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OPTOMECHATRONIC TECHNOLOGIES APPLIED IN INNOVATIVE INDUSTRY

Key words: Innovative industry, optomechatronic technologies, knowledge transfer.

Abstract: A priority for enhancing innovation and competitiveness in industry is the implementation of innovative optomechatronic solutions, which, coupled with automation and robotisation of manufacturing processes, ensure increased production efficiency, and increased product quality. The qualities of optomechatronic systems are derived from the principles of photonic sensors and the use of information encoded in the image. Thanks to the rapid progress of research and development in the field of optomechatronics, realized in research and development units, it is possible to implement advanced systems for the multiparametric quality inspection of manufacturing processes in industry. The article presents an overview of achievements in the field of basic research and the research and development of optomechatronic technologies. Some selected examples of automated optical inspection systems and solutions that incorporate innovative optomechatronic technologies are discussed. The summary shows trends in the development of optomechatronic technologies for the needs of innovative industry aimed, among others, at the development of material technologies for the production of high resolution sensor structures, imaging methods in various electromagnetic spectrum ranges, and the development of intelligent image processing and image analysis algorithms.

Technologie optomechatroniczne w innowacyjnym przemyśle

Słowa kluczowe: innowacyjny przemysł, technologie optomechatroniczne, transfer wiedzy.

Streszczenie: Priorytetowe znaczenie dla podwyższania innowacyjności i konkurencyjności w przemyśle ma wdrażanie innowacyjnych rozwiązań z obszaru optomechatroniki, co w połączeniu z automatyzacją i robotyzacją procesów wytwarzania zapewnia zwiększenie efektywności produkcji i podwyższenie jakości wyrobów. Walory systemów optomechatronicznych wynikają z zasad działania sensorów fotonicznych i możliwości wykorzystania informacji zakodowanej w obrazie. Dzięki szybkim postępom prac badawczo-rozwojowych w obszarze optomechatroniki, realizowanych w jednostkach naukowo-badawczych, możliwe są wdrożenia zaawansowanych systemów do wieloparametrycznej kontroli jakości procesów wytwarzania w przemyśle. W artykule przedstawiono przegląd osiągnięć w obszarze badań podstawowych oraz prac badawczo-rozwojowych dotyczących technologii optomechatronicznych. Omówiono wybrane przykłady autorskich rozwiązań systemów automatycznej optycznej inspekcji, w których zastosowano innowacyjne technologie optomechatroniczne. W podsumowaniu przedstawiono trendy rozwoju technologii optomechatronicznych na potrzeby innowacyjnego przemysłu, ukierunkowane m.in. na rozwój technologii materiałowych do wytwarzania struktur sensorów o wysokiej rozdzielczości, metody obrazowania w różnych zakresach widma elektromagnetycznego oraz rozwój inteligentnych algorytmów przetwarzania i analizy obrazów.

Introduction

Optomechatronic systems have their origin in the integration of scientific and practical knowledge areas including photonics, optoelectronics, mechanics, and computer science. Optomechatronics as a term describing a new area of multidisciplinary research and technological innovation was introduced at the beginning of the 21st century. The first comprehensive compilation of issues in the field of optomechatronics was the work of H. Cho [1] in which the author proposed a general classification of optomechatronic systems according to the criterion of their functionality. The optomechatronics area includes various scales of designed systems and devices: nano, micro, and macro. Research achievements and selected examples of practical applications in the field of micro-optomechatronics, as well as trends in the development of nano-optomechatronics, including near-field optical systems, are presented in [2]. Articles presenting research results in the area of optomechatronics are published in recognized journals, mainly related to mechatronics [3]. Since 2007, the *International Journal of Optomechatronics* has been an important place for the publication of works related to optomechatronics, as well as other scientific journals, such as *Advanced Optical Technologies, Sensors, Image, and Vision Computing*.

The complex nature of the design and implementation of optomechatronic systems emerges for many reasons. The first is the multidisciplinary nature of the area of research and application, which places the highest demands on researchers and designers of optomechatronic systems. Another is the high dynamics of technology in photonics technology, which often has short time intervals between the introductions of next-generation solutions. Physical phenomena in photonics are the main factors directly influencing the complexity of research and modelling of optomechatronic structures. Their correct identification and interpretation determines the final success of implementing a functional optomechatronic system in the industry. The issue to be considered in experimental research is the impact of environmental factors. The practical experience of the authors gathered during the implementation of numerous research and industrial projects indicates that the work environment is a critical factor in the effective application of optomechatronic systems. An integrated methodology for the design and implementation of innovative optomechatronic systems, taking into account the important aspects of this process, is presented in [4]. The author of the paper pointed out that the unique, specialized nature of optomechatronic systems requires an individual approach in design and implementation.

The achievements in the field of optomechatronic technologies are closely correlated with the dynamic development of innovative industry. More and more production systems are equipped with optomechatronic systems that perform tasks such as the monitoring of technological processes, quality inspections of manufactured products, the positioning of parts in robotic systems, and the prototyping of material structures. Optomechatronic systems have outstanding features, such as the possibility of non-contact measurement, the use of information encoded in the vision image to assess the condition of the object, high immunity to interference factors, the ability to detect signals in the extended electromagnetic spectrum, and the possibility of integration into automating systems for technological processes. The most common feature of optomechatronic systems is the modularization of the structure, which integrates optoelectronic sensors for specialized tasks, dedicated microcomputers, and mechatronic modules. Optomechatronic systems have become indispensable in many industries, including automotive, aviation, and special production. The increasing role of optomechatronic technology in increasing the level of innovation in the economy is indicated in the priorities of strategies for the development of the research and industry [5].

1. Research area and main directions for the development of optomechatronic technologies for industry

Innovative research in optomechatronics is reflected in the following main areas:

– Cognitive research – covering new knowledge as a result of scientific research in the field of electromagnetic radiation and interaction with matter;
– Technological progress resulting from the use of innovative scientific and practical knowledge in the industry; and,
– Social interaction – creating new interactions between operators and production systems, based on the mapping of natural mechanisms of vision and the recognition of features in the image.

The main areas of multidisciplinary research and development focused on innovative optomechatronic technologies, specifically for process monitoring and quality inspection, are shown in Figure 1. Generating innovative solutions in the field of optomechatronics and the transfer of the gained knowledge to practical applications is a multi-stage process. The initial stage usually consists of fundamental research involving theoretical work or original experimental research conducted to observe and analyse phenomena, mainly in the field of photonics, which may be the conceptual basis of advanced optomechatronic technologies.

The observation of the phenomena of light and matter interaction (Fig. 2) and the identification of radiation properties that can be used in the design of the functionality of the optomechatronic system are particularly important.

The choice of the attributes of the coherent or non-coherent radiation used effects the applied encoding of the object information. The phenomena of radiation interactions with matter are the basis for the functioning of optomechatronic systems that measure various physical quantities, including geometrical dimensions, displacement, force, pressure, and temperature. The methodology for designing and implementing the optomechatronic systems [4] is an indispensable support for the implemented research and implementation projects.

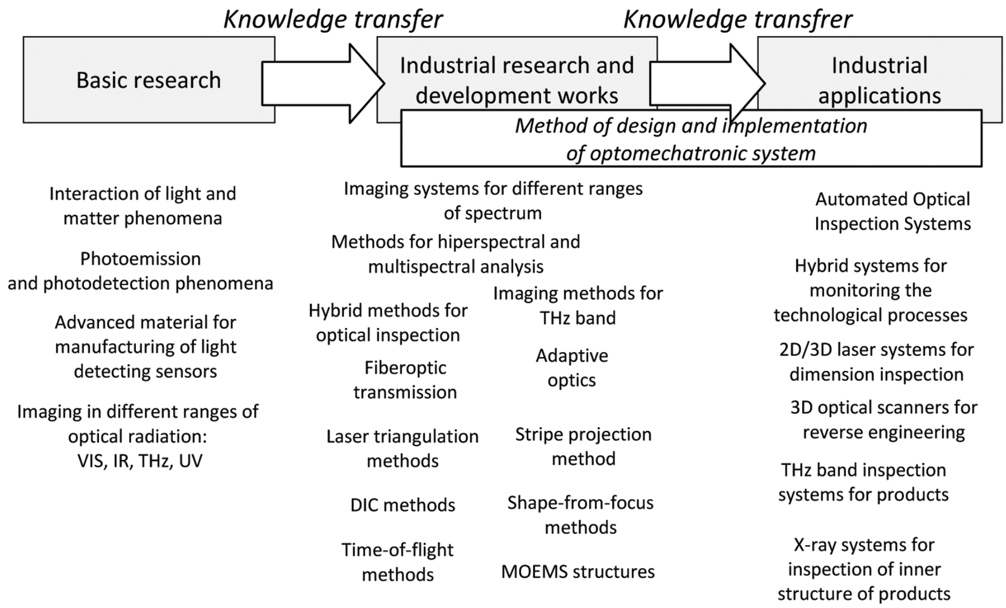

Fig. 1. Knowledge transfer in the area of optomechatronics with a focus on applications in an innovative industry

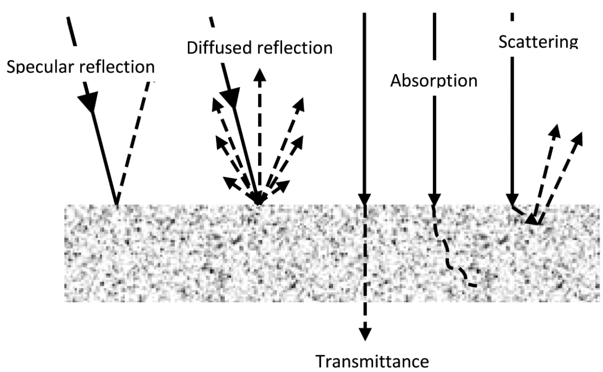

Fig. 2. Interaction of light with matter

Priority areas of research from the point of view of the current needs of innovative industries include the following:

- The development of sensor technology that enables imaging in various electromagnetic spectrum ranges with ever greater resolutions and acquisition velocities;
- Hybrid methods and systems utilizing the fusion of images recorded in different electromagnetic spectrum ranges;
- MOEMS technologies;
- Terahertz imaging technologies;
- 3D imaging methods;
- The development of high performance image processing and analysis algorithms; and
- Increasing the efficiency of data processing and analysis algorithms.

Basic research on the interaction of electromagnetic radiation with materials is crucial in the selection of imaging methods that provide effective acquisition of object information. One of the issues of inspection of materials with high reflectivity in industry is the selection of lighting methods and the design of image processing and analysis algorithms [6, 7]. A broad analysis of the issues of designing the lighting methods for the measurement zone in the inspection of high reflectivity metal surfaces is presented in [8]. The results of the research have been successfully used in developing optical inspection systems in the visible band for product quality inspection in the automotive industry. Due to the difficulty of inspecting highly reflective metal surfaces in the visible band, the alternative is using the method of infrared deflectometry. An example of a model car body inspection system using the deflectometry method is presented in [9]. The micro-milling tool wear inspection method based on the analysis of light scattering on the surface of the cutting edge, was proposed in [10]. In the future, a tool inspection system can be used in automated production systems with autodiagnostics. Inspection of internal surfaces of openings, especially of small diameters, is still a significant problem and a technical challenge in the machine industry. The development of a 3D hole inspection system requires resolution of problems of miniaturization of vision and lighting systems [11]. An inspection system for machine openings using an endoscopic laser scanner is presented in [12]. The phenomenon of the thermal deformation of the material structure as a result of high power laser beam illumination was used in a thermovision system to detect cracks in metal products [13].

The use of infrared radiation sensors makes it possible to obtain information on the thermal state of an object and to analyse the surface and subsurface structure of an inspected product. Recent research results on infrared detector structures and development trends are presented in [14], where needs were indicated to increase sensor resolution, to develop MOEMS structures, and to use hybrid sensors for imaging in two radiation ranges, middle and far infrared (MWIR and LWIR). Infrared imaging methods have made it possible to design advanced inspection systems in the manufacturing processes [15]. By combining visible and infrared imaging, hybrid systems have been developed to detect and identify product defects with greater efficiency in relation to standard solutions. An example of such a solution is the development of a hybrid inspection system for the quality inspection of aluminium profiles in the hot extrusion processes [16]. Hybrid vision methods have also been used for monitoring of the friction stir welding processes [17] as well as glass furnace [18]. Vision inspection and reconstruction of 3D shapes of high temperature steel products in the steel industry and the metal industry is a particularly difficult issue. Most of the present inspection methods are based on the use of projections on the surface of the product and 2D image analysis. Above 1200°C, the energy efficiency of a steel product is comparable to, or even exceeds, the intensity of white light reflected from the surface of an object, which limits or even makes it impossible to use white or red light and CCD cameras. The method of inspecting 3D shapes of products in high temperature conditions using a stereo vision system and the projection of blue stripes was presented in [19].

The current direction of research in the area of inspection methods is imaging in the terahertz range covering radiation range from about 0.1 THz to 10 THz [20, 21]. The property of terahertz radiation, used in the development of inspection methods, is intensive absorption by water and metals. The results of previous research confirm the great potential of using terahertz imaging to inspect the structure of materials in various industrial applications. The main limitation in developing industrial applications is imaging resolution [22].

A unique sensor for angular displacement measurements of rotating machine components based on reflected light modulation is presented in [23]. The sensor uses a system consisting of a light ray tube emitting a laser beam and a receiving optical fibre. The use of coherent laser light attributes was the basis for the functionality of the 6-DOF system for measuring linear displacement errors presented in the paper [24]. The system employs a mirror system and laser light sensors in the X, Y, and Z directions. The combination of optoelectronic technology and MEMS microstructures allows the development of new sensors for measuring different physical quantities. One of the main directions of basic research on photonic structures is sensors for measuring physical quantities. Examples of the results of this work are, among others, semiconductor sensors for simultaneous temperature and displacement measurements presented in [25]. A flexible optical pressure sensor for use as a touch sensor in robotics and electronic appliances is presented in [26]. The sensor uses the phenomenon of changing the intensity of the radiation beam in the fibre during deformation.

Examples of model solutions for measuring systems for determining 3D shapes of objects and geometric measurements using laser scanning and structural light are presented in [27]. The developed measurement methods can be used to inspect the quality of products manufactured in various industries. The issues of designing vision systems using 3D imaging methods for automated measurement and quality inspection in industrial manufacturing are presented in monograph [28]. The author pointed out methods of laser triangulation and stereovision using structural illumination as the basic methods from the point of view of the application possibilities for quality inspection of products in industry.

To a large extent, the photonic properties of the materials determine the areas of possible utilisation of inspection methods. Inspection of products made of transparent materials, where one must deal simultaneously with reflections, dispersion, and light transmission within the structure, is a research area requiring the development of special imaging methods. In optical inspection systems for transparent materials in industry, inter alia, suitable optical radiation ranges, structural illumination, and algorithms for image analysis and fault detection [29] are used.

An important area of optomechatronic technology is the development of adaptive optics, in particular liquid lenses, in order to construct visual inspection systems capable of adapting optical system parameters to different imaging conditions [30]. Examples of practical applications include lenses with variable focal lengths that allow for adjustment of the distance of observation in a few milliseconds [31].

The specific nature of the industry, resulting from the technology used and the quality inspection requirements of the manufacturing process, generates autonomous research areas directed to the needs of these industries. An example is the electronic component industry, where the standard is full quality inspection of all products with maximum efficiency. Review of optical inspection systems used in the electronics industry is presented in [32], where the authors present, among others, the development of hybrid methods combining various optoelectronic techniques and data analysis algorithms.

Apart from research in the field of material technologies and photonic structures, which are the basis of physical models of optomechatronic systems, computer algorithms for image processing and analysis are an important and indispensable element.

Research and development on vision systems utilizing a synergetic combination of artificial intelligence and biological analogy is aimed at qualitative changes in the efficiency of object identification and recognition processes. Recent developments in this area, inspired by the observed processes of sight in biology, are reported in [33]. The use of biological vision mechanisms will be a feature of optomechatronic systems in the future, allowing for increased efficiency and the reliability of inspection systems.

The general overview of vision systems and their applications in a variety of industrial branches during the timespan of previous decade was presented in [34]. As the most significant challenges to the modern vision systems applied in industry, the author points out the flexibility of the vision systems and their ability of adaptation to evolving tasks, and the development of advanced sensors and interfaces for human-vision system cooperation. The prevailing group of solutions used in industry are the systems for automated optical inspection used in production systems. One of the problems and limitations of such systems is the range of the inspected types of products, the number of quality parameters, and the efficiency of the inspection process. It is recognized that the highest saturation in advanced high-performance automated optical inspection systems occurs in the electronics manufacturing industry. Manufacturers of these systems have been specializing in AOI technologies for many years and have their own research and development work. The proposed AOI system is essentially based on the same vision inspection methods, with the aim of increasing the measurement resolution and inspection performance. Metal and machine industries, on the other hand, are struggling with the huge variety of manufactured products and the need for dedicated inspection systems in the face of the lack of flexible multi-tasking systems. Examples of innovative AOI systems have been developed and implemented for multiparametric quality inspection of bearing rollers [35]. The extremely high level of online systems for over 40 types of product defects detected in the production lines does not give full satisfaction to its designers due to the need for very specific adaptations to specific types of products. The anticipated further development of the system will involve the application of breakthrough solutions in terms of the structure of the vision module, including adaptive optics for adjusting the imaging field to different dimensions of inspected rollers, intelligent lighting systems, and multispectral cameras. It should be emphasized that, for economic reasons, a significant number of optomechatronic systems used for various industrial tasks are the result of the modernization of existing machinery. On a machine platform equipped with mechatronic systems, control and power systems are installed that are innovative optomechatronic modules that significantly increase the functionality of the system and adapt the machine to the new higher requirements. The most important cognitive and industrial achievements identified in the review of research in the area of optomechatronics are presented in Table 1.

Table 1. Cognitive and industrial achievements in the area of optomechatronic technologies

No.	Research area	Cognitive achievements	Industrial applications
1	Technologies for manufacturing sensor structures	[14]	[14]
2	Methods for the inspection of surface of highly reflective metal products	[6], [7], [8], [9], [10], [11]	
3	Hybrid imaging methods and systems	[15], [16], [17], [18]	[15], [16], [17], [18]
4	Techniques for terahertz imaging	[20], [21], [22]	
5	AOI methods and systems for multiparametric quality inspection	[32], [35]	[30], [33]
6	Methods for the inspection of transparent materials	[29]	[29]
7	Fibre optic sensors	[23]	
8	MOEMS structures	[25], [26]	
9	3D imaging methods	[27], [28]	[28]
10	2D/3D laser scanning methods	[28]	[28]
11	Adaptive optics	[30]	[30], [31]
12	Algorithms for image processing and analysis based on biological mechanisms	[33]	

A review of research and industry implementation shows that optomechatronic technologies are intensively being developed. The results of the conducted research are advanced inspection methods and numerous experimental and prototype demonstrators. A relatively modest number of the developed innovative solutions achieve the level of implementation maturity. It can be considered that this is an objective occurrence resulting mainly from the high requirements of the manufacturers for the real effectiveness of the proposed new solutions and their reliability in industrial working conditions. That is why industry applications mainly include visual inspection systems for production for which the strong market demand exists and for which the effectiveness of implementation has already been confirmed in economic terms.

2. Examples of authors' applications of innovative optomechatronics solutions in the industry

The authors of the article carried out a number of research and development activities in the area of innovative optomechatronic technologies for industry and research within the Institute for Sustainable Technologies - NRI in Radom. Prioritized research directions, adopted on the basis of foresight methodologies [36] and recent analysis of the needs of innovative industries, as well as many years of experience, include the following:

– Automated optical inspection methods and systems for high performance multiparametric product quality inspection in industry;
– Specialized LED lightings for use with unique vision systems;
– Hybrid methods and systems utilizing the fusion of images recorded in different electromagnetic spectrum ranges;
– The application of 2D/3D laser triangulation methods for the inspection of product geometry;
– The application of terahertz imaging in inspection systems; and
– High-performance image processing and analysis algorithms.

The results of the accomplished works are cognitive achievements in the field of optomechatronic technologies and unique innovative optomechatronic systems, which have been applied in scientific research and industrial practice. The presented optomechatronic systems are selected examples of research and development activities conducted at Institute with the participation of the authors of the article.

2.1. Inspection system using terahertz imaging

A research area with a large future potential for practical applications in industry and other areas of the economy involves terahertz imaging. Current work in research centres is still undergoing basic research and the modelling of imaging systems using the first commercially available terahertz radiation detectors and illuminators or experimental systems constructed in laboratories (Fig. 5). Presented examples of the use of inspection systems using terahertz imaging are model or prototype solutions.

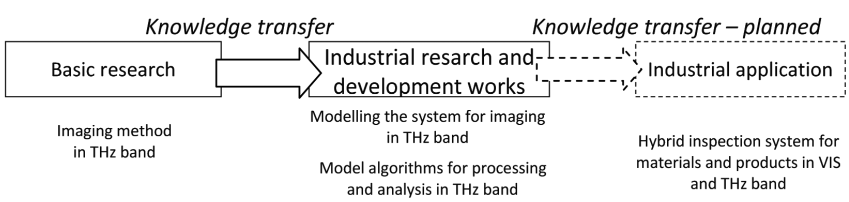

Fig. 5. Process of carrying out research and development in the field of terahertz methods and imaging systems

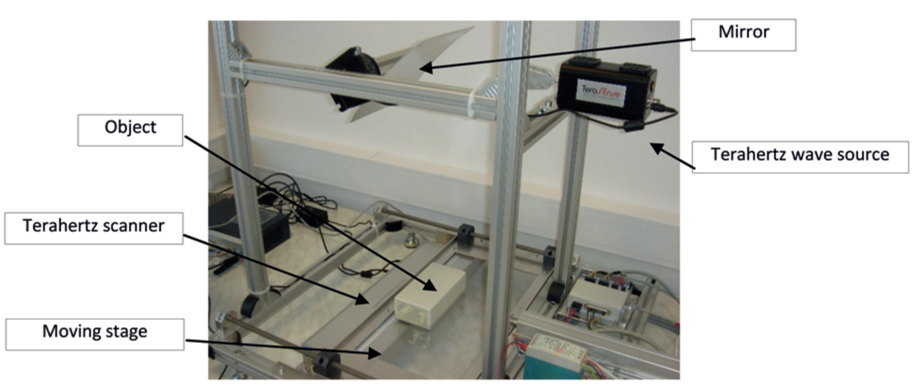

Fig. 6. Image of an experimental stand for terahertz imaging

ITeE – PIB conducts research to identify potential areas of the application of terahertz imaging inspection systems in industry and to develop a hybrid inspection system for manufacturing processes using terahertz and visible light fusion [22]. The developed experimental test system (Figure 6) employs a 0.1 THz radiation source and a 256-pixel scanner, which allows a resolution of approximately 1.5 mm [37]. The principle of operation of the system consists in the acquisition of the radiation penetrating through the test material by a linear detector.

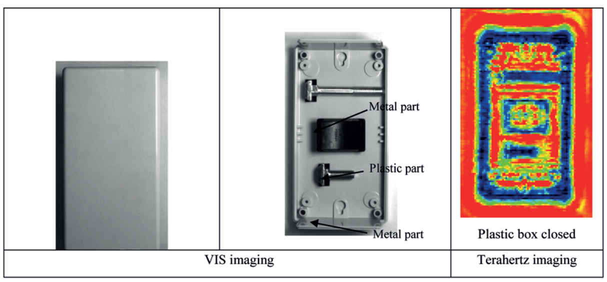

Fig. 7. An example of using terahertz imaging to detect the contents of a plastic package

The example shown in Figure 7 shows the ability to detect items in a plastic container. The terahertz imaging reveals contours of parts inside the container made of different materials. In this case, they are metal and plastic components of a different structure than the material of the container.

Research is focused on the use of higher-resolution imaging systems and the development of algorithms for recognizing features of objects in recorded images. The preliminary results show the following possibilities for the use of hybrid THz-VIS imaging systems in industry:

- The inspection of completeness of assembly in closed enclosures;
- The detection of undesirable metallic elements in loose materials or process fluids, discontinuous material detection; and,
- Ceramics, wood, water content analysis in the materials studied.

2.2. System for inspection of glass products

A very high demand for high-performance optical inspection systems is found in glassworks producing products with a large variety and in large amounts. ITeE-PIB performs advanced research and development works in the field of vision methods and systems for multiparametric on-line quality inspection of glass products in production processes (Fig. 8).

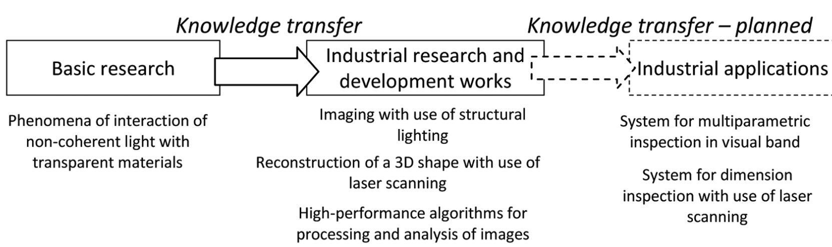

Fig. 8. The process of research and development work on methods and systems of quality inspection of glass products

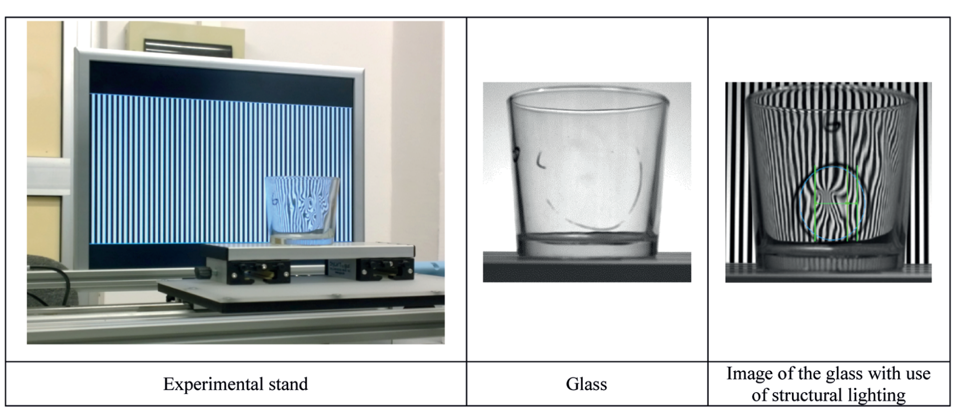

Fig. 9. Imaging tests using structural light

The results of the current experimental research in laboratory conditions are the methods for quality inspection of glass products using VIS cameras and structural lighting [29]. Some defects in the structure of glass products are due to deformation and unevenness of the wall thickness. Detecting defects in a 2D image using standard lighting methods is practically impossible. On the other hand, defects of this kind can be detected indirectly by the use of a distortion of the background image after passing through the deformed glass layer (Fig. 9). In this case, the background is a pattern of contrasting bands.

Work continues on the design of the vision system and image analysis algorithms for high speed inspections at several thousand pieces per minute under the actual glassworks manufacturing conditions. Within the framework of the conducted research, a method of reproducing the 3D shape of a glass product using laser scanning was also developed. When illuminating the walls of a glass product, there are phenomena of light transmission through the glass and internal reflections on the glass-and-environment border that interfere with measurement. The proposed method uses a coating on the surface of the glass product made of a layer of white penetrant with a thickness of several micrometres, which effectively eliminates unwanted phenomena. In the process of scanning the side surface of the product during its rotation, an image of surface development with a visualization of defects is obtained (Fig. 10).

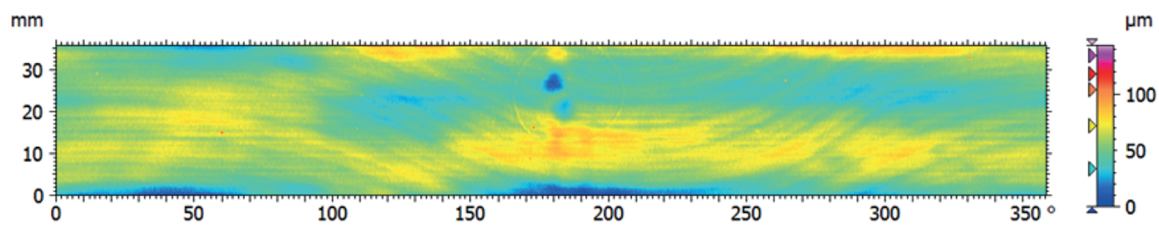

Fig. 10. Sample image of the side surface of the glass in expanded view after laser scanning

The developed method for inspecting the dimensions of glass products is used in off-line quality inspection for selected samples of the production batch.

3. Trends in the development of optomechatronic technologies

Multidisciplinary research and development in the field of optomechatronics is a key feature and a prerequisite for achieving quality progress in this area and developing breakthrough optomechatronics technologies. A generator of new research issues and trends in the development of optomechatronic technologies aimed at industrial applications is an analysis of the needs of entrepreneurs, whose priority is to increase the efficiency of production. It means constant pursuit of the increased productivity of production processes through automation and robotisation and product quality enhancement.

Achieving these goals is possible through R & D works covering the following areas:

– The development of material technologies, including nanotechnologies that enable the generation of sensor structures with a large scale of integration and increasing their measurement resolutions;
– The development of multispectral sensor structures for simultaneous imaging across different electromagnetic spectrum ranges;
– The development of adaptive optics, including the use of liquid lenses;
– The development of MOEMS and NOEMS structures enabling the construction of miniaturized control and measurement devices;
– The development of terahertz band imaging technology to inspect the internal structures of manufactured products;
– The adaptation of mechanisms of biological vision and intelligent recognition of image features in algorithms of optomechatronic systems; and,
– The miniaturization and modularization of control and measurement systems equipped with advanced flexible and multi-tasking programs and remotely accessed databases to quickly adapt the system to current tasks.

The high degree of the integration of basic research, research and development works, and technological and structural solutions in the field of optomechatronics makes it possible to quickly and efficiently transfer the obtained solutions to applications in the innovative industry.

Conclusions

Performance in the field of optomechatronic technology is one of the main determinants of the development of innovative industry. The use of photonic sensors, hybrid systems using a variety of electromagnetic spectrum, the development of algorithms for image processing and analysis, and mechatronic devices, enable the automation of the task of monitoring the technological processes and quality inspection of products at ever higher levels. Optomechatronic systems are now becoming indispensable in many industries, including automotive, aviation, and special production. In the process of the transferring knowledge to industrial practice, the fundamental barrier is the effective transformation of qualitatively new model solutions to the prototype level with the required implementation maturity. Innovative measurement and inspection methods presented in numerous publications are often still experimental.

Among the predicted directions of development of optomechatronic technologies for the needs of innovative industry, multispectral sensors, and hybrid inspection systems that use imaging in different spectrums, including terahertz radiation and 3D imaging methods will play increasing significant roles.

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