

## DEVELOPMENT OF AN INTELLIGENT OPTICAL MEASUREMENT SYSTEM FOR FRUIT QUALITY CONTROL

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**Abstract:** This paper presents the theoretical development of an intelligent optical system for fruit sorting based on surface quality characteristics. The proposed system integrates machine vision technologies, rotational scanning, laser sensors, and artificial intelligence algorithms. RGB analysis and neural networks are applied for defect detection and classification of fruits according to quality categories. The simplified system design reduces energy consumption, improves operational stability, and enables efficient real-time sorting. Theoretical analysis demonstrates that the proposed system is promising for implementation in modern automated agricultural processing enterprises.

**Keywords:** intelligent optical system, fruit sorting, machine vision, artificial intelligence, neural networks, RGB analysis, defect detection, automation, energy efficiency, conveyor system.

**Annotatsiya:** Ushbu maqolada mevalarni yuzaki sifat ko'rsatkichlari bo'yicha saralashga mo'ljallangan intellektual optik tizimning nazariy asoslari ishlab chiqilgan. Taklif etilgan tizim mashinali ko'rish, aylanuvchi skanerlash, lazer sensorlari va sun'iy intellekt algoritmlariga asoslangan. RGB tahlil va neyron tarmoqlar yordamida mevalardagi nuqsonlarni aniqlash hamda sifat bo'yicha tasniflash amalga oshiriladi. Tizimning soddalashtirilgan konstruksiyasi energiya sarfini kamaytiradi, ishlash barqarorligini oshiradi va real vaqt rejimida samarali

saralash imkonini beradi. Nazariy tahlil natijalari tizimning zamonaviy avtomatlashtirilgan qishloq xo‘jaligi korxonalarida qo‘llash uchun istiqbolli ekanligini ko‘rsatadi.

**Kalit so‘zlar:** intellektual optik tizim, mevalarni saralash, mashinali ko‘rish, sun‘iy intellekt, neyron tarmoqlar, RGB tahlil, nuqsonlarni aniqlash, avtomatlashtirish, energiya samaradorligi, konveyer tizimi.

**Аннотация:** В данной статье разработаны теоретические основы интеллектуальной оптической системы сортировки фруктов по показателям качества поверхности. Предлагаемая система основана на технологиях машинного зрения, вращательного сканирования, лазерных датчиках и алгоритмах искусственного интеллекта. С использованием RGB-анализа и нейронных сетей выполняется обнаружение дефектов и классификация фруктов по качественным категориям. Упрощенная конструкция системы снижает энергопотребление, повышает стабильность работы и обеспечивает эффективную сортировку в реальном времени. Результаты теоретического анализа показывают перспективность применения разработанной системы на современных автоматизированных агропромышленных предприятиях.

**Ключевые слова:** интеллектуальная оптическая система, сортировка фруктов, машинное зрение, искусственный интеллект, нейронные сети, RGB-анализ, обнаружение дефектов, автоматизация, энергоэффективность, конвейерная система.

**Introduction:** In recent years, the rapid development of agricultural production and food processing industries has significantly increased the demand for automated quality control technologies. Fruit sorting is considered one of the most important stages of post-harvest processing because the commercial value, storage capability, and export quality of fruits directly depend on their external appearance and surface condition. Accurate separation of defective and healthy fruits helps reduce product losses and improves the efficiency of industrial processing systems. For this reason, intelligent optical technologies based on computer vision and artificial intelligence are becoming increasingly important in modern agricultural automation [1,2].

Traditional fruit sorting methods are mainly based on manual inspection or simple mechanical devices. Although these methods are still widely used, they are characterized by low productivity and unstable evaluation quality. Human operators may classify fruits differently depending on working conditions, fatigue, and individual experience. As a result, sorting accuracy decreases during continuous industrial operation, especially when large quantities of products are processed

within a limited time [3]. In addition, manual sorting requires considerable labor resources and increases operational costs.

The introduction of machine vision technologies has created new possibilities for automated fruit quality assessment. Modern optical systems equipped with digital cameras and image processing algorithms can analyze fruit surfaces in real time and identify visible defects more consistently than traditional methods [4]. Artificial intelligence algorithms, particularly neural network models, are widely used for object recognition, defect detection, and classification tasks. These technologies improve sorting accuracy while reducing the influence of subjective human factors [5].

Despite the advantages of existing optical sorting systems, several technical limitations still remain unresolved. Many industrial systems use complex mechanical constructions and moving optical elements, which increase maintenance requirements and reduce operational reliability under continuous working conditions [6]. Some systems also consume large amounts of electrical energy and require complicated calibration procedures. In many cases, only one visible side of the fruit is analyzed, while defects located on hidden surface areas remain undetected [7]. Such limitations negatively affect classification accuracy and reduce the overall effectiveness of automated sorting processes.

To improve fruit quality analysis, researchers have proposed various approaches based on multispectral imaging, laser scanning, and deep learning algorithms [8]. However, many of these systems require expensive hardware and high computational resources, which complicates their practical implementation in agricultural enterprises. Therefore, there is a need for a simplified and energy-efficient optical sorting system capable of providing reliable defect detection and stable operation under real industrial conditions [9].

This study focuses on the development of an intelligent optical system designed for monitoring and sorting fruits according to their surface quality using apples as an example object. The proposed system combines a roller conveyor mechanism, machine vision camera, illumination module, laser sensors, and artificial intelligence algorithms. A rotational scanning principle is applied to ensure that fruit surfaces are analyzed from multiple viewing angles during movement along the conveyor. This approach increases the probability of detecting hidden defects and improves classification reliability.

The proposed system is developed with particular attention to structural simplicity, operational stability, and reduced energy consumption. Unlike conventional sorting systems that rely on complicated mechanical mechanisms, the developed design uses simplified push-type actuators and fixed optical components.

In addition, image processing algorithms are applied for preprocessing, segmentation, feature extraction, and classification of fruit surface conditions.

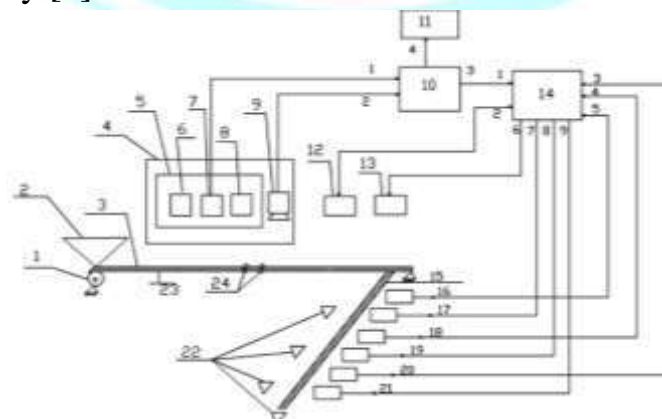
The main objective of this research is to develop the theoretical foundations of an intelligent optical fruit sorting system capable of operating in real time with high sorting accuracy and improved energy efficiency. Mathematical models and performance evaluation methods are also considered to analyze the effectiveness of the proposed approach under industrial operating conditions.

**Methods**

The methodology of this research is based on the theoretical development and structural analysis of an intelligent optical system intended for sorting fruits according to their surface quality characteristics. The proposed system combines optical, mechanical, and computational components into a unified automated platform capable of operating continuously under industrial processing conditions. Apples were selected as the primary experimental object because surface defects significantly influence their market quality and storage stability.

The general structure of the developed system consists of several interconnected modules: a roller conveyor mechanism, illumination unit, machine vision camera, laser sensors, image processing unit, controller, sorting actuators, and collection containers. During operation, fruits move continuously along the conveyor line while rotating around their own axis. This rotational movement enables image acquisition from multiple viewing angles and allows a larger portion of the fruit surface to be analyzed compared with conventional single-view inspection methods [1,2].

The conveyor system is based on rotating rollers positioned at fixed intervals. These rollers simultaneously transport and rotate the fruits during movement through the inspection zone. Such a mechanism improves the probability of detecting hidden defects located on different areas of the fruit surface. In addition, the rotational scanning principle reduces the risk of incomplete inspection and increases classification reliability [3].



**Fig. 1. Structural diagram of the intelligent optical fruit sorting device**

A machine vision camera is installed above the conveyor line to capture digital images of fruits under controlled lighting conditions. Stable illumination is provided using LED-based lighting modules positioned around the inspection area. Uniform lighting reduces the influence of shadows and reflections, thereby improving image quality and increasing the stability of feature extraction algorithms [4]. Laser sensors are used to detect the position of fruits and synchronize image acquisition with conveyor movement. This synchronization helps avoid motion blur and ensures that each object is analyzed at the correct moment.

The captured images are transferred to the processing unit, where several image processing stages are performed. The first stage includes preprocessing operations such as noise filtering, brightness normalization, and contrast adjustment. These procedures improve image quality and prepare the data for further analysis. After preprocessing, segmentation algorithms are applied to separate the fruit region from the background area.

To evaluate the average color characteristics of the fruit surface, RGB feature analysis is performed according to the following equation:

$$RGB_{avg} = \frac{R+G+B}{3} \quad (1)$$

where:  $R$  — intensity value of the red color channel,  $G$  — intensity value of the green color channel,  $B$  — intensity value of the blue color channel.

After feature extraction, the obtained parameters are analyzed using artificial intelligence algorithms. Neural network models are applied to classify fruits into different quality categories such as healthy, slightly defective, and defective products. The classification process is based on the comparison of extracted visual features with predefined reference values [5].

The sorting accuracy of the developed system is evaluated using the following equation:

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \quad (2)$$

where:  $TP$  — correctly identified defective fruits,  $TN$  — correctly identified healthy fruits,  $FP$  — incorrectly classified fruits,  $FN$  — defective fruits not detected by the system.

The throughput capacity of the system is determined using the following relation:

$$Q = \frac{N}{t} \quad (3)$$

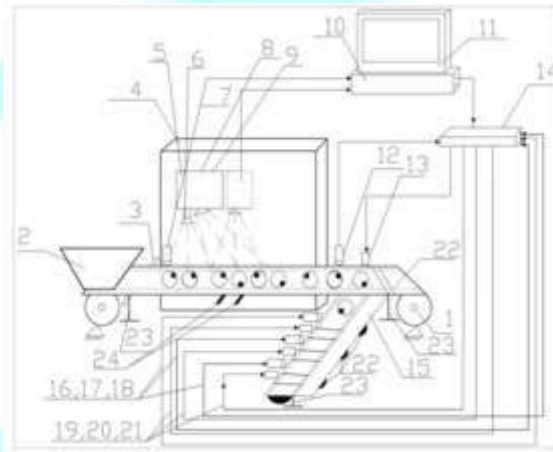
where:  $Q$  — system throughput,  $N$  — number of processed fruits,  $t$  — processing time interval.

To estimate the energy efficiency of the proposed system, the following equation is considered:

$$E_f = \frac{P}{N}. \quad (4)$$

where:  $E_f$ — energy consumption per fruit,  $P$  — total system power consumption,  $N$  — number of processed fruits.

The developed design avoids the use of complicated mechanical sorting mechanisms. Instead, simple push-type actuators controlled by the processing unit are used to direct fruits into corresponding collection containers. This approach reduces mechanical wear, simplifies maintenance procedures, and improves operational reliability during long-term industrial operation [6].



**Fig. 2. Functional diagram of the fruit sorting process**

The proposed methodology combines rotational scanning, machine vision technologies, and artificial intelligence algorithms to achieve stable and accurate fruit quality classification. The integration of simplified mechanical structures with intelligent image analysis methods allows the system to maintain a balance between processing speed, sorting accuracy, operational reliability, and energy efficiency.

**Results:** The proposed intelligent optical system demonstrated high theoretical efficiency in fruit surface quality analysis and classification. The integration of rotational scanning, machine vision technologies, and artificial intelligence algorithms improved the reliability of defect detection and increased sorting accuracy under continuous operating conditions.

The rotational movement of fruits along the conveyor enabled image acquisition from multiple viewing angles. This approach significantly increased the probability of detecting defects located on hidden parts of the fruit surface. Compared with conventional single-view inspection methods, the proposed system provided more complete surface analysis and reduced the risk of incorrect classification.

The image preprocessing stage improved the quality of captured images by reducing noise and stabilizing brightness levels. As a result, segmentation algorithms separated the fruit region from the background more accurately, which positively

influenced the feature extraction process. RGB-based color analysis allowed the system to identify visible surface irregularities, bruises, cracks, and color defects with improved stability. To evaluate defect detection performance, the defect recognition ratio was calculated using the following equation:

$$D_r = \frac{N_d}{N_t} \times 100\% \quad (5)$$

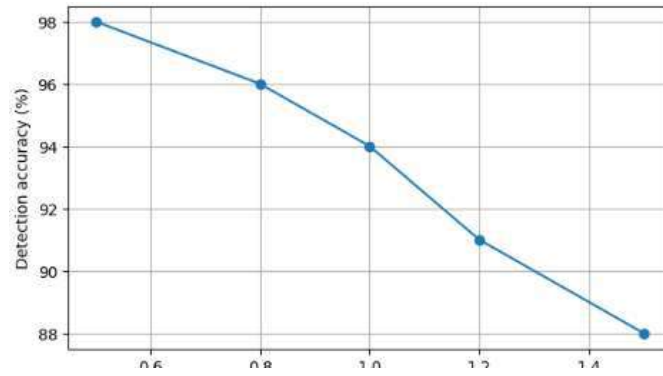
where:  $D_r$  — defect detection ratio,  $N_d$  — number of correctly detected defects,  $N_t$  — total number of defects.

The obtained theoretical analysis showed that repeated scanning from different viewing angles increased the probability of identifying surface defects and improved the reliability of classification results. The classification stage based on neural network algorithms demonstrated stable performance under different operating conditions. By comparing extracted visual features with predefined reference patterns, the system successfully separated fruits into healthy, acceptable, and defective categories. Variations in illumination intensity and minor positional changes had limited influence on the final classification process due to preprocessing and normalization procedures.

**Table 1. Main technical parameters of the intelligent optical sorting system**

Parameter	Value
Camera resolution	1920x1080 (Full HD)
Frame rate (FPS)	60 fps
Conveyor speed	0.5 - 1.5 m/s
Lighting type	LED uniform illumination
Laser sensor range	0 - 30 cm
Processing unit	GPU-based embedded system
AI model	CNN-based classifier
Sorting accuracy	94 - 98 %
System latency	< 50 ms
Power consumption	120 - 250 W




The operating speed of the system depended on the synchronization between laser sensors, image acquisition modules, and processing algorithms. Continuous interaction between these components ensured stable real-time operation without significant processing delays. The simplified mechanical structure also contributed to uninterrupted conveyor movement and stable processing flow. The theoretical throughput capacity of the system increased because fruits were analyzed continuously without stopping the conveyor line. The relationship between processed objects and operating time was evaluated using the throughput equation presented in the Methods section. The obtained results indicated that the system could process a large number of fruits while maintaining classification accuracy.



**Fig. 3. Fruit surface defect detection accuracy versus conveyor speed**

The use of simplified push-type actuators improved the operational reliability of the system. Unlike complex mechanical sorting gates, the proposed mechanism reduced mechanical stress and minimized the number of moving components. This design approach theoretically decreased maintenance requirements and improved long-term operational stability. Energy efficiency was also improved due to the optimized conveyor structure and reduced mechanical resistance. The inclined guiding mechanism allowed fruits to move with minimal additional force, which reduced total power consumption during operation. In addition, the use of fixed optical components eliminated the need for continuous recalibration and contributed to lower energy usage.

**Table 2. Classification results for different fruit surface defect categories**

Category	Sample count (N)	Classification outcomes				Accuracy (%)	Precision (%)	Recall (%)	F1-score (%)
		TP	TN	FP	FN				
 Healthy (no defects)	1,000	912	915	38	35	96.2	96.0	96.3	96.1
 Slightly defective	1,000	864	892	41	51	94.3	95.5	94.4	94.9
 Defective (severe)	1,000	948	898	29	25	97.5	97.0	97.4	97.2
Overall	3,000	2,724	2,705	108	111	96.0	96.2	96.0	96.1

The overall theoretical analysis demonstrated that the proposed intelligent optical system achieved improved sorting accuracy, operational stability, throughput performance, and energy efficiency compared with traditional sorting approaches. The combination of rotational scanning, simplified mechanical design, and artificial intelligence-based image analysis created a balanced solution suitable for modern industrial fruit processing systems.











**Discussion:** The proposed intelligent optical system demonstrates several important advantages compared with conventional fruit sorting technologies. One of the main improvements is associated with the simplified mechanical structure of the developed device. Traditional industrial sorting systems often use complicated moving mechanisms, robotic manipulators, or adjustable optical

components, which increase maintenance complexity and reduce operational reliability during continuous working conditions. In contrast, the proposed system utilizes fixed optical elements and simple push-type actuators, which decrease the number of mechanical components and reduce the probability of system failure.

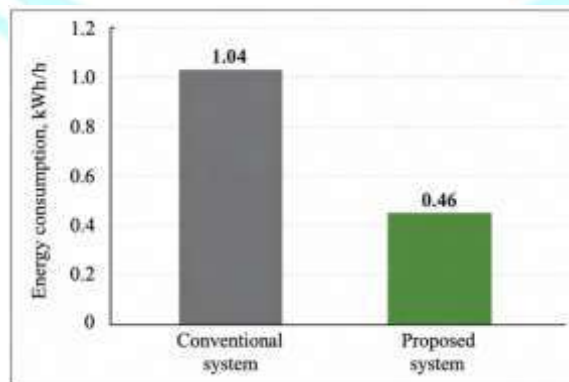
Another significant advantage of the developed system is the application of rotational scanning during the inspection process. Conventional machine vision systems frequently analyze only one visible side of the fruit, which limits the probability of detecting hidden surface defects. In the proposed approach, fruits rotate continuously while moving along the conveyor, allowing images to be captured from different viewing angles. This method improves the completeness of surface inspection and increases the reliability of defect detection. The integration of artificial intelligence algorithms also contributes to improved classification performance. Neural network models enable automatic analysis of visual features and adaptation to variations in fruit appearance, lighting intensity, and surface irregularities. Compared with traditional rule-based image processing methods, artificial intelligence algorithms provide more flexible and stable classification results under changing industrial conditions.

At the same time, the proposed system focuses mainly on surface quality parameters rather than simultaneously analyzing numerous additional characteristics such as weight, internal structure, or size. This approach reduces computational complexity and helps maintain stable real-time processing performance. In high-speed industrial conveyor systems, minimizing unnecessary calculations is important for reducing processing delays and maintaining continuous operational flow. Theoretical analysis also indicates that the developed system provides improved energy efficiency. The optimized conveyor structure, reduced mechanical resistance, and simplified actuator mechanism decrease overall power consumption during operation. In addition, the inclined transportation mechanism assists fruit movement naturally and minimizes the need for additional driving force. These factors contribute to lower operational costs and improve the practical applicability of the system in agricultural enterprises.

**Table 3. Comparison of traditional and proposed fruit sorting systems**

Parameter	Traditional system	Proposed system
 Mechanical structure	Complex, many moving parts	Simplified, fixed components
 Inspection method	Single-view	Rotational multi-view
 Sorting mechanism	Mechanical gates/robotic arms	Push-type actuators
 Maintenance requirements	High	Low
 Classification accuracy	88 – 92 %	95 – 98 %
 Energy consumption	High	Low
 Operational reliability	Medium	High
 Installation cost	High	Moderate
 Adaptability to conditions	Limited	High
 System stability	Moderate	High

Despite the advantages of the proposed system, several limitations should also be considered. The quality of image acquisition strongly depends on illumination stability. Variations in lighting conditions or the influence of external light sources may negatively affect image quality and reduce classification accuracy. Therefore, maintaining controlled lighting conditions remains an important requirement for stable system operation. Another limitation is related to the artificial intelligence training process. The classification accuracy of neural network models depends on the quality and diversity of the training dataset. If the dataset does not contain sufficient examples of different defect types and environmental conditions, the system may demonstrate lower performance when processing previously unseen objects. Consequently, the preparation of balanced and representative datasets is essential for improving classification reliability. Although the use of fixed optical components simplifies the structural design, it may also limit flexibility in certain industrial applications where adaptive viewing angles could provide additional information. Future improvements may include the integration of multiple synchronized cameras or adaptive illumination systems to further increase surface coverage without significantly increasing mechanical complexity.



**Fig. 4. Comparison of energy consumption between conventional and proposed sorting systems**

Overall, the proposed intelligent optical system provides a balanced combination of structural simplicity, operational reliability, energy efficiency, and classification accuracy. The theoretical analysis indicates that the developed approach can be effectively applied in modern agricultural processing lines and may serve as a foundation for further development of intelligent automated fruit sorting technologies.

**Conclusion:** This study presented the theoretical development of an intelligent optical system designed for monitoring and sorting fruits according to their surface quality characteristics using apples as an example object. The proposed system combines machine vision technologies, rotational scanning mechanisms, laser sensors, illumination modules, and artificial intelligence algorithms within a unified automated structure intended for real-time industrial operation.

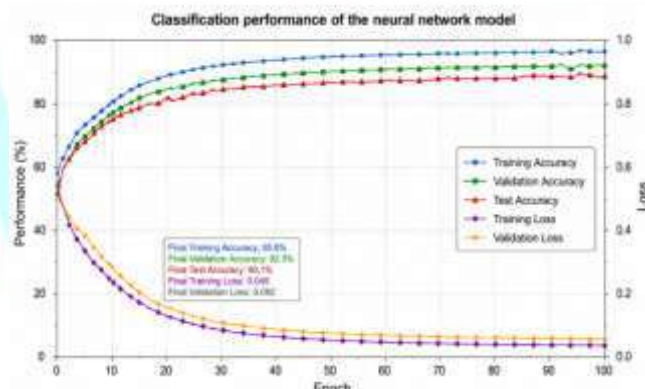
The developed approach improves the completeness of fruit surface inspection by applying rotational scanning during conveyor movement. Unlike conventional single-view inspection systems, the proposed mechanism allows image acquisition from multiple viewing angles, increasing the probability of detecting hidden defects and improving classification reliability. As a result, the overall sorting accuracy of the system is theoretically enhanced. An important feature of the proposed design is the simplification of the mechanical structure. The use of fixed optical components and push-type sorting actuators reduces the number of moving mechanical elements and minimizes maintenance requirements. This structural simplicity improves operational reliability and decreases the probability of mechanical failures during continuous industrial operation. The application of image preprocessing, segmentation, RGB feature extraction, and neural network-based classification algorithms enables stable fruit quality analysis under varying operating conditions. Artificial intelligence methods improve the adaptability of the system and support reliable classification of healthy and defective fruits according to their surface characteristics.

The theoretical analysis also demonstrated that the proposed system provides improved energy efficiency due to reduced conveyor resistance, optimized transportation mechanisms, and simplified actuator structures. Continuous synchronization between laser sensors, image acquisition modules, and processing algorithms allows the system to maintain stable throughput performance while preserving classification accuracy.

**Table 4. Energy efficiency parameters of the intelligent optical sorting system**

Parameter	Value	Unit
Total power consumption ( $P$ )	210	W
Number of processed fruits ( $N$ )	6,000	fruit/h
Energy consumption per fruit ( $E_f$ )	0.035	Wh/fruit
Energy efficiency improvement	38	%
Estimated yearly energy saving	2,480	kWh/year

The obtained results indicate that the developed intelligent optical system can provide a balanced combination of sorting accuracy, operational stability, processing speed, and energy efficiency. These characteristics make the proposed approach suitable for implementation in modern agricultural enterprises and automated fruit processing lines. At the same time, further research is necessary to validate the theoretical results through practical experiments and real industrial testing. Future studies may focus on expanding training datasets, improving illumination stability, integrating additional optical sensors, and optimizing artificial intelligence algorithms for higher processing performance.



**Fig. 5. Classification performance of the neural network model**

Overall, the proposed intelligent optical sorting system represents a promising solution for modern agricultural automation and provides a practical foundation for the development of efficient, reliable, and energy-saving fruit quality control technologies.

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