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METHODS OF 3D IMAGING USED IN QUALITY INSPECTION SYSTEMS IN MANUFACTURING

Key words: 3D image, 3D imaging method, triangulation, stereovision, SFF, TOF.

Abstract: This paper presents a review of methods used for the acquisition of 3D images. A classification of such methods into contact and contactless and into active and passive methods is given. Special attention is given to show imaging methods that can be used for tasks involving product-manufacturing systems.

Metody budowy obrazu 3D wykorzystywane w systemach kontroli jakości w procesach technologicznych

Słowa kluczowe: obraz 3D, metoda obrazowania 3D, triangulacja, stereowizja, SFF, TOF.

Streszczenie: W artykule zaprezentowano przegląd metod wykorzystywanych w akwizycji obrazów 3D. Przedstawiono klasyfikację tych metod z podziałem na metody kontaktowe i bezkontaktowe, aktywne oraz pasywne. Szczególną uwagę poświęcono metodom obrazowania, które mogą być stosowane w procesach wytwarzania produktów.

Introduction

The role of visual systems operating in production lines is to replace the operator and to perform inspection and measurement operations. This is necessitated by a significant increase in the efficiency of manufacturing lines and a greater range of controlled parameters of products. An increase in requirements that are determined for product quality inspection systems have led to the situation where the operator is no longer capable of performing multiple tasks. In addition, the development of manufacturing technologies in many industries has created the need to observe products using ranges of electromagnetic waves and frequencies that are not visible to the operator.

Vision systems that employ 2D image processing belong to a well-developed field of knowledge, and they are used in industry to perform a wide range of inspection tasks. Topics relating to vision system design and various approaches to defining functions of the studied system and its operating parameters in industrial environment are given in papers [3], [4], [12], and [13]. Analysis of the these publications and experience in the implementation of such systems show that guidelines must be develop for the development of vision systems operating in industrial conditions and detailed parameters should be adopted as early as in the phase of preparing a preliminary design. It should be noted that the design of vision systems intended for operation in production lines requires the designer to know the relevant manufacturing technology and the specifications of the machines used in the process. This involves a detailed analysis of the operating conditions of the visions system and the determination of disturbances that may occur in the production line. Designing a vision system has an interdisciplinary nature that combines theoretical knowledge with engineering experience in the field of machine construction and operation.

In many industrial applications, measurement and inspection tasks require the construction of hybrid systems that involve combining several measurement technologies, such as 2D visual systems that make it possible to analyse the image acquired when assessing the quality of the surface of manufactured products, laser systems that allow the inspection of borehole depth, and systems of sensors that allow checking if the assembly is complete. Equally often, comprehensive solutions are used that comprise several vision systems intended to inspect a set of parameters characterising the same product. Implementing such a comprehensive system in a production line requires a system designer with sufficient experience and must also take into consideration tasks performed by maintenance automation specialists. Installing a vision system in a production line does not usually involve an increase in the number of line maintenance operators. At the same time, operators' responsibilities are increased to include a wide range of tasks associated with the operation of vision systems. These extra tasks are often beyond the experience of automation specialists, electricians, and mechanics employed at production lines. Consequently, highly complex systems that require specialised training on the part of operators are perceived as complicated and operator-unfriendly. This is particularly clear in lines whose set-up is often rearranged when the type of the manufactured product changes.

When 3D images are used in automated measurement systems, the level of interest in this technology increases with the increased automation of the manufacturing process. Several methods for the acquisition of 3D images can be identified, but while taking into account the conditions prevailing in the production line and differences in the quality of 3D images resulting from the acquisition method, it should be noted that only some of these methods can be used in an industrial environment. In selecting an acquisition method of a 3D image for a specific industrial task, criteria for the method's assessment must be identified. In the case of industrial operations, the method should have the resolution of the 3D image acquisition attainable in the presence of disturbances occurring in the production line and simultaneously allow one to perform the measurement. This requires the designer to combine knowledge presented in theoretical papers that is needed to analyse the task from the perspective of the imaging method selection with the verification of the adopted premises, which is done by performing industrial tests.

Contact methods for 3D image acquisition can be classified into destructive and non-destructive ones. Destructive methods of image acquisition require cutting the studied object into layers. This is done by removing successive layers of the material. Next, measurements are made for each cut layer, which are used to create a 3D image. Among contact non-destructive methods, one can distinguish methods based on coordinate measuring machines (CMM) and on arms allowing product description based on surface and edge data. Contactless methods used to build 3D images can be classified into two groups. The first group comprises methods based on recording electromagnetic radiation passing through the studied object. These methods include computer tomography and magnetic resonance. The other group comprises methods based on the registration of electromagnetic radiation reflected by the object. These include non-optical methods, such as radars and sonars, and optical methods used in 3D vision systems that register light reflected from the object's surface onto CMOS or CCD sensor matrices.

Analysis of the usefulness of various methods for 3D image acquisition from the perspective of their application to industrial inspection systems shows that only some of these methods can be applied for these purposes. A large group of methods cannot be effectively applied in industry due to their long image acquisition time, susceptibility to disturbances occurring in production lines, sensitivity to varying illumination conditions, or the impossibility of performing effective calibration. It is important to carry out a classification of imaging methods from the perspective of their application

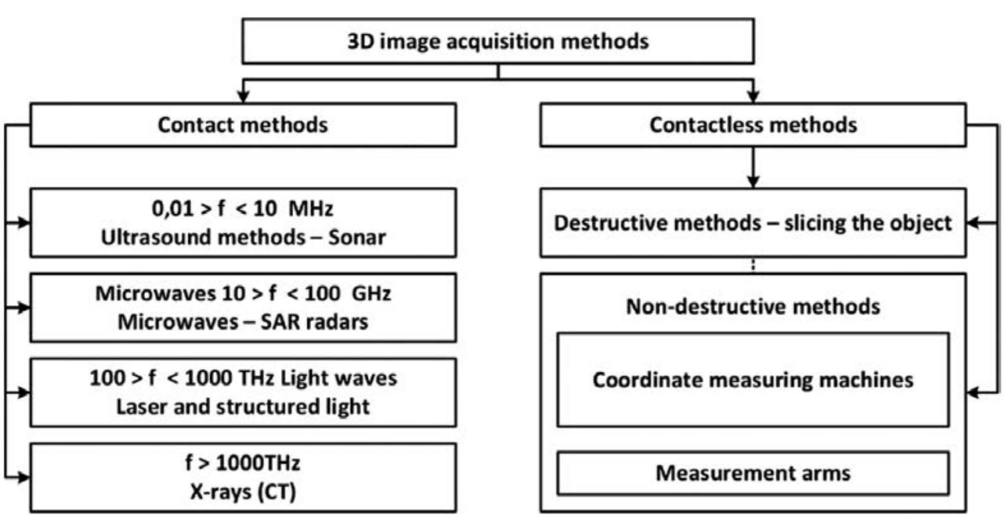

Fig. 1. Contact and contactless methods of 3D image acquisition

in industrial conditions. This would make it possible to identify areas of the application of each analysed method with respect to the product parameter inspection and to the processes occurring in manufacturing systems.

1. Material and methods

Most of the vision systems for 3D image acquisition are based on the solution copied from nature, known as stereovision. Based on two registered images of a scene observed by the left and right eyes, an image is created in the brain that allows the formation of spatial information. There are two trends in the development of methods based on a stereovision system. The first trend involves increasing the number of images recorded with a greater number of cameras observing the scene. The second trend involves the use of one camera and is associated with developing algorithms for obtaining spatial information with the use of additional illumination of the scene, the varying scene geometry, the object's surface properties, or the parameters of the optical system.

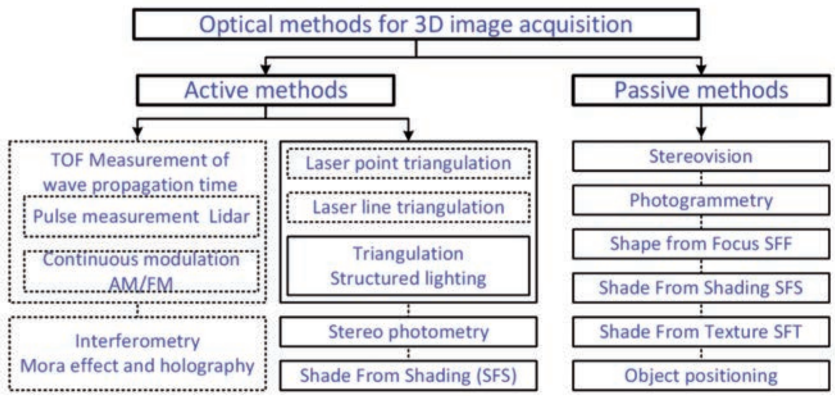

Fig. 2. Active and passive methods used for 3D image acquisition

Optical methods for the construction of 3D images can also be classified from the perspective of the lighting used in the process of image formation. The classification into passive methods, which use the natural lighting of the scene, and active methods, which use artificial lighting, is shown in Fig. 2. Active methods most often employ laser or diode lighting as well as various types of projectors. Methods of image formation not requiring additional lighting are referred to as passive methods. In active methods, additional lighting of the scene is provided by a selected light source, and then one registers the image that is the result of the interaction of the lighting with the surface of the object present in the observed scene. In contrast to active methods, passive methods do not require artificial lighting. In applications used in industrial environment, however, one can observe significant changes in illumination conditions, which affect the quality of a 3D image. In such cases, additional illumination is used, which makes it possible to reduce or altogether eliminate variation in illumination. As a result of the introduction of additional (structured) light, the methods classified as passive become active.

Time of Flight (TOF) methods are based on the measurement of the propagation time of electromagnetic waves emitted by the source towards the scene and registered on the matrix after they have been reflected from the objects constituting the scene. The propagation time is measured directly using pulses released by the source and received by the measurement system. The propagation time can also be measured indirectly on the basis of determining the phase difference between the released and received light at continuous modulation of the emitted light frequency [6], [5], [4]. A 3D image of the observed space acquired using a Laser Measurement Sensor (LMS) allows one to determine points that outline a profile located in the measurement plane. Determining a set of profiles allows one to build a 3D image. The method is used to conduct imaging from long distances up to tens of meters, thus allowing one to build a 3D image of the working space around machines and production lines. With the increase in the distance between the measurement system and the object, the imaging resolution ΔR decreases, and its value depends also on the angular divergence of the radiation beam.

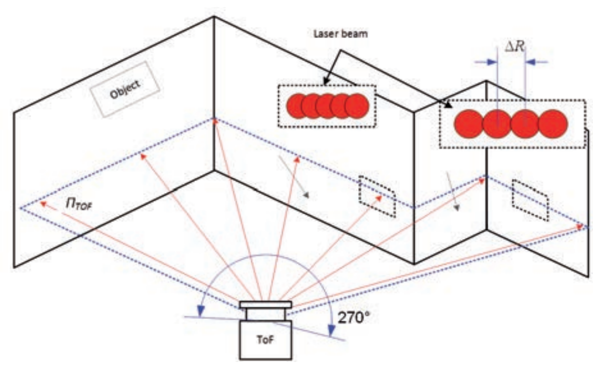

Fig. 3. Acquisition of a distance profile in the measurement plane Π_{TOF} on surfaces positioned at various distances from the measurement system

In Fig. 4 one can see a room with marked positions of operators O1 to O6 and their routes about the room. The shape of the moving objects is blurred because of the time of image acquisition. Fixed elements of the scene are imaged without blur and their resolution depends on the distance from the TOF system. In Fig. 4b, one can see an operator working at his workstation, and the shape of his silhouette is distorted.

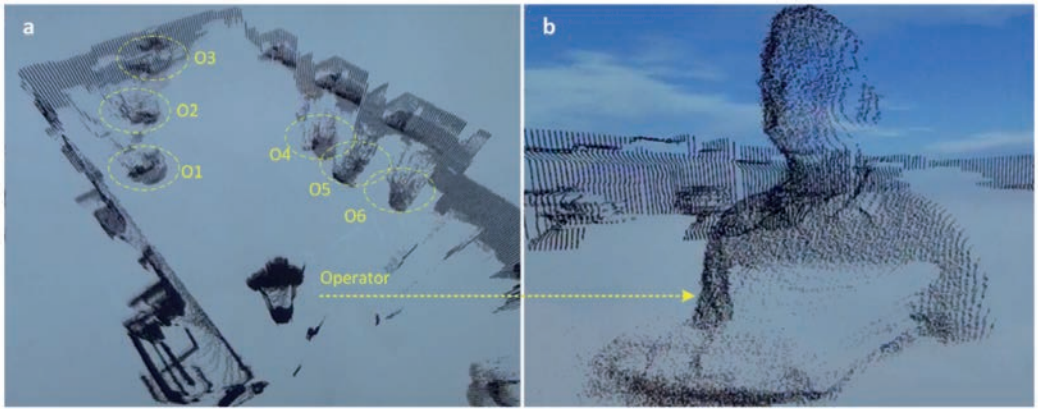

Fig. 4. A 3D image obtained using the TOF method (a) the entire room's image, (b) the operator's image

These distortions result from the variety of materials and geometric structures of the imaged objects present in the system's working space. The surfaces disperse or absorb the measurement beam to various degrees that prevents the measurement of the distance from the object for all points constituting the distance profile. For such materials, measurements can be made, but from much closer distances.

The SFF method (Shape from Focus) makes possible the acquisition of 3D images with the use of information about the sharpness in selected areas of a 2D image. A series of 2D images is prepared with a camera in such a way that the focal plane of each image is at a different height relative to the measurement basis (Fig. 5). The position of the object plane depends on the DOF (*Depth of Field)* parameter, which describes the range of changes in the distance from the objective in which a sharp image is recorded. The DOF value is related to the distance from the object and to the value of the focal distance as well as the aperture size. This is a very significant parameter for building 3D images of an object with several surfaces located at different heights. Parameters of the objective should be selected so as to reduce to a minimum the DOF and thus make it possible to record a series of images – each with a very small distance range [10, 11]. In Fig. 4, one can see the acquisition of a 3D image with the use of a calibration standard. The series of three 2D images is registered in such a way that the image plane is located at three heights, denoted as DOF1-3.

Images are analysed to determine areas of good sharpness and are scaled with the use of information on parameters of the optical system and the positioning of the camera for each 2D image separately. The last stage of building a 3D image involves filtering the image to remove distortions that occurred as a result of connecting sharp images originating from successive 2D images. In Fig. 6, one can see the height standard used to register a series of images and a set of pixels that constitute an area of good sharpness determined in one of the 2D images.

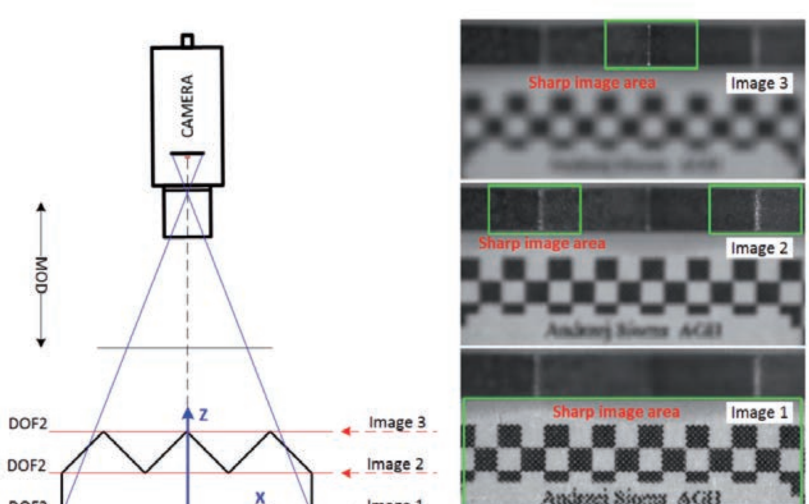

Fig. 5. A method for a 3D image acquisition based on DOF information

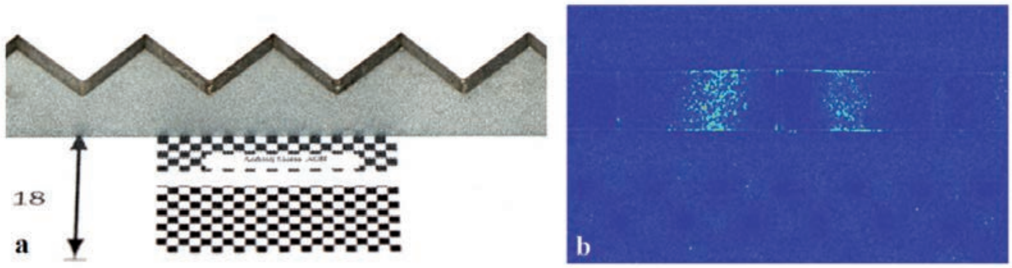

Fig. 6. The height standard used to construct a 3D image and an example of an image after segmentation that shows an area with good sharpness

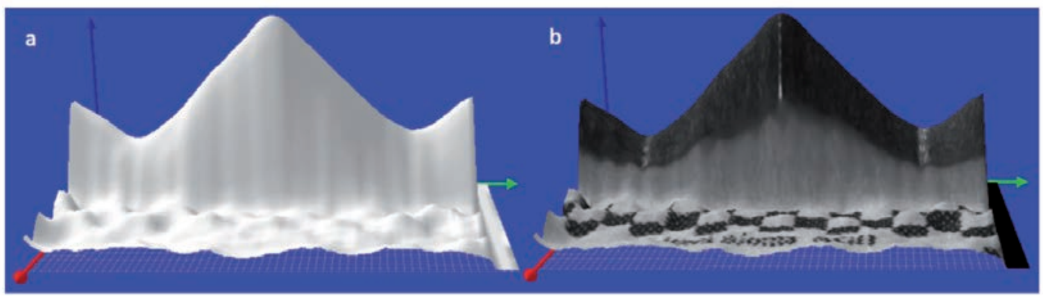

Fig. 7. A 3D image of the height standard determined based on a series of 25 2D images

The resolution of a 3D image is defined for each axis of the coordinate system. Along the X- and Y-axes, the resolution is determined based on the field of vision and the resolution of the matrix used in the camera. The resolution along the X-axis depends on the number of 2D images made in the whole series, on the algorithm used for segmentation of sharp areas, and on the type of filtration of the 3D image. For instance, for the pattern shown in Fig. 4 and a series consisting of 25 2D images, a 3D image of the height standard is shown in Fig. 6.

Throughout the acquisition of a series of images, the same illumination conditions should be ensured, because a change in the illumination prevents the reproduction of the real shape of the object. This method fails when a 3D image of smooth and highly reflective surface is built. In addition, during the acquisition of a series of images, the object should have a fixed position relative to the vision system. Recording a greater number of 2D images with a telephoto lens with a small DOF allows one to achieve greater resolution of imaging along the Z-axis of the coordinate system. However, this extends the time of the acquisition of the target 3D image.

The stereovision method for 3D image acquisition involves the use of images registered by two cameras capturing the image of the same scene. It is also possible to use a single camera with a positioning system that makes it possible to change the camera's position relative to the observed scene. The configuration of a 3D vision system employing a single positionable camera is known as motion stereo (MS) and is used in industry in robotizing and inspecting workspaces at the production line [1], [2], [9]. Pairs of images in a stereovision system should be registered in a synchronous manner at the same moment to eliminate possible changes in the object's position and changes in the scene illumination. This is of great importance in the case of artificial illumination used in industrial production lines. Images were pre-analysed and then a disparity image was determined, i.e. an image describing differences in the position of the corresponding points in 2D images registered by two cameras. Figure 8 shows a target disparity image prepared for a pair of images presenting an engraved surface without structured lighting.

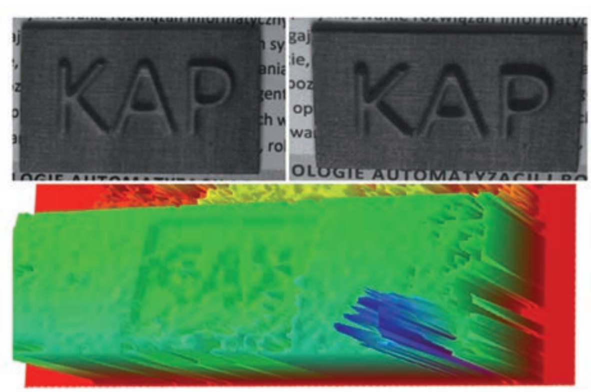

Fig. 8. A 3D image of the height standard built from a series of 25 2D images

Based on the disparity image and using algorithms that make it possible to transform an intermediate disparity image, a 3D image is built. It is a raw image, in which distortions can be seen mainly at the object's edges.

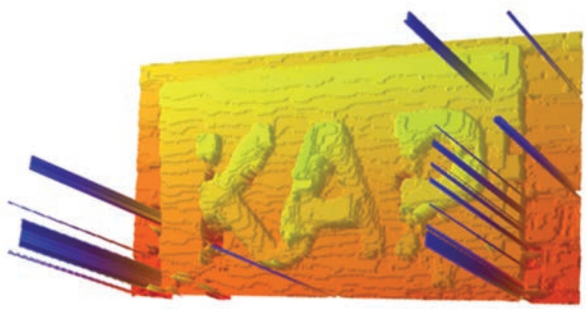

Fig. 9. A 3D image of the studied object acquired by a stereovision system

Among the method's limitations is the lack of the possibility to build spatial images of elements with surfaces without visible surface texture. It is then difficult to determine a disparity image and to properly image the object's shape. To such objects belong elements subjected to finishing operations, e.g., surface polishing. A disadvantage of this method is its high sensitivity to changes in the object's illumination and changes in how light is reflected from the surface, which are seen as changes in the object's shape.

Due to its limitations, the stereovision method requires the use of additional illumination in the form of structured light – thus improving 3D imaging. Structured light is used to illuminate the object and is generated in the form of monochromatic bar codes of various frequencies or in the form of coloured linear codes. The choice of the illumination method determines the algorithm for image processing and isolating the spatial information in the form of a 3D image.

Laser triangulation is an active method that requires the imaged object to be illuminated with an additional source of light, which is most often a linear laser beam [7], [8]. A laser beam forms on the surface of the object a profile, which maps the object's shape and position. An example of the geometry of the vision system in operation and the image of the laser beam registered in the camera are shown in Fig. 10. Analysis of the position and shape of the laser beam in the image makes it possible to determine the height profile of the object. In order to register a complete 3D image, the object must be moved relative to the immobile laser-camera system in the direction perpendicular to the plane defined by the laser beam, so that successive parts of the object are illuminated. For each position of the object, images of the laser beam illuminating successive surfaces of the object are recorded. The object's 3D image is obtained by calculating all registered images of the laser beam into height profiles, followed by combining them into a 3D image. Height profiles are placed in the image with a resolution resulting from algorithms for determining profiles in a 2D image, and with a resolution resulting from the object's shift in the measurement stand.

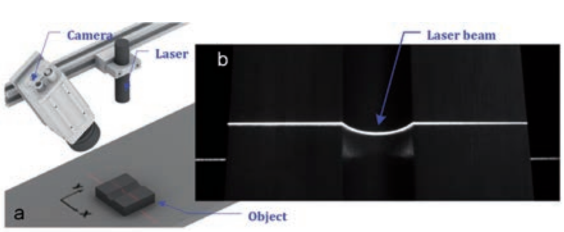

Fig. 10. Triangulation: a – Vision system configuration, b – Laser beam image registered by the camera

The method of registering each height profile of the object is shown in Fig. 11. The matrix built into the vision system registers the image of the laser beam projected onto the object. Based on the known vision system parameters describing the geometry of the mutual laser-matrix position, coordinates of all points of the height profile are determined. The triangulation system is designed to comply with the required imaging parameters, i.e. the field of vision, the expected resolution of imaging, and parameters determining the conditions for installing the system in the production line.

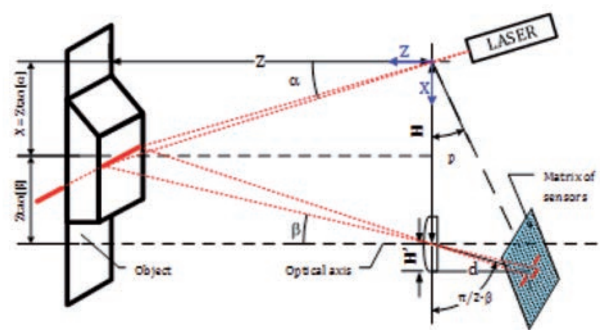

Fig. 11. Diagram of measurements taken with a laser beam and a 2D sensor matrix

Combining a selected number of profiles as subsequent rows of the matrix representing a 3D image makes it possible to reconstruct the shape of the studied object. The triangulation image also contains distortions resulting from the reflection of the beam from the object's edges. Also observed are disturbances from highly reflective surfaces and from surfaces strongly dispersing the laser beam. Reconstruction of real surfaces of an object requires doing a series of transformation and filtering operations in the image before the measurements of the image are taken. An example of the triangulation image is shown in Fig. 12.

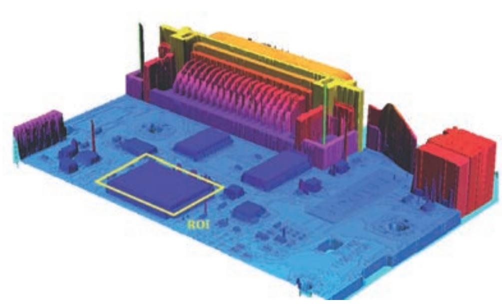

Fig. 12. An example of an electronic board's 3D image obtained by laser triangulation

2. Results and discussion

Analysis of 3D image acquisition methods from the perspective of the possibility to apply them in industrial environment shows that, when selecting the method, one should assess parameters describing the work environment of the system and the resistance of each method to varying conditions of illumination and to changes in the geometric structure of the surface. The use of extra illumination in active methods makes it possible to acquire a range of images with a resolution difficult or even impossible to obtain by using passive systems. This is of great significance, particularly when building vision-based measurement systems to be installed in production lines.

3D imaging systems can be successfully used for both product quality inspection and for imaging of workspaces of production lines and sites. Based on the analysis of available solutions, it can be stated that four methods of imaging currently have the greatest potential for industrial implementation. These methods are presented in Fig. 13.

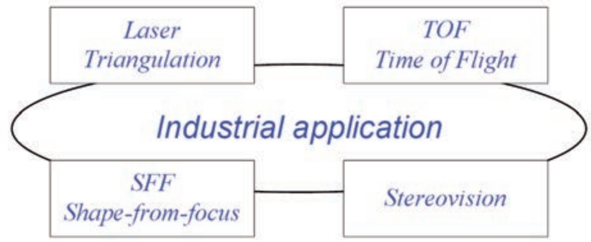

Fig. 13. Methods for acquisition of 3D images as part of industrial operations

Analysis of the methods for the acquisition of 3D images shows that there is a possibility of using 3D vision systems for a wide range of industrial measurement and inspection tasks. It should be noted, however, that images recorded with the presented methods differ in many ways, e.g., they can attain various resolutions, they can offer the possibility of calibrating the image and the imaging range, and they can differ in how disturbances affect the extent to which they reproduce the object's shape and space. When comparing the group of active and passive methods, one's attention should be drawn to the way the studied objects are illuminated. Therefore, it can be clearly stated that, in industrial tasks, methods of active imaging should be used, which is dictated by the need to become independent from changes in the illumination conditions. Active methods are based on using various principles of measurement of spatial information. In ToF methods, the quantity measured is the propagation time. In the MTL method, laser illumination is used, whereas structural illumination is used in stereovision. The SFF method is based on the use of a light source that evenly illuminates the product in the process of spatial information acquisition. In the figure below, methods used for building 3D images are presented. The diagram shows the attainable resolutions of the measurement of spatial information as a function of distance at which imaging using each of the methods is possible. The diagram also shows the areas describing industrial applications involving tasks associated with inspection of the product's quality parameters and the inspection of working space of machines and robots installed in production lines.

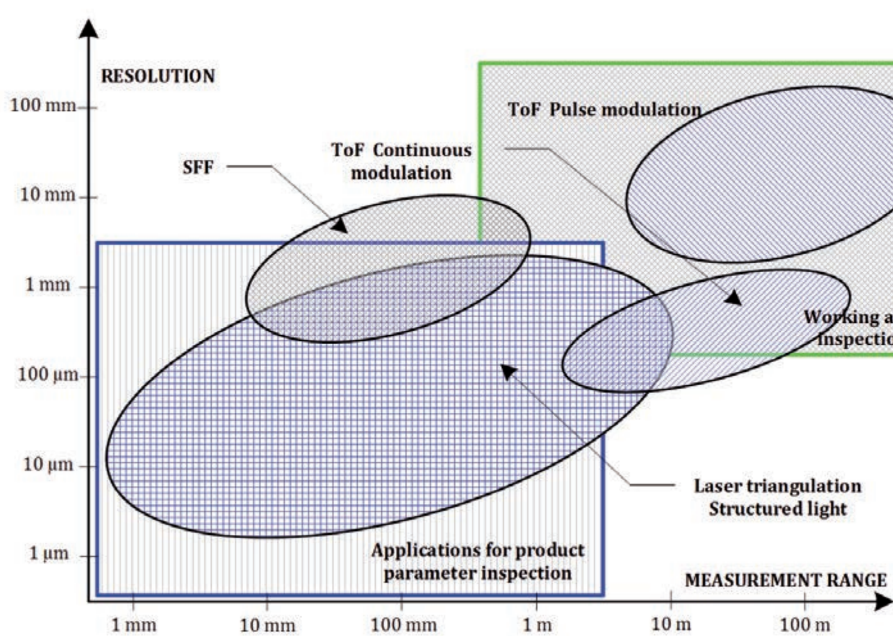

Fig. 14. The range of implementation of 3D systems to industry taking into consideration the measurement range and resolution of methods for construction of 3D images

The widest range of application for the task of inspection of product's parameters is offered by methods based on laser triangulation and stereovision using structured illumination. These methods can be used for tasks involving the construction of a 3D image and for the measurement and inspection of the product's shape parameters.

The resolution of imaging depends on the adopted system's configuration and the components used, such as sensor matrices, optical systems, and laser illuminators, as well as on the geometric structure of the imaged object's surface.

The working space is mostly inspected using methods based on the measurement of the propagation time. The resolution attainable in constructing a 3D image of the space depends on the modulation method adopted, the distance from objects constituting the scene, the technique is used to measure the propagation time, and the phase shift and the positioning method used by the measurement system. However, this method makes it possible to build an image of very distant objects, which allows one to build 3D images of, e.g., transport routes in industrial plants and inspect these routes for the presence of obstacles and the possibility of collisions. Inspection of the space up to distances of several meters can also be successfully performed using the laser triangulation method and SFF methods based on using the information on the sharpness of areas that constitute the inspected space's image.

When taking measurements that make possible the description of parameters determining the product's workmanship quality using a 3D image, one should chose the laser triangulation method, stereovision, or the SFF method. However, this requires performing preliminary studies in order to make possible the preparation of the feasibility study, as well as choosing a method of building a 3D image. In industrial applications, it is of primary importance to check the adopted concept of building a 3D vision system in industrial conditions. This verification allows one to identify disturbances present in the production line and to up-date the premises adopted when designing the system.

Conclusions

When analysing the structure of automated manufacturing systems, it should be noted that vision systems performing the tasks of quality inspection are the source of data for numerous information systems operating in industrial plants. These data are used by TQM systems, machinery management systems, and manufacturing execution systems (MES). When performing measurement and inspection tasks, vision systems are installed in manufacturing systems, in systems ensuring safety of machines and operators, and in logistic systems. In recent years, a rapid development of vision systems has been noted regarding both their inspection functions and the efficiency of image analysis. This is also seen as the introduction of 3D vision systems that have greater calculating power requirements. Each of the 3D imaging methods requires a much greater number of 2D images and then the creation of 3D images on the basis of these 2D images. Some imaging methods are not yet ready for implementation in industry. This paper presents a description of imaging methods and results that allow one to perform industrial tasks. It should be emphasised that each of these systems must be specifically designed for a given industrial application while taking into consideration the required operating parameters of the system.

However, it should also be noted that the development of methods for the acquisition and analysis of 3D images enables one to considerably extend the range of measurement and inspection tasks that can be performed in industrial conditions with a simultaneous increase in the number of controlled parameters and a shortening of the inspection time. It allows one to increase the number of inspection operations performed in the product's single image. The development of the 3D image analysis methods is one of the fastest developing fields of image analysis. In addition, the selection of the appropriate method allows one to perform imaging in a wide range of dimensions concerning both the product and the working space at a production line. The development of 3D vision systems will focus on equipping them with I/O protocols for communication with HMI interfaces and databases that would make it possible to incorporate them directly into industrial automation systems as well as systems for production tracing and management.

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