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THE TEST SYSTEM FOR MODELLING IMAGING METHODS USING X-Ray TECHNOLOGIES

Key words: X-Ray imaging, non-destructive testing, quality inspection, electromagnetic radiation.

Abstract: X-Ray imaging is a tool used for non-destructive inspection of the internal structure of products and measurements of geometric dimensions of products of any shape. The non-destructive nature of measurement techniques using X-Rays has enormous potential for wide application in many industries. At the Institute for Sustainable Technologies – National Research Institute in Radom, a universal research system for modelling X-Ray imaging methods was designed and manufactured, which was intended for performing automatic inspection of products using X-Rays. The developed system will be used in research and development works carried out jointly with industrial partners to develop innovative product inspection systems. The article describes the mechanical structure of the device, the control system, the ranges of parameters at which it is possible to carry out inspections of products using X-Rays, as well as exemplary test results.

System badawczy metod obrazowania X-Ray

Słowa kluczowe: Obrazowanie rentgenowskie, nieniszczące metody pomiarowe NDT, kontrola jakości, promieniowanie elektromagnetyczne.

Streszczenie: Obrazowanie rentgenowskie jest narzędziem wykorzystywanym do nieniszczącej kontroli wewnętrznej struktury wyrobów oraz pomiarów wymiarów geometrycznych produktów o dowolnych kształtach. Nieniszczący charakter technik pomiarowych wykorzystujących promieniowanie rentgenowskie ma ogromny potencjał do szerokiego zastosowania w wielu gałęziach przemysłu. W Instytucie Technologii Eksploatacji – Państwowym Instytucie Badawczym w Radomiu zaprojektowano i wytworzono uniwersalny system badawczy modelowania metod obrazowania X-Ray, przeznaczony do wykonywania automatycznej inspekcji wyrobów z wykorzystaniem promieniowania rentgenowskiego. Opracowany system zostanie wykorzystany w pracach badawczo-rozwojowych realizowanych wspólnie z zakładami przemysłowymi w celu opracowania innowacyjnych systemów inspekcji wyrobów. W artykule opisano konstrukcję mechaniczną urządzenia, system sterowania, podano zakresy parametrów, przy których możliwe jest prowadzenie inspekcji wyrobów z wykorzystaniem promieniowania rentgenowskiego, a także przedstawiono przykładowe wyniki badań.

Introduction

X-Ray imaging is a tool used for non-destructive inspection of the internal structure of products and measurements of geometric dimensions of products of any shape. X-Ray technologies are used in many fields such as medicine, biology, material science, and in many industries, including in the engineering, aerospace, oil, gas, and food industries. Measurement systems using X-Rays compared to conventional measuring, e.g., tactile and optical methods, enable the non-destructive measurement of the product, which is often not possible with any other measuring technique. The non-destructive nature of measurement techniques using X-Rays has enormous potential for wide application in many industries.

The use of X-Ray imaging methods in industrial applications for product inspection is a constantly evolving market [1, 2]. It is important to develop apparatus that allows shortening the time of inspection of products in mass production [3] and obtaining better resolution and accuracy of measurements [4].

Assuming that the test object consists of N elements, the principle of X-Ray inspection is described by the following equation:

$$I = I_0 \sum_{i=1}^{N} exp\left[-\alpha_i\left(Z_i, E\right)\rho_i z_i\right] \quad (1)$$

where I_0 is the intensity of the beam of the radiation source, I is the intensity recorded on the detector, α_i is the mass absorption coefficient of i-th element $i = 1..N$ with the atomic number Z_i, density ρ_i and layer thickness z_i. E is the energy of the radiation photon [5].

Using Equation (1) and mass tables absorption coefficients available, e.g., on the NIST website (N*ational Institute of Standards and Technology*) [6], it is possible to anticipate inspection results and design devices for detecting product defects. This approach is only possible for objects with a simple structure and full material specification. Even then, it is extremely complicated and requires the use of special simulation software. The full specification of the objects studied in industry is rare. Manufacturers often use semi-finished products and raw materials of unknown composition, properties, or internal structure. For this reason, the development of an X-Ray inspection system is associated with high expenditure on the construction of the device and the lack of certainty that it will fulfil its function.

Therefore, at the Institute for Sustainable Technologies – National Research Institute in Radom, a research system for modelling X-Ray imaging methods (ITeE_XR_1) was developed and manufactured, and it is used to carry out automatic product inspection using X-Rays. The system allows performing experiments in a wide range of parameters, including changing the distance of the X-Ray generator from the tested object (50–700 mm), changing the distance of the X-Ray detector from the tested object (10–150 mm), the transport speed of the tested products (0–4m / s), the voltage and current of the generator (40–60 kV; 13.3 mA, max. 800W), and the detector resolution (29–48 µm). The developed solution allows performing feasibility studies for X-Ray inspection equipment in the fields of the selection of radiation beam properties, the inspection area geometry, the materials and geometry of transport systems, as well as image processing and analysis algorithms.

1. Mechanical design of the X-Ray imaging system

In the ITeE_XR_1 system, the inspected product is moved between the generator and the X-Ray detector, and images are recorded, which are then analysed by a computer program. The products inspected are moved on conveyors simulating the dynamics of product movement on a production line. The analysis of registered data is carried out by a computer program prepared individually for each type of product.

In order to reduce the weight of the device, because a larger part of it is made up of lead protective shields, the skeleton of the frame is made of aluminium profiles. The structure of the device consists of three main modules: (1) an external chamber in which (2) the inner chamber and (3) a cabinet with elements of the control system are placed (Figure 1). From the front side there is an operator panel, a sliding door of the measuring chamber, and a signal lamp that informs the user of the activation of the radiation generator and the measurement.

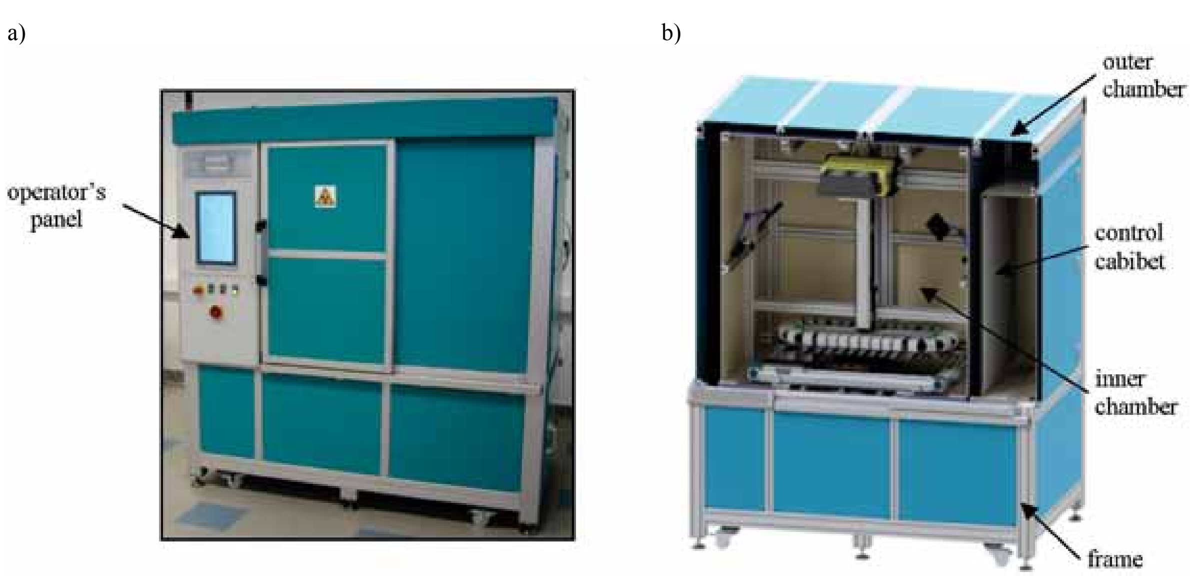

Fig. 1. The research system for X-Ray imaging methods: a) general view of the system, b) cross-section of the 3D model showing the internal measurement chamber

All actuator elements of the test system were placed inside the measuring chamber that provides protection for the user and the environment against radiated X-Rays (Figure 2). The outer chamber is covered with steel shields, while the measuring chamber is covered with steel support shells that are tightly covered with lead shields. Moreover, all gaps and joints are filled with lead. The project of guards made of lead was developed by an authorized Radiological Protection Inspector, and the permission of the National Atomic Energy Agency was obtained to launch devices using X-Ray sources. In order to replace and reduce the air temperature inside the measuring chamber and to effectively cool the generator, the device is equipped with two fan modules.

In the measuring chamber, there is a generator and an X-Ray detector attached to two independent positioners. The generator has the ability to move vertically in the range of 0–700 mm, and the detector can move in the range of 0–150 mm. The generator positioner is used to change the position of the source in order to determine the beam width, and the detector positioner allows one to adjust the position of the detector and thus change the magnification of the recorded X-Ray images. Thanks to the possibility of changing the distance of the generator and detector from the tested product, the measurement resolution can be adjusted. The internal chamber is equipped with two vision modules consisting of a panel illuminator and a camera with a lens. The modules are used to observe the chamber during the tests. It is also possible to carry out measurements using the hybrid method by using one vision module to measure the geometrical dimensions of the tested products.

The device is equipped with two modules for transporting the tested objects to the inspection zone: linear drive and an XTS linear servomotor enabling movement of the tested objects with a maximum speed

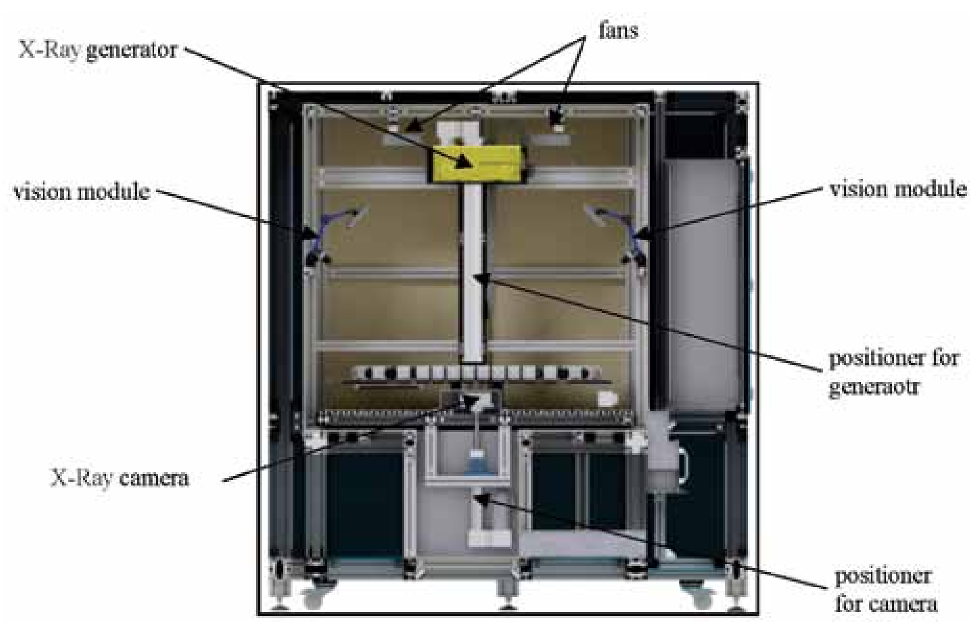

Fig. 2. General view of the inner chamber

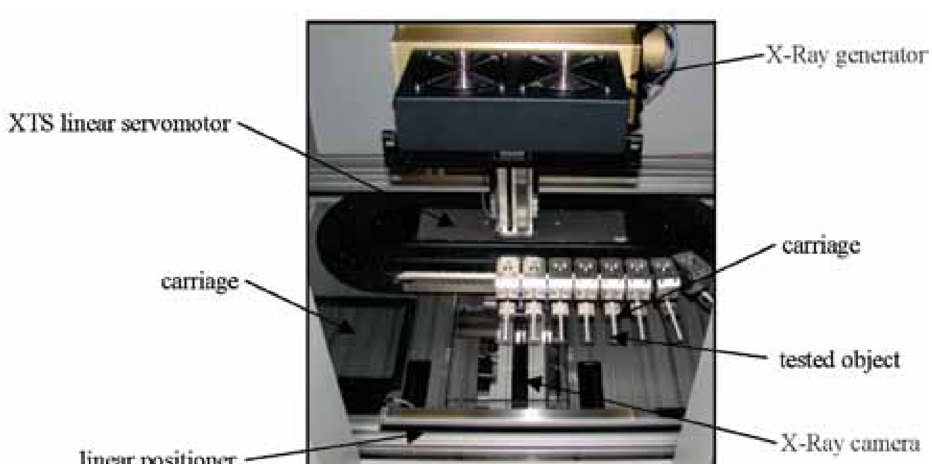

Fig. 3. The view of the filter segment inspection system

of 4 m/s. The XTS linear transporter is used to simulate a fast production process by positioning products placed on eight trays that are attached to independent carriages moving on a closed loop track. The linear drive enables the transport of products in the inspection zone by reciprocating movement. The module is equipped with a tray on which one can place bulk materials, e.g., sugar, tobacco or products of larger dimensions and weight, maximum 5 kg.

The system is equipped with several security modules. The door of the measuring chamber was secured with a double safety sensor and lock. If the door is not fully closed, it is not possible to start the X-Ray generator. The covers of the detector module and the cable tract have been secured with safety sensors. If there is attempt to remove the cover, the radiation generator will be automatically turned off. Cable glands are located in the chamber in places where the radiation effect is limited. In order to prevent the X-Rays from escaping from the measuring chamber, the cable tracts are designed in the shape of a labyrinth.

The required documentation has been collected, including the necessary permits to launch the developed device that meets the requirements defined in the safety standards, and it has been positively verified by the Radiological Protection Inspector.

2. Control system

The control system (Figure 5) is functionally divided into two modules – one responsible for controlling mechatronic elements, i.e positioning systems and protective circuits, and the second one responsible for cooperation with measuring systems. In the mechatronic positioning systems, a modern XTS linear servo motor was used [6] with eight carriages traveling on a shared closed track as well as three classic linear positioners with one axis modules and servo motors. From the point of view of motion control, the XTS drive works as eight interdependent servo axes. For this reason, in the role of the main controller, the system uses an IPC industrial computer with adequate computing power that controls all drive systems via the industrial EtherCAT network [7]. The control computer is connected to a graphic panel with a touch screen located in the front of the device. For measuring systems, i.e. for controlling a radiation generator, for recording radiation using a "frame grabber" and for monitoring the workspace, a separate industrial computer was assigned, whose task, apart from image recording, is real-time analysis of the collected images. The measuring computer was placed in the control cabinet of the device. For the operator's convenience, peripheral devices such as a monitor, a keyboard, and a computer mouse were set up on a separate work stand near the device. Both computers communicate over Ethernet using a protocol specifically developed for this purpose. The control system has been designed with a safety system based on Safety-over-Ethercat (SoE) [8].

The device is equipped with an electronic security system built into the control system of the system. On the operator's panel (Fig. 6), there is a main power switch with a safety switch function, a safety switch, a lamp to indicate the activity of the radiation source, and an additional safety switch on the cable that allows placing it in a convenient place near the operator's stand. The main switch for an emergency stop of the device can only be used as a last resort, and it is recommended to use safety switches.

The logical structure of safety systems (Figure 7) has been divided into two levels of operation. The emergency shutdown and the total stoppage of the device's operation takes place after the activation of one of the safety switches. The systems related to the generation of X-Rays are then switched off, the possible movement of mechatronic elements is stopped, and the supply of circuits with a voltage exceeding 24VDC is disconnected. Circuits with lower operating voltage remain switched on, ensuring operation of

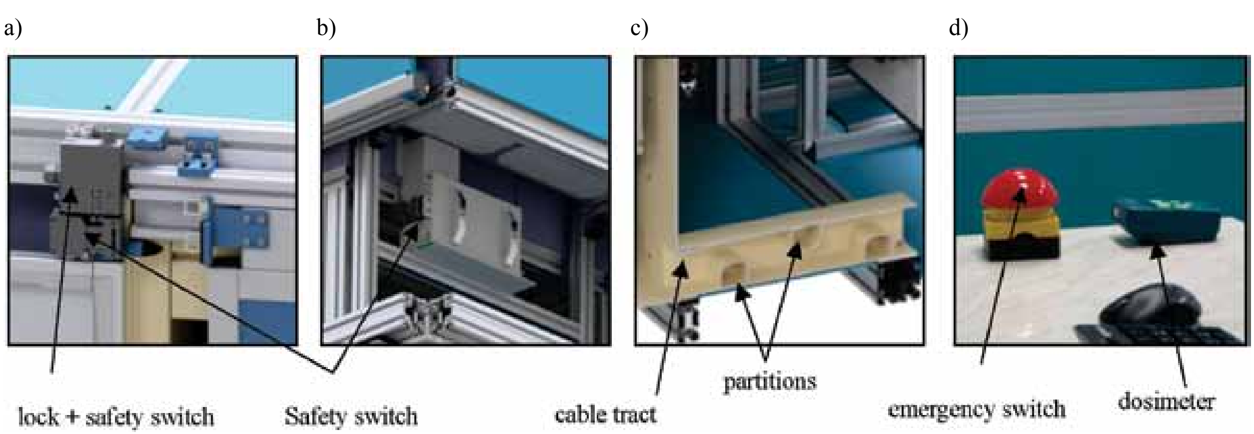

Fig. 4. Drawing of elements of the security system: a) door module of the measuring chamber, b) side cable entry module, c) bottom tract with partitions, d) equipment for the operator's stand

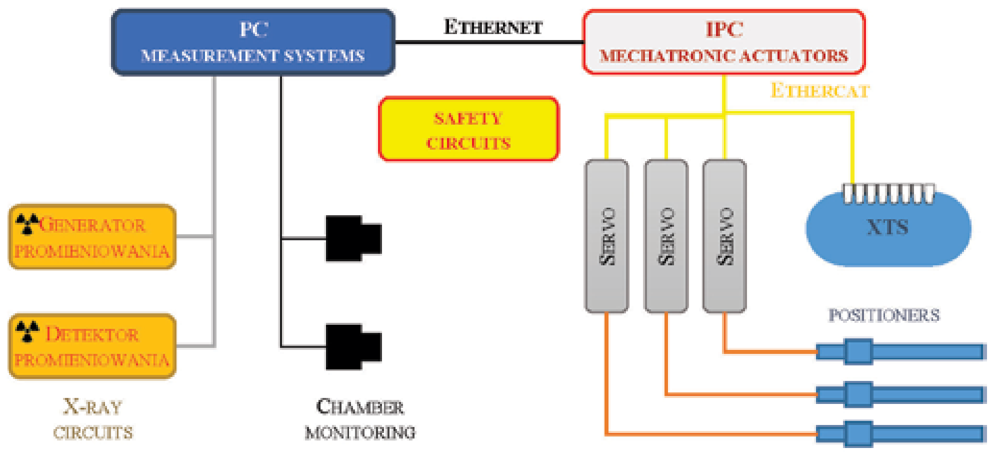

Fig. 5. Block diagram of device control systems

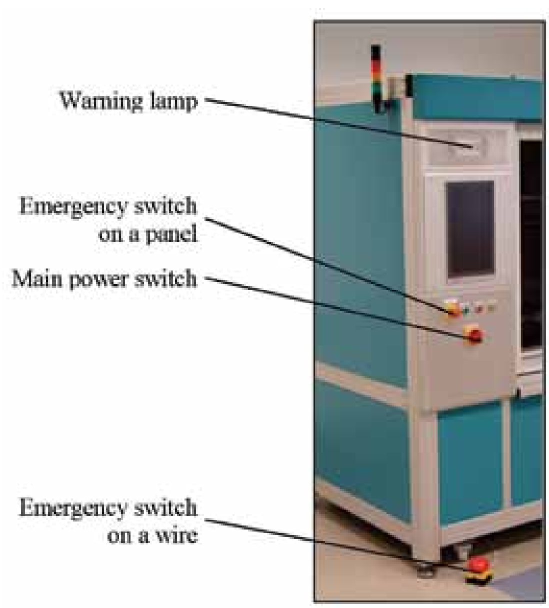

Fig. 6. Arrangement of security system controls

the control system. The working chamber is secured by two independent devices. It is a stand-alone door opening sensor, equipped with a shape activator and a second sensor integrated with an electromagnetic lock cooperating with a shaped bolt. Activation of any of these two independent devices completely prevents the start of the radiation generator. In addition, by opening the chamber door or opening one of the protected guards, the research system is partially deactivated. Systems related to the generation of X-Rays are locked, the permissible speed of movement of mechatronic components is limited, and all circuits remain active. The operation of mechanical systems with the door open is an acceptable mode of operation of the device, allowing for the appropriate positioning of elements inside the measuring chamber and loading objects subjected to inspection, but it is unacceptable to activate the radiation generator in this mode.

Fig. 7. Schematic diagram of the operation of safety systems

The operation of safety systems has been implemented in two levels. The internal level responsible for disabling the X-Ray generator and limiting the speed of motion of the drives is included in the external level in such a way that the activation of security at the external level also triggers the protection at the internal level. This dependence is implemented using security logic, as described below.

The hardware structure of safety systems (Figure 8) is based on the Safety modules of the *IPC* controller, working under the control of the certified *TwinSAFE* system [9]. The modular design of the *IPC* controller used in the device allows the installation of special I / O modules and the Safety CPU module, which operates independently of the main IPC controller (*IPC CPU*) and its inputs and outputs (*IPC I/O*) on the same communication bus (*EtherCAT*).

With such a structure of control systems, direct communication of the safety controller with the main controller is guaranteed. Devices triggering the activation of the safety system, i.e. safety switches (one on the operator's panel, the other is mobile on the wire) and sensors for opening the doors and cable glands are connected to the safety inputs, and the executive systems, i.e. the door interlock and safety relays are connected to

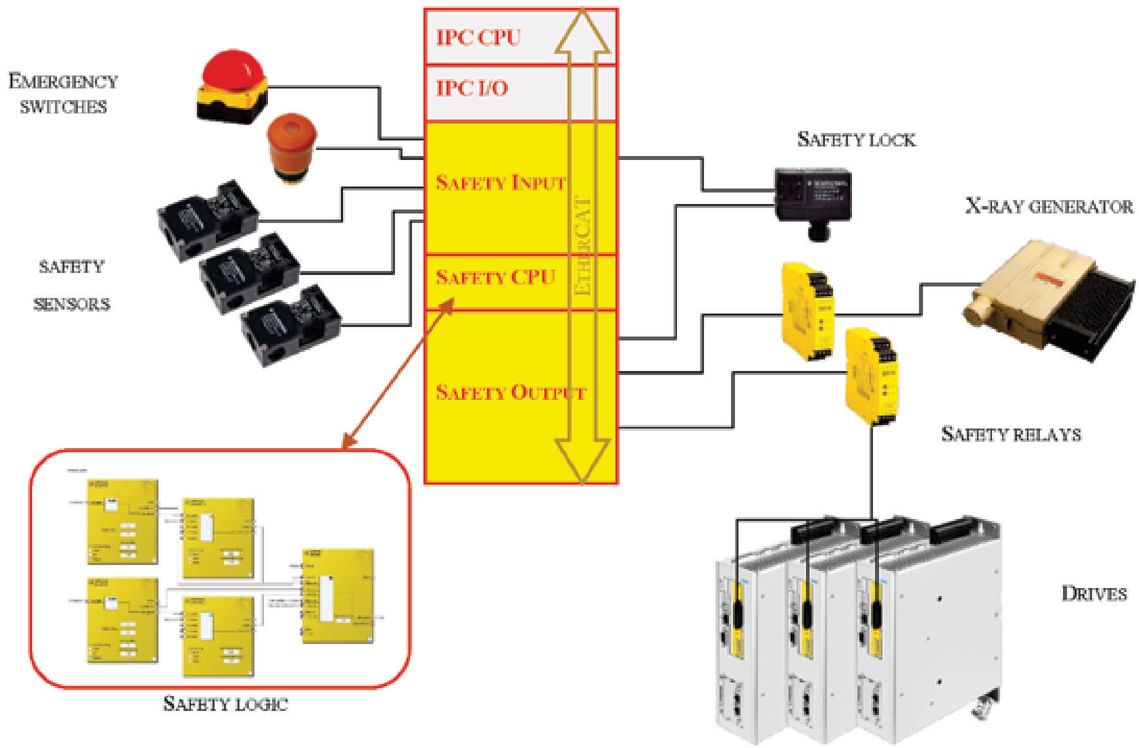

Fig. 8. Structure of safety systems

the safety outputs. The logical dependencies between the safety inputs and outputs are realized on the program path in the safety controller, which gives permission to the main IPC controller to work on individual components. The *TwinSAFE* system is a built-in safety controller system and allows the implementation of complex logical dependencies. It complies with the SIL3 IEC 61508 and Cat 4 Pl e DIN EN ISO 13849-1 standards [10]. The use of a software driver and the appropriate logic and mathematical rules allows obtaining the appropriate data redundancy, ensuring the correct performance of operations in the security system and self-monitoring of the safety system. This allows one to obtain the SIL 3 safety level in accordance with IEC 61508 [10].

3. Image acquisition, processing and analysis

The presented X-Ray inspection system (Fig. 9) is based on Hamamatsu X-Ray scan-line camera C12300-321 [11], X-Ray source IXS060BP800P378 provided by AVJ Technologies [12] and image acquisition system with industrial PC equipped with PCI-Express frame-grabber PHOENIX D24-PE1 providing Active Silicon [13] camera-link interface.

The X-Ray beam begins at a 1.2 mm focal spot and spreads at an angle of 10 degrees to the camera scan-direction and 80 degrees to the perpendicular direction.

The X-Ray source acceleration voltage is 60 kV with maximal current of 13.3 mA. Scan-line camera ensures 20000 lines/s scanning speed. Each line is 4608 pixels long. The pixel size of scan line is 48 µm, which ensures 960 mm/s maximum scanning speed. The intensity of acquired images is tuned by 18 amplifiers conditioning signals from 18 equally spaced line sections to fit to measurement range of a 12 bit analogue to digital

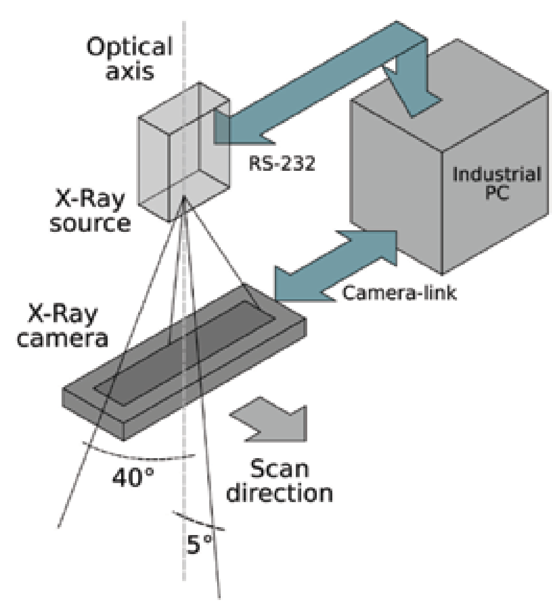

Fig. 9. X-Ray beam geometry and image acquisition system

converter. The camera software can set 64 predefined gains for each section independently.

The camera operates in TDI mode (*ang. Time Delay Integration*) and uses 150 additional detection lines. In Fig. 10, the principle of operation of TDI mode is presented [14]. The image of a moving object is measured synchronously by all 150 lines. Its movement speed is set in such a way that all lines register the same signal that, after summation, becomes much stronger if related to noise. The summation is implemented in a CCD array (Charge Coupled Device), which strongly increases camera's sensitivity, shortens exposure time, and increases scanning speed.

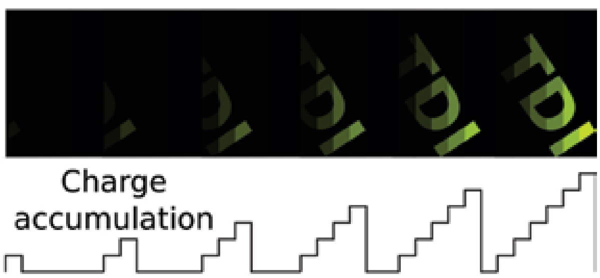

Fig. 10. Principle of operation of TDI mode [15]

The increase of scanning speed forces high demands for image processing and analysis software. Efficient application of such techniques as frame buffering and parallel processing is critical for successful inspection.

In the designed system, the image acquisition and camera configuration software modules were integrated with Adaptive Vision Studio (AVS) environment. Images grouped and acquired in frames with user defined lengths are processed by the pipeline of software functions. A graphical programming interface based on functional programming pattern with a wide range of diagnostic tools allows rapid prototyping of image processing algorithms.

Some randomly selected images registered by designed system are shown in Fig. 11.

In Fig. 12, a sample of software potential to process and analyse acquired images is presented. One of the sleeves from Fig. 11 was inspected. The positions and diameters of drills were estimated, and the inner diameter of the sleeve was measured. The software allows the presentation of results in the form of numbers as well as in the form of graphics (see colour markers in Fig. 12). The results were obtained by an algorithm implemented with 7 functional blocks presented in the figure.

Conclusion

The article presents a research system for modelling inspection methods using X-Ray technologies. The design of the developed system allows studying objects moving at linear speeds up to 4 m/s. The device chamber ensures operator safety during testing. Radiological measurements showed no leakage of X-Rays outside the device while working with the maximum parameters of the generator. The adjustable position of the generator and detector allows the simulation of various parameters of the optical path. By changing the mutual position of the source relative to the object and the radiation receiver, it was possible to carry out tests on objects of various sizes and to simulate variable measurement resolution. The use of a conveyor in the form of a linear motor operating in a closed loop track equipped with 8 carriages allows simultaneous examination of small batches of products with variable linear motion parameters during the inspection. The tests confirmed the ability to conduct measurements with a resolution of up to 29 μm and demonstrated the suitability of the device for simulating fast production processes.

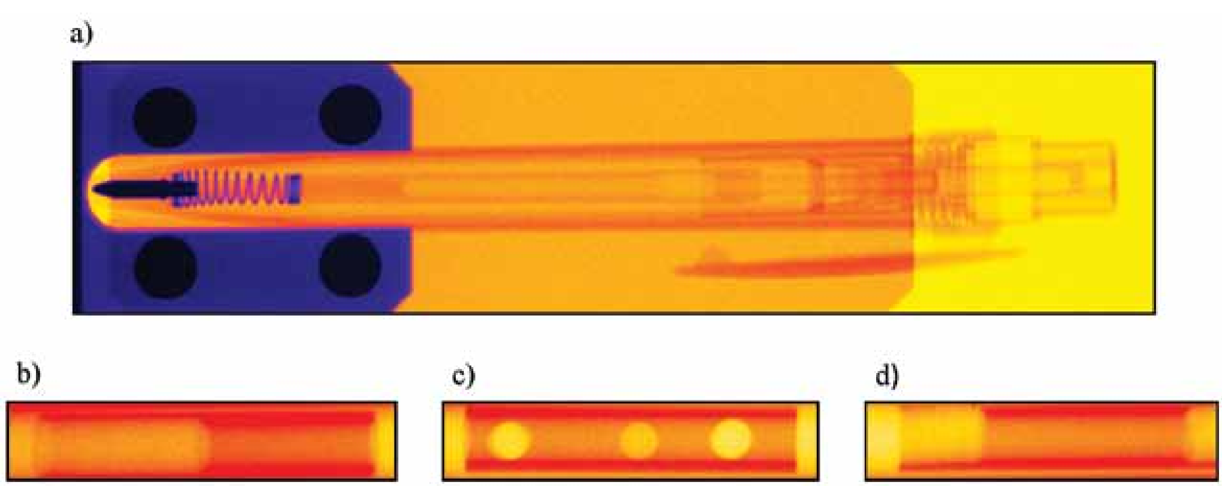

Fig. 11. Samples of registered images: a) ball pen, b) sleeves broached from the left side, c) sleeve with through-bores on both sides, d) sleeves broached from both sides

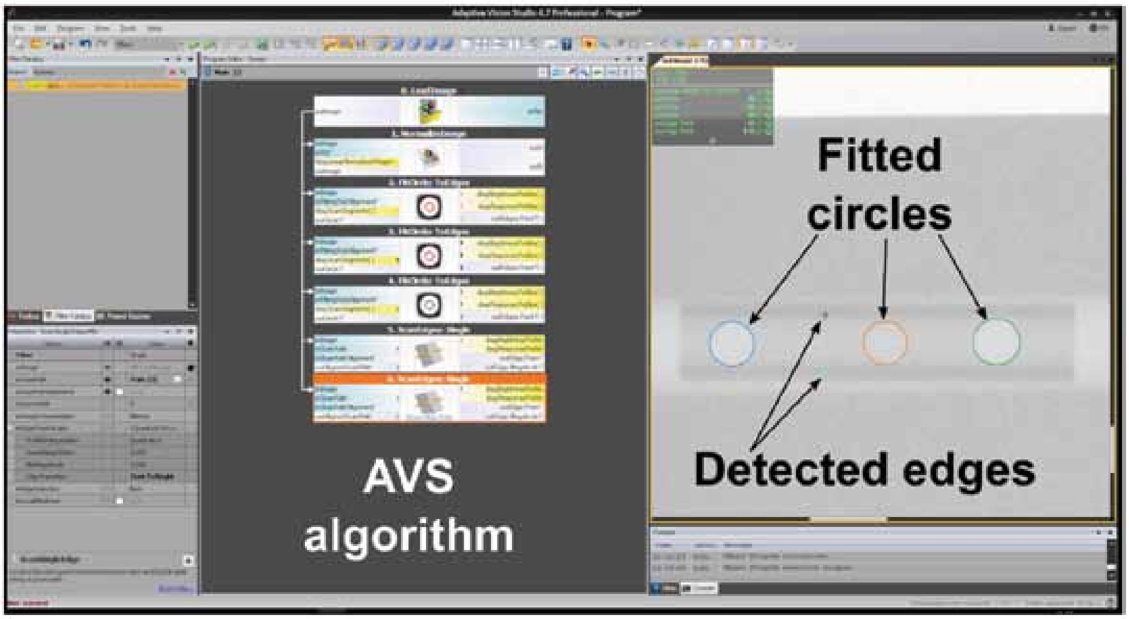

Fig. 12. Illustration of analytic potential of integrated software

The developed research system for modelling inspection methods using X-Ray technologies enables conducting research in the fields of the development of inspection methods in industry using high-speed production lines, e.g., in the tobacco, food, and aircraft industries. In addition, the research system enables the development of design guidelines for prototype devices for manufacturers of machinery and equipment for serial use on production lines.

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