtually every aspect of the image-capturing process, thereby influencing the success of applications that rely on machine vision technology [40].

After image acquisition, machine vision systems typically include several major steps (**Fig. 2.**) for processing and interpreting visual information: image pre-processing, segmentation, feature extraction, pattern recognition/classification, and decision-making [39].

Image pre-processing includes various techniques to enhance the quality and clarity of acquired images before further analysis [41]. The most common methods for image pre-processing include grayscale conversion, noise reduction, histogram equalization, image enhancement, and image normalization [39].

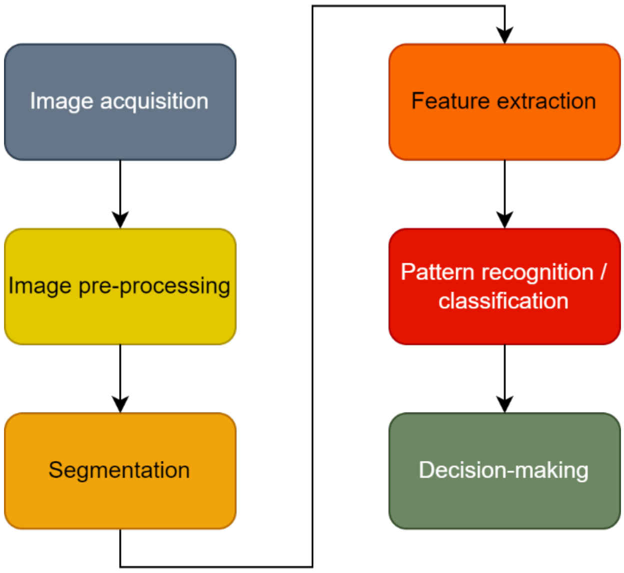

Fig. 2. Major steps for processing and interpreting visual information in machine vision systems.

Segmentation is the process of partitioning an image into meaningful regions or objects to simplify further analysis. Segmentation techniques determine the boundaries and regions within an image, allowing for more efficient and accurate recognition of objects or features of interest. Segmentation techniques can be based on intensity thresholds, edge detection, region growing, or clustering algorithms [42][43][44][45]. Feature extraction involves extracting relevant visual features from the segmented regions, which can include shape, texture, colour, or spatial relationships [46][47]. These features are then used to characterize and describe the objects or regions of interest in the image. Pattern recognition/classification is the step in which machine learning algorithms or other mathematical methods are applied to identify and classify objects or patterns based on the extracted features from the previous steps [48]. This step involves comparing the extracted features with a pre-defined set of criteria or patterns to determine the class or category to which an object belongs. Decision-making is the final step in the machine vision process, where a decision or action is made based on the classification or recognition results [39].

4. Application of AI and Machine Vision in the Food Processing Industry

The food processing industry, similar to other processing sectors, relies on obtaining raw materials and converting them into final food products. However, unlike in other processing industries, the raw materials in the food industry are perishable and susceptible to spoilage [49]. This underscores the importance for the food processing industry to optimize its operations and ensure quality control throughout the production process [50]. The strategy of managing the food chain is often described as "from farm to table" or from "field to fork," highlighting the critical need for maintaining strict time frames for ensuring quality and safety during food processing from harvesting or production until it reaches consumers' plates. Artificial intelligence has emerged as a powerful tool in the food processing industry to address these challenges and enhance various aspects of the production process such as:

- Food quality and safety determination (raw materials): AI systems can analyse and evaluate the quality of food products based on various parameters such as appearance, texture, taste, and aroma [51]. This can help ensure that only high-quality and safe raw materials are used in the production process. Also, AI can be used to monitor and inspect finished food products, ensuring that they meet the required quality standards.
- Control tools: AI can be used to monitor and control various aspects of food processing operations, such as temperature, humidity, pressure, and other critical variables. This ensures that the production process is optimized for efficiency and consistent quality.
- Food processing: AI can optimize and automate various processes in food processing, such as ingredient mixing, cooking, packaging, and labelling, to improve efficiency and consistency [52][53].
- Food sorting and Packaging: AI can automate the sorting process of food products based on quality, size, colour, or other characteristics [51].
- Predictive maintenance and optimization of food processing equipment: AI can analyse data collected from sensors and machines to predict when maintenance or repairs are needed, reducing downtime and maximizing equipment efficiency [51][54].
- Sales forecasting and supply chain management: AI can analyse historical data, market trends, and consumer behaviour to accurately forecast sales demand and optimize the supply chain, ensuring efficient production and minimizing wastage [55][56].
- Generally, AI can be employed in almost all parts, if there is enough data for model development, the problem can be reduced to optimization, classification, pattern recognition or decision-making. These applications of AI in the food processing industry have the potential to significantly improve efficiency, quality, and safety throughout the entire production process, ultimately leading to higher customer satisfaction and a more sustainable food industry [55]. Furthermore, the integration of machine vision in food process engineering allows for real-time monitoring and analysis of food products [57]. This enables quick detection and response to any quality or safety issues, ensuring that only safe and high-quality products are delivered to consumers. In summary, AI and machine vision have numerous applications in food process engineering, including improving traceability, detecting contaminants, ensuring employee safety and hygiene, optimizing production processes, and enhancing overall quality and efficiency. In recent years, machine learning and machine vision have played a crucial role in enhancing various aspects of the food processing industry [47][58].

5. Challenges and Opportunities in AI-Driven Food Engineering

Artificial intelligence-driven food engineering has the potential to revolutionize the food industry by improving productivity, efficiency, and quality. But, as with all new technologies, there are some challenges and opportunities that need to be addressed [21].

One of major the challenges in implementing AI-driven food engineering is the availability and quality of data. High-quality data is crucial for training AI models and ensuring accurate results. Advanced artificial intelligence models require extensive data sets, posing challenges in terms of acquisition, storage, and processing. This also results in increased expenses and complexity during the implementation phase. AI models also require diverse and representative data to avoid bias and ensure fairness in their predictions [59]. Designing artificial intelligence models capable of managing the inherent variability in food products and processes presents a significant challenge. Initial investment and infrastructure requirements for implementing AI are also challenges and might be barriers for small and medium-sized enterprises that need to be addressed [60].

A related issue that arises is the lack of skilled professionals who possess knowledge in both the technological and food science dimensions of AI-driven food engineering[51]. Integrating AI technology into established food processing systems can present challenges and often demands considerable adjustments or upgrades [21]. Complying with stringent food safety and quality regulations when implementing AI technologies can be difficult. It is common for AI-driven systems to exhibit limited interpretability, posing difficulties in comprehending and articulating the reasoning that underlies their decisions [51]. AI recently received a lot of media attention and raised many questions which can result in scepticism or ethical concerns among consumers regarding AI in food production, affecting market acceptance.

Despite these challenges, there are also significant opportunities in AI-driven food engineering. Utilizing AI technology in the food industry can result in improved productivity and greater efficiency [57]. It can automate repetitive complex tasks such as sorting, grading and packaging of food by enabling machines to handle products with variability [61][62][63][5][64]. AI can also optimize processing parameters, leading to improved quality and reduced waste [57]. Enhanced quality control can be achieved with AI systems capable of detecting defects, contaminants, and foodborne pathogens in real-time, ensuring safer products for consumers [65][6]. Additionally, AI can help in product development by analysing consumer preferences and trends, allowing for more personalized and innovative food options [6][66][67]. Furthermore, AI can assist in supply chain management by predicting demand, optimizing inventory levels, and improving logistics [68][69][70][71]. In summary, AI and machine vision have the potential to revolutionize the food processing industry by enhancing productivity, improving product quality and safety, and optimizing supply chain management.

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