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INNOVATIVE OPTOMECHATRONIC TECHNOLOGIES IN THE TOBACCO INDUSTRY

Key words: tobacco industry, quality inspection, optomechatronic technologies.

Abstract: The manufacturing of production machinery for the tobacco industry is an area in which particularly intensive research and development works are carried out aimed at increasing the quality of products in accordance to the zero-fault policy, while ensuring high production efficiency. Achieving the highest process parameters is possible thanks to innovative optomechatronic technologies. The review of selected key achievements in the field of optomechatronic technologies and our own achievements presented in the article include methods and inspection systems used for quality inspection in the tobacco industry, as well as other industries where similar or analogous problems of detecting and identifying product defects occur. As examples of the authors' research and implementation achievements presented are advanced optomechatronic systems for the inspection of tobacco semi-finished products. Cognitive problems and technical barriers as well as methods of solving them are presented. The developed systems meet the highest requirements in terms of accuracy and speed of measurements. Their qualities were confirmed during tests in industrial conditions.
The summary presents the main trends in the implementation of innovative optomechatronic technologies for the inspection of products in mass production in the tobacco industry and other areas of the economy, as well as the directions of further research and development carried out by the authors.

Innowacyjne technologie optomechatroniczne w przemyśle tytoniowym

Słowa kluczowe: przemysł tytoniowy, kontrola jakości, technologie optomechatroniczne.

Streszczenie: Branża maszyn produkcyjnych dla przemysłu tytoniowego jest obszarem, w którym prowadzone są szczególnie intensywne prace badawcze i rozwojowe ukierunkowane na podwyższanie jakości wyrobów zgodnie z zasadą „zero braków" przy jednoczesnym zapewnieniu wysokich wydajności produkcji. Osiągnięcie najwyższych parametrów procesu umożliwiają innowacyjne technologie optomechatroniczne. Przedstawiony w artykule przegląd wybranych najważniejszych osiągnięć w obszarze technologii optomechatronicznych oraz własnych dokonań w tym zakresie obejmuje metody i systemy inspekcji zastosowane do kontroli jakości w branży tytoniowej, a także innych branżach, gdzie występują analogiczne lub zbliżone zagadnienia wykrywania i identyfikacji wad produktów. Jako przykłady autorskich osiągnięć badawczych i wdrożeniowych przedstawiono zaawansowane systemy inspekcji optomechatronicznej półproduktów tytoniowych. Zaprezentowano występujące problemy poznawcze i bariery techniczne oraz metody ich rozwiązywania. Opracowane systemy spełniają najwyższe wymagania w zakresie dokładności i szybkości pomiarów. Ich walory zostały potwierdzone w trakcie testów w warunkach przemysłowych.
W podsumowaniu przedstawiono główne trendy we wdrażaniu innowacyjnych technologii optomechatronicznych na potrzeby inspekcji wyrobów w produkcji masowej w branży tytoniowej oraz innych obszarach gospodarki, a także kierunki dalszych prac badawczo-rozwojowych prowadzonych przez autorów.

Introduction

The level of production efficiency depends, to a large extent, on the efficiency of production processes, the quality of manufactured products, and production costs. Traditional solutions based on organoleptic or mechanical quality inspection of products, especially in mass production processes, do not ensure the achievement of zero-fault requirements. The main limitations relate to the accuracy, repeatability, and speed of inspection, which is a critical barrier in the production processes, for example, with a capacity of thousands of pieces per minute. Overcoming these limitations is possible through the use of innovative optomechatronic technologies [1–4].

The manufacturing of production machinery for the tobacco industry is an area in which particularly intensive research and development works are carried out that are aimed at solving the mentioned problems, but only a few available publications present scientific and research achievements in the field of automated inspection of mass-produced goods of this industry. This is mainly due to formal limitations conditioned by agreements between the creators of innovation and the implementing unit or due to business secrets determining the possibility of disclosing the details of the developed methods and construction solutions of inspection systems, which is related to the competition among the global tobacco companies. However, the number of patents that protect the developed solutions is significant, confirming the intensity of research, development, and implementations carried out in this field in the tobacco industry. The analysis of many properties of tobacco products, such as dimensions, heterogeneous structure, colours, and interaction with light shows that, from the point of view of possible applications of optical inspection methods, they are similar to many food and pharmaceutical products, as well as fabrics or plastic products. Therefore, the review of selected key achievements in the field of optomechatronic technologies presented in the article covers inspection methods and systems used for quality inspection in selected industries where similar or analogous problems of detecting and identifying product defects occur.

Depending on the specifics of mass-produced goods, in order to detect existing defects, different techniques of spectroscopy in the range of the optical spectrum, from infrared to ultraviolet, are used, making use of the effects of the interaction of light with the tested material, e.g, transmission, diffusion with a partial reflection in the structure of the material, and directional reflection [5]. Wide possibilities of the application of optical inspection methods and the configuration of vision systems dedicated to quality assessment tasks, e.g., agricultural products, have been confirmed, among others, in the works [6–7]. Optical inspection methods are used, among others, to inspect the quality of tobacco leaves [8]. The area of research and development, which is characterised by a significant similarity of the problems being solved, is the inspection of the quality of textiles [9–10]. An important aspect of the quality inspection of mass-produced goods indicated in these works is the creation of a defect database to support the automatic process of product inspection. Imaging in the near-infrared, ultraviolet spectrum, and the use of hyperspectral cameras enables the detection of features and defects of products that are not perceived by the human eye [11–13]. The new direction of research is the use of terahertz imaging for inspecting material structures, food, pharmaceuticals, and tobacco [14]. However, the basic limitation of currently available inspection systems in the non-ionizing terahertz band is the low imaging resolution of 1–2 mm [15]. The possibility of using terahertz imaging to assess the density of the tobacco, the filter segment, and the water content [16] was experimentally confirmed. An interesting method of detecting air bubbles with dimensions greater than 1 mm in silicone rubber using laser lighting, while moving at a speed of up to 8 m/s, but with a significant measurement error, is presented in [17]. At the initial stage of the development of tobacco product inspection systems, the technical level allowed the detection of only some defects of products, e.g., the lack of a component in the final product [18–19]. A vision system for inspecting the cigarettes to detect cracks and defective cuts (v-cut) with a yield of up to 12,000 pcs/min is presented in paper [20]. To inspect the geometric dimensions and shape of the final product, as well as the filters and the tobacco segments, laser scanning systems are used that apply vision systems with structured light [21]. A very difficult issue in accurate measurements of the position of tobacco segments is the blurring of the image of the edge of the segment due to the phenomenon of scattering and the inadequate contrast of the image. To solve a similar problem, concerning detection of defects in the polarizing filter, dedicated edge-of-light lighting was used [22]. In high-throughput processes, the key to determining the effectiveness of the inspection system is to ensure high accuracy in detecting defects and high inspection performance. For this purpose, high-speed cameras and high-performance image processing and analysis algorithms are used. For example, detecting defects of sizes from 2 mm x 2 mm at a rate of up to 3,600 pcs/min in the bottle inspection system has been achieved by applying edge points double classifying and least squares fitting algorithm [23]. Achieving very high efficiency of the inspection process, in the range of several thousand per minute, requires the use of fast cameras and simple yet efficient algorithms for image processing and analysis, real-time systems, and concurrent processing [24]. For example, simple algorithms that perform edge detection and histogram analysis were used to effectively inspect surface defects in the grinding process [25]. The real-time system for automatic quality inspection of fibre-reinforced plastics (FRPs), using the LabVIEW RT module and the FPGA image processing module, is presented in [26]. There are no reports presenting the issues of the speed of communication between the inspection system and equipment included in the technological line and its impact on the efficiency of the inspection process.

The issues of designing the vision systems for quality inspection in manufacturing processes as well as the implementation of developed prototype systems are presented, among others, in the works [2, 27–28]. Optical modelling, including the analysis of light interaction with the surface under study, the selection of appropriate lighting techniques, and simulation tests, is an indispensable preliminary step in the design of vision systems [29]. 3D imaging systems using 3D laser scanning, stereovision, the shape from focus (SFF) method, and the currently developed time of flight (TOF) method are used to inspect the quality of three-dimensional parts [30]. In the process of producing cigarettes, inspected are the filters with flavoured capsules located inside, among others. One of the patented solutions for measuring the position of the capsule is the use of microwaves [31]. Quality inspection in the production of tobacco products also includes the verification of the completeness of the packages and the correct placement of cigarettes [32]. An overview of the current state of optomechatronic technologies used in vision inspection systems and the latest development trends, including inspection in three dimensions, the standardisation of interfaces of machine vision system components, increasing integration in the scope of construction and software, and the application of hyperspectral imaging are presented in industry materials [33]. Using literature analysis and the experience of the authors of the article, typical defects of tobacco products and methods of their detection are presented in Table 1.

Table 1. Methods for detection of defects of tobacco products within the production process

Product	Defect/Parameter	Method	Accuracy	Inspection rate	State of the method	Author
Final product	Lack of filter	Reflective optical sensor	Unknown	Unknown	Applied in production	[18]
		Fibre optic sensor	Unknown	< 4 ms/pc		[19]
Final product	Lack of tobacco segment	Transmissive infrared sensor	Unknown	Unknown	Applied in production	[18]
		Induction sensor	Unknown	< 4 ms/pc		[19]
Multi-segment filter	Alignment of tobacco filters	Transmissive laser sensor	Unknown	Unknown	Applied in production	[34]
Final product	Lack of foil	Induction sensor	Unknown	< 4 ms/pc	Applied in production	[19]
Final product	Wrapper (damage, alignment) Lack of filter segment	Vision inspection	Unknown	Unknown	Applied in production	[35]
Final product	V-cut Crack	Vision inspection	99.99%	12,000 pcs/min	Applied in production	[20]
Final product	Ovality	Vision inspection with structural lighting	approx. 0.2 mm	600 pcs./min	Experimental	[21]
Filter	Lack of capsule Capsule alignment	Microwave sensor	Unknown	Unknown	Applied in production	[31]
Tobacco segment Filter	Structure density Water content	Terahertz imaging	Unknown	Unknown	Experimental	[16]
Pack of products	Shape of the pack	3D vision inspection	0.2°	< 3 sec/pc	Experimental	[32]

The increasing role of optomechatronic technologies in enhancing the level of innovation in industry, including the tobacco industry, has been indicated in the priority strategies for the development of research and development works. Strategic, tactical, and operational barriers existing in practice at various levels of management have been identified and analysed in the field of optomechatronic technologies [36].

1. Examples of applications of innovative optomechatronic solutions in the tobacco industry

Research and development works aimed at applying innovative optomechatronic technologies in the tobacco industry are conducted at the Institute for Sustainable Technologies National Research Institute in Radom in close cooperation with International Tobacco Machinery Poland. The high efficiency of implemented projects is ensured by a systemic approach based on the methodology of work implementation in subsequent stages, including the following: feasibility study, development research, and the implementation process of the developed and verified prototype. The results of joint projects include a filter alignment inspection system in the process of the assembly of combined filters and the system of optical inspection of tobacco rods.

1.1. System for inspection of filter segment alignment

In the production process of multi-segment filters (combined), there is a problem of the misalignment of the segments before they are glued in the paper wrapper and cut into packets. The process of transporting segments takes place at a speed of around 500 m/min. Currently, manufacturers use shorter and shorter segments, whose length (dimension in the axial direction) is close to their diameter. For such proportions, there is the risk of the segment rotating in such a way that its axis will be non-parallel (Fig. 1).

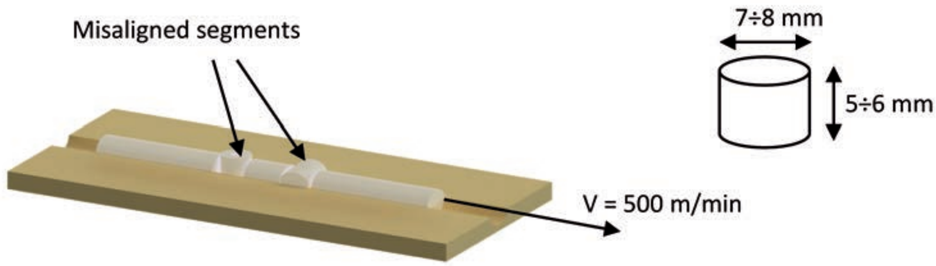

Fig. 1. Sample layout of filter segments with indicated incorrect alignment

The developed inspection system enables the detection of filter segments in various inverted positions in the stream of transported segments [37]. The laser scanning method was used to identify the position of the segment (Fig. 2). The minimum scanning resolution adopted along the filter segments is approx. 2 mm, which ensures a minimum of 2 profiles for each scanned segment at a maximum speed of a stream of 500 m/min. The system ensures the high accuracy of segment profile measurements of 20 micrometres.

The sample images of scans of the stream of filter segments recorded using the laser head are shown in Fig. 3.

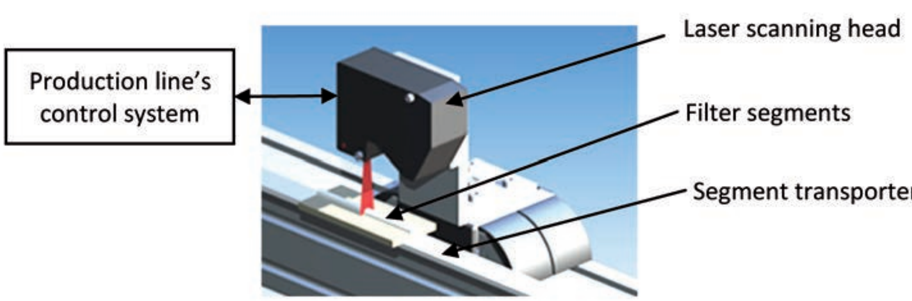

Fig. 2. Diagram of the system for filter position inspection

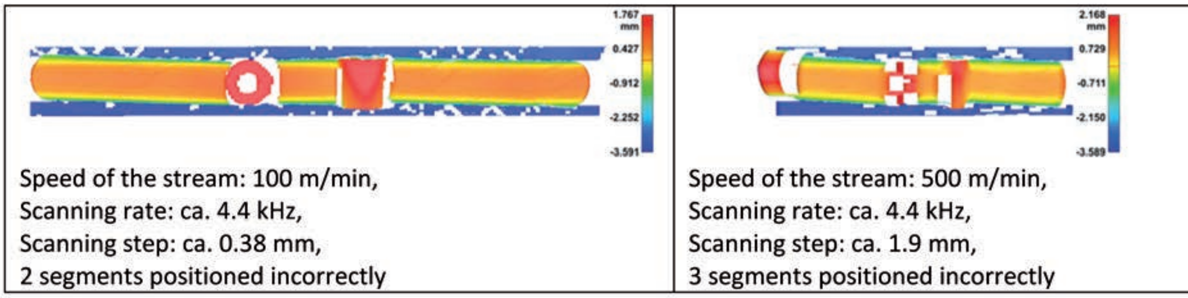

Fig. 3. The sample images of scans of the stream of filter segments with indicated misaligned segments

The images were obtained as a result of the assembly of subsequent registered 2D profiles with a scanning step of approx. 0.4 mm and approx. 1.9 mm, respectively. In the second case, the scanning resolution along the travel axis of the filter segments is much smaller, but it still meets the requirement of a minimum of two scans per segment. Examples of registered single profiles of 2D filter segments are shown in Fig. 4.

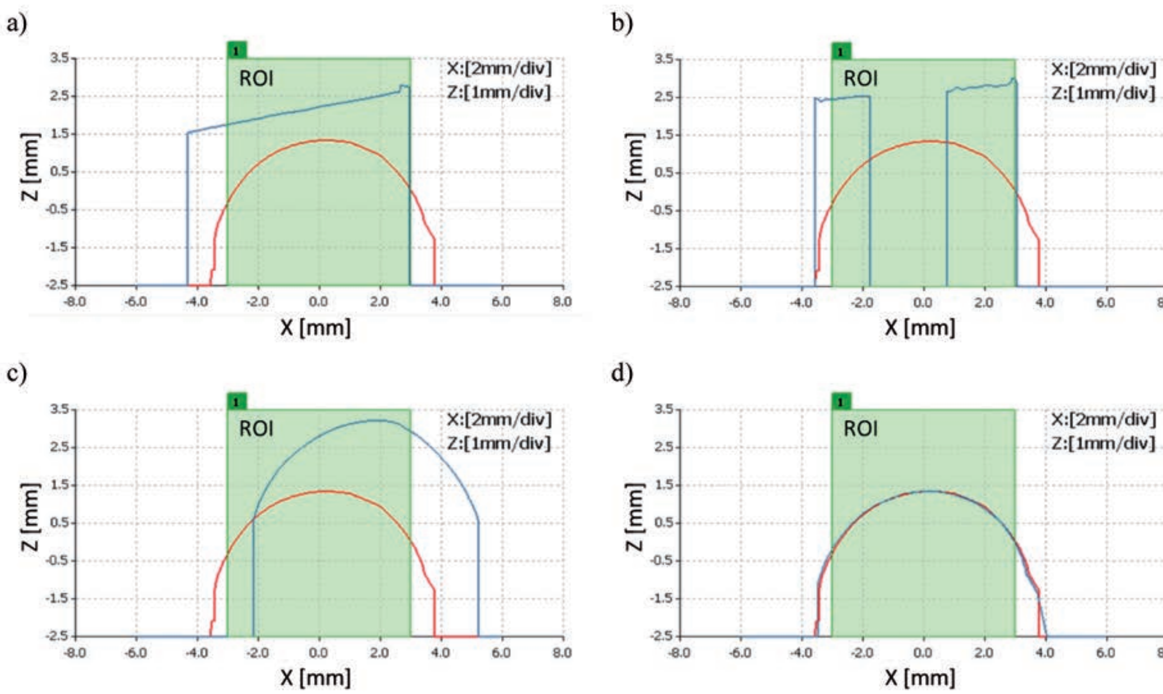

Fig. 4. Sample 2D profiles of scanned filter segments (blue – current profile, red – reference profile, ROI – region of interest in which the analysis is performed)

The first three examples concern the situation of the incorrect positioning of the filter segments, for which there is a large deviation between the scanned current profile (blue) and the registered reference profile (red). The reason for this situation may be the rotation of the segments (Figs. 4a, 4b) or the misalignment of the segment in the vertical Z-axis (Fig. 4c). If the segment is correctly positioned, the registered profile has a shape and position similar to the reference profile (Fig. 4d).

An important issue in the developed system for the inspection of the position of filter segments is the selection and parameterisation of algorithms for processing and analysing the recorded data. The applied measurement system enables the registration of profiles with a greater than required scanning frequency, which may be, for example, 8 kHz or more, with the limitation of the measuring range and the use of binning mode. However, the inclusion of simultaneous analysis of registered profiles limits the achieved maximum scanning frequency significantly. The assumed minimum scanning resolution along filter segments of 2 mm at a speed of 500 m/min determines a minimum scanning frequency of about 4.2 kHz. This means that the total recording time and analysis of a single profile is no more than approx. 0.24 ms. Achieving such high efficiency requires using the simplest yet sufficiently effective algorithms for processing and analysing registered profiles. The parameterisation of the measurement system was made using a hardware controller dedicated to the laser measuring head.

1.2. System for optical inspection of tobacco rods

The tobacco rod is the basic component in the production of cigarettes (Fig. 5). Its shape is similar to a cylinder with diameter D in the range of 4 – 8 mm and length L in the range of 40 – 160 mm. As a semi-finished product in the production process, it is cut into two parts that are part of the final product. Measurements of the length of the tobacco segment are one of the priorities in the process of inspection of the tobacco rod. The need for such measurements has two reasons. The first is to maintain the permissible content of nicotine in the cigarette. The second is to minimise the manufacturer's losses as a result of exceeding the planned amount of tobacco or to minimise customer complaints in a situation where the amount of tobacco is less than the declared one.

In addition to the inspection of the geometric dimensions of the rod, in the course of production, it is also required to inspect the correct order of individual segments in the rod, as well as the protrusion of the tobacco segments and spacing between segments. Considering the efficiency of the machine producing tobacco rods, the inspection speed should not be less than 5,000 pcs/min.

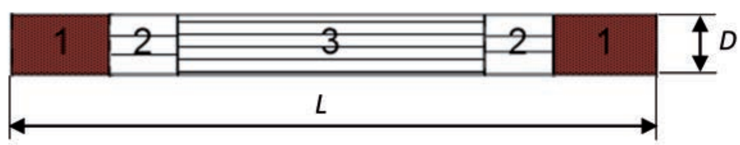

Fig. 5. Double tobacco rod: 1 – tobacco segment, 2 – cellulose acetate pipe, 3 – a roll of polylactate bound foil

The effect of close cooperation between the Institute for Sustainable Technologies – PIB and International Tobacco Machinery, Poland, is a system for optical inspection of the tobacco rods on the transport drum. The process of the development of the solution included a feasibility study, model tests on a laboratory stand, development studies, and the implementation of a verified prototype. The reasons for the high level of difficulty in solving the problem result mainly from the following conditions:

– High process speeds (up to 10,000 pcs/min) required the use of highly efficient methods of obtaining information about the inspected object and algorithms for processing and analysis of measurement data.
– There was no repeatability of the geometric structure of the tobacco rods.
– There was an interaction of light with materials present in the product.

The developed inspection system uses an imaging method that utilises the original back-light LED illuminator (Fig. 6). The vision module includes a 5 MPx camera and telecentric lens. The resolution of the measuring system is approx. 50 µm. The LED illuminator is located inside the drum. The high value of the luminous flux of the illuminator enables imaging in the transmission system.

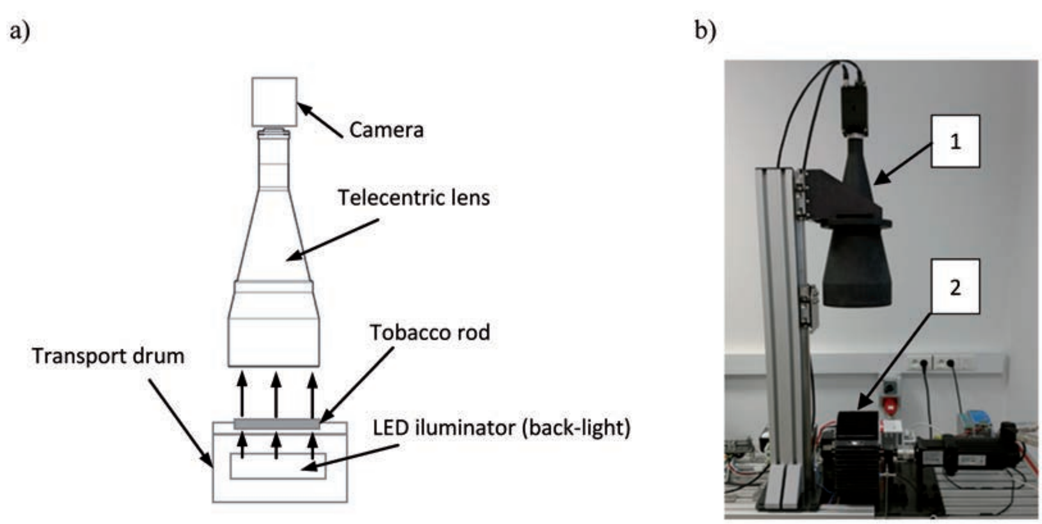

Fig. 6. Inspection method for tobacco rods: a) diagram, b) test stand: 1 – vision module, 2 – transport drum

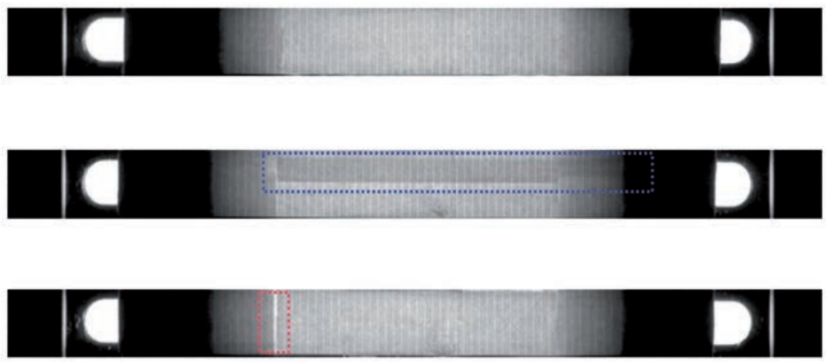

Fig. 7. Examples of registered images of tobacco rods

The effect resulting from the greater absorption of light by the tobacco segment is clearly visible on the images at the border between the rod segments (Fig. 7). One of the factors hindering the measurements is the possible random occurrence of the area of the double wrapper (blue line) of the rod in the ROI in which the position of the edges between the segments is determined. The use of backlighting with the appropriate light intensity allows effective detection of spacing between individual segments (red line).

Due to the high efficiency of the production process and the necessity to ensure the inspection of each product ("zero fault" rule), an important issue is the time stability of the response of the video system to the signal triggering the inspection. In the sequential system, the response of the inspection system must occur before the inspection of the next product. In the developed system, at an inspection rate of 5,000 pcs/min, subsequent camera trigger signals occur with an interval of 12 ms (Fig. 8).

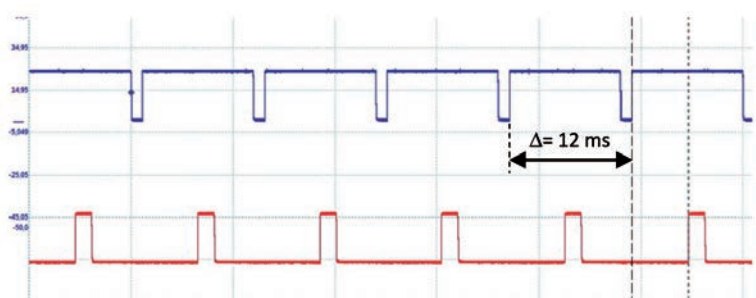

Fig. 8. An example of time sequence of the vision system response (red) to the inspection trigger signal (blue)

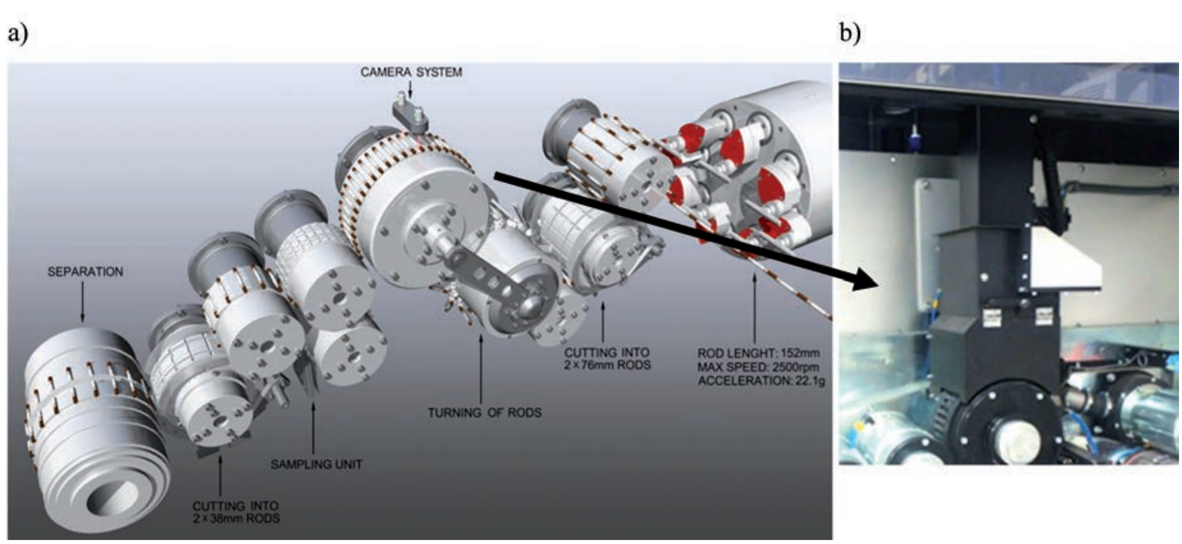

Fig. 9. Implementation of the vision system in the Solaris machine: a) diagram of the kinematic system, b) photo of the vision system mounted in the machine

For measurement of the length of the tobacco segment, the error statistics was analysed. The standard deviation is close to 0.1 mm.

The inspection cycle should also take into account the time of data exchange between the inspection system and the machine control system. Such requirements have made it necessary to use a real-time system (RTOS).

The developed vision system was implemented at ITM Poland in the Solaris machine used for the production of tobacco rods (Fig. 9).

The feasibility study was carried out in subsequent stages. One of the main goals was to experimentally confirm the maximum efficiency of the inspection process in subsequent versions of the system in which advanced hardware and software solutions were used (Fig. 10). During the tests, the phenomenon of image blur was observed for the maximum rod transport speed in the inspection zone. The experimentally determined image acquisition time to avoid image blurring is about 100 μs.

Obtained results of tests in industrial conditions confirmed the achievement of the planned efficiency of the inspection process at the level of required accuracy and repeatability of measurements. Computed standard deviation near 0.1 mm is stable in the full range of the inspection rates.

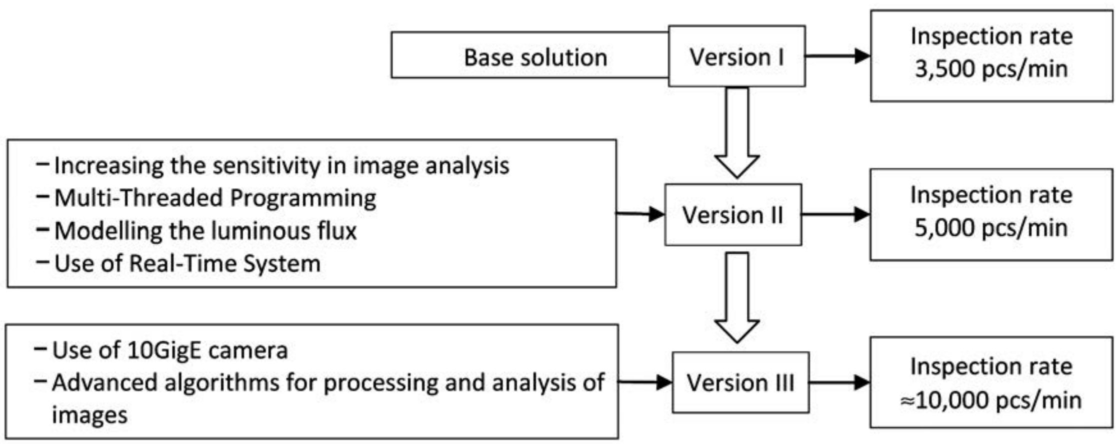

Fig. 10. Diagram of the completed feasibility study of the system of inspection of tobacco rods

Conclusions

Based on the analysis of the results of our own research, development works carried out so far for tobacco industry machines, and the state of the art, the following main trends in the implementation of innovative optomechatronic technologies in this area have been indicated:

– The application of imaging methods in various ranges of electromagnetic spectrum, including hybrid methods enabling image fusion;
– The application of multispectral imaging;
– The development of information technologies enabling very fast data transfer; and,
– The development of real time systems.

The use of optomechatronic technologies enables significant improvement in the quality of tobacco products at various stages of the technological process. The research and development work carried out as well as the practical verification of the obtained results made it possible to achieve the high accuracy and repeatability of on-line measurement results in real time, while ensuring maximum efficiency of the inspection process. Advanced vision systems using imaging in various spectral ranges enable the effective detection of defects of mass-produced goods at speeds up to 10,000 pcs/min.

The developed systems meet the highest requirements in terms of accuracy and speed of measurements. Their qualities were confirmed during tests in industrial conditions. A systemic approach consisting in applying the methodology of research and development works was divided into stages: feasibility study, development research, and the implementation of the developed and verified prototype. This ensures an effective process of knowledge transfer to industrial practice with the minimisation of risk accompanying innovative enterprises. Continued research and development works are targeted, among others, at the application of inspection methods in various ranges of the electromagnetic spectrum, including hyperspectral techniques and information technologies enabling very fast data exchange between the inspection system and process control modules. The achieved cognitive and technical results also allow the application of the developed solutions in many other branches of industry and the economy producing products on a mass scale, aimed at increasing the quality and reducing costs in “zero fault” systems.

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