Building Blocks of a Third-Generation Automatic Defect Recognition System

Frank HEROLD, Sönke FRANTZ and Klaus BAVENDIEK, YXLON International, Hamburg, Germany
Rolf-Rainer GRIGAT, Hamburg University of Technology, Hamburg, Germany

Abstract. Fully automatic, third-generation X-ray inspection systems for non-destructive testing (NDT) use the latest technologies in image-processing hardware and software. For aluminum castings, one-hundred percent inspection of critical parts' safety has become the standard, particularly in the automotive industry. The widespread variety of parts to be inspected, e.g. parts like wheels, 'knuckles' or pistons when staying within the scope of automotive technology, or alternatively parts used in aviation technology, demand a broad range of flexibility with respect to an "Automatic Defect Recognition" (ADR) system.
Moreover, each casting foundry has its own specific requirements. For instance, some need a direct feedback of inspection results to optimize their casting process, whereas others want to find only certain kinds of defects. Reliable defect recognition is sometimes a major challenge. Defects can have arbitrary shapes and often show up in various positions and sizes. Depending on the test involved, parts defects can be low in contrast or even 'hidden' behind a part structure, meaning that some traditional algorithms will at best find only fractions of such defects. Last of all, operators of such an ADR system prefer to exert little effort toward configuring the system. At any rate, introductory training for a new test part should be managed with a minimum of downtime and at a central, restful place if possible.
This article is going to show how a flexible ADR system can be achieved using software building blocks to cope with all the different requirements and demands. The result is an individualized, reliable and user-friendly solution that makes use of the latest technologies and algorithms. A so-called 'general X-ray testing process' is thus going to be introduced along with general software building blocks such as part-type recognition, image acquisition, defect recognition, including image registration, as well as the analysis and classification of defects regarding a given specification. ADR methods are furthermore compared using different prior knowledge about the structure of the part to be tested.

Introduction

Fully automatic X-ray inspection systems for non-destructive testing (NDT) in the third generation [3] have been developed to fulfill the manifold requirements of today's casting foundries. In the case of aluminum castings, one-hundred percent inspection of critical parts' safety has become the standard, especially in the automotive industry. The variety of typical test parts in the automotive industry ranges from wheels to 'knuckles' to pistons, yet there are also alternate scopes of application, e.g. in aviation technology.

The general X-ray testing process applicable for all X-ray inspection systems is defined in the following section. Distinct building blocks toward realizing the basics of a third-generation Automatic Defect Recognition (ADR) system are explained afterward. Additional optional building blocks and special functional extensions lead to a flexible and user-friendly ADR system that has been configured to provide exactly the needed functionality. Moreover, this flexibility allows the ADR system to keep up with new requirements, yet with a minimum of future investment.

1. Definition of Building Blocks

1.1 General X-ray Testing Process

An X-ray inspection system that includes ADR systems normally consists of a radiation-shielded cabinet containing an X-ray tube detector system for image acquisition and a manipulator system for positioning the parts to be tested. A conveyer system to load and unload the test parts in a batch process is needed in addition. Yet even when all the mechanical prerequisites are available and the quality of mechanical engineering is excellent, the intelligent part is still missing: for instance, a reliable ADR system controlled by software in which defects in castings are recognized by specialized image-processing software that performs an intelligent X-ray image analysis. In the following we are therefore going to focus on the software component of an X-ray inspection system, and especially on the software building blocks of such a system.

Generally speaking, all tasks or even the software building blocks of today's known X-ray inspection systems can be mapped using the *general X-ray testing process* depicted in Figure 1.

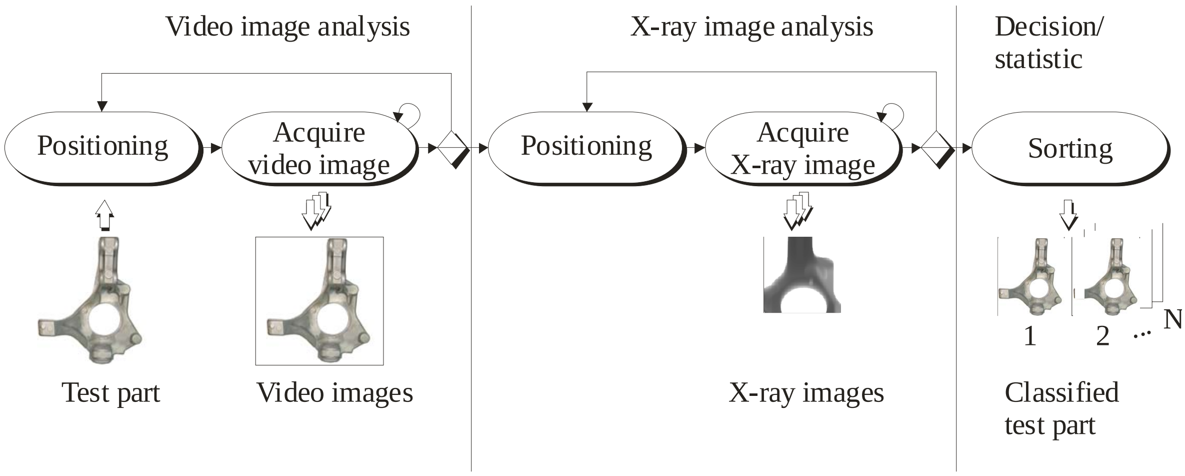


Figure 1. General X-ray testing process

After loading the part to be tested, a video image analysis is usually performed as shown in Figure 1. The part must be positioned, then one or more digital video images are acquired to do a surface inspection or part-type recognition, for example specially for wheels, or even for certain kinds of structural parts.

The next step is actual X-ray image analysis. With the aid of the X-ray tube detector system, one or more images are again acquired of the positioned test part, but this time X-ray images. These are used to perform X-ray image analysis, which may also include detailed classification of the type of defect.

In the last step, the tested part is unloaded depending on the current test results. The simplest case would be a simple good/bad decision in which output is sorted the same way. In the case of a detailed defect-type classification, special sorting by type will be applicable as mentioned later on.

In the following section we are going to describe typical tasks from which the software building blocks have been derived, as well as how these building blocks can be combined to provide an individualized NDT solution.

1.2 General Tasks and Modes

The third generation of fully automatic ADR systems has been distributed to the market after more than ten years of development. Modes of operation other than an automatic mode are still needed, especially for prototype development, low-volume production lines or during the setup of new product series. As of here we are going to concentrate on three modes: *manual*, *semi-automated* and *automated*.

As explained in the preceding section, X-ray inspection systems for different types of parts to be inspected have had basic tasks in common until now. But the difference lies in the details. First of all, X-ray inspection systems differ regarding their modes of operation (e.g. manual, semi-automated or automated). Next, they can be divided according to their fields of application (e.g. wheels, structural parts). Lastly, the number of different pre-processing and post-processing steps are unique. As will be shown later on, these modes are built up on top of each other.

The *manual mode* for testing castings is the underlying operational mode. The software only performs tasks passively in this mode. On the one hand these involve tasks to control machinery, e.g. setting the right voltage and current or positioning the part to be tested. The other hand revolves around tasks toward displaying acquired X-ray images. D isplaying algorithms for image enhancement is useful to ensure optimal defect recognition by the human operator. The operator makes the final decision and is responsible for how precisely the part is to be classified. Usually the operator just makes a good/bad decision, but different decision levels are conceivable. The test results may then be stored, as well as the display parameters. After that the operator has to induce unloading of the tested part depending on its test result.

In the so-called *semi-automated mode*, general control tasks for machinery are shifted to the ADR software system, but the human operator still makes the final test decision. The ADR software merely provides decision support by highlighting potential defects in the X-ray image. Parameters to control machinery are thus teachable, e.g. during online testing the learned parameters concerning voltage and current and the dedicated position can be recalled to capture an X-ray image automatically. It is therefore possible to test parts from low-volume production lines consistently using the same view. An X-ray image analysis is performed additionally in order to recognize potential defects automatically and highlight those defects in the displayed X-ray image. With the aid of such highlighted defects in the X-ray image, the human operator’s attention is turned to critical positions that represent potential defects. Yet the operator still remains responsible for classification of any defects found, and must induce unloading of the tested part in an adequate way, i.e. in the simplest case, the operator must make a good/bad decision.

The *automated mode* means that both the control of machinery and the test decision are made by the ADR software on a fully automated basis. The loading and unloading of parts to be inspected is furthermore done fully automatically during the batch-testing process. Recognized defects in parts are classified via a given test specification. The test results of the automatic defect recognition step are usually compiled in a statistic. The possibility also exists to review the test process or to compare the test result with reference results from a previous test, e.g. for auditing purposes, although an inspection program has to be trained to learn all needed parameters for controlling machinery and performing defect recognition automatically in the course of a setup phase. If several different parts are to be tested within the same ADR system, part-type recognition is also needed.

Table 1. Tasks (software building blocks) and modes of operation.

Hardware Control			
Task	**Manual**	**Semi-automated**	**Automated**
Load / unload test parts – interactively	✓	✓	–[1]
Load / unload test parts – automatically	–[1]	–[1]	✓
Control of X-ray tube – interactively	✓	✓	✓
Control of X-ray tube – teachable	–	✓	✓
Control of manipulator – interactively	✓	✓	✓
Control of manipulator – teachable	–	✓	✓
Setup imaging device	✓	✓	✓
Image Processing			
Task	**Manual**	**Semi-automated**	**Automated**
Image display	✓	✓	✓
Automatic image acquisition	–	✓	✓
Image enhancement	✓	✓	✓
X-ray image analysis – defect recognition	–	✓	✓
Load / save parameters	✓	✓	✓
Load / save test results	✓	✓	✓
Definition of test specification	–	–[1]	✓
Classification by test specification	–	–[1]	✓
Statistic of test results	–	–[1]	✓
Process review	–	–[1]	✓
Part-type recognition	–	–[1]	✓
Hardware guard	–	–[1]	✓
Special Image Processing			
Task	**Manual**	**Semi-automated**	**Automated**
Detailed type classification of defects	–	–[1]	–[1]
Part-type recognition for wheels	–	–[1]	–[1]
Crash protection	–[1]	–[1]	–[1]
Additional Pre- and Post-Processing			
Task	**Manual**	**Semi-automated**	**Automated**
Surface inspection	–	–[1]	–[1]
Mold recognition	–	–[1]	–[1]
Part sorter	–	–[1]	–[1]
Feedback to casting process	–	–	–[1]
Functional Extensions			
Task	**Manual**	**Semi-automated**	**Automated**
Filter without prior knowledge	–	✓	–[1]
Filter with prior knowledge, 1 image	–	–[1]	–[1]
Filter with prior knowledge, n image	–	–[1]	✓
Filter with prior knowledge, 3D model	–	–[1]	–[1]
Classification by ASTM E2422 (ASTM E155)	–	–[1]	–[1]

✓ mandatory, – impossible, –[1] optional

Furthermore, a hardware guard must verify that the general image quality is still applicable for the testing process, e.g. when intensity of the X-ray beam varies or there has been an error during image acquisition. To be avoided no matter what the case is that the X-ray image analysis becomes 'blind'.

The tasks needed to enact the three different modes of operation explained above are listed in Table 1 under the headings *Hardware Control* and *Image Processing*. Each task within the table stands implicitly for an optional software building block that can be added or left out individually.

1.3 Building blocks and special tasks

In Table 1, mandatory tasks or even building blocks for each mode (manual, semi-automated, automated) are marked with a '✓', and the impossible or optional tasks are respectively marked with a '–'. The combination of several building blocks creates a stand-alone X-ray inspection system that fulfills the specialized individual requirements of, for example, a certain casting foundry.

As shown in the column 'Semi-automated', several building blocks are marked as optional. For instance, it would be possible to use a defined test specification to classify highlighted defects so that the operator could use this as additional decision support.

Another distinctive feature of X-ray inspection systems is the field of application, e.g. wheels or a certain structural part. A specialized solution that takes the characteristics of these kinds of test parts into consideration must therefore be applied. Under the heading *Special Image Processing* (see Table 1), the specific software building blocks are listed as examples. For instance, as mentioned above in the case of the automated mode, if the concrete type (e.g. gas hole, shrinkage etc.) of a recognized defect is supposed to be determined, then a detailed classification method must be used in addition to standard classification. Another example is part-type recognition specialized for wheels. There the algorithm takes advantage of the roundness of wheels, and the valve hole is used to determine an exact initial orientation of the actual wheel. During the positioning of such parts to be tested, and particularly for large-structured parts, it is important that neither the test part itself nor the X-ray tube detector system or any other part inside the cabinet becomes damaged as the result of a collision. A building block that performs collision protection and has been configured for a certain X-ray inspection system at a particular foundry will prevent such destructive behavior.

X-ray inspection systems also differ due to the manifold requirements of casting foundries and their special mechanical environment before and after actual X-ray image analysis in the radiation-shielded cabinet. As examples we are going to introduce optional scenarios, each of which can be handled by a certain software building block.

An optional video image analysis could be used to carry out surface inspection before X-ray image analysis. A human operator usually performs such inspection, but image-processing methods are consistently able to carry out these inspection steps in an objective manner. For example, flashes on castings, missing material or other surface defects like cracks could be recognized immediately prior to X-raying so that further testing of these parts may no longer be necessary. That information might even be useful in subsequent testing.

Molds for the same type of castings may differ in their construction, e.g. due to optimization of the casting process. Mold recognition may thus be necessary in order to adapt selected parameters of X-ray image analysis automatically.

In the case of a detailed classification of defect type, it would make sense to sort the tested parts coming out by their type class. Moreover, a detailed classification of defect type makes it possible to conclude the cause of the defect directly from the type class. Third-generation ADR systems will also detect anomalies that are smaller than specification tolerances. Process feedback of the test results to the casting process would thus enable the caster to initiate countermeasures, even before the defect size exceeds test specifications for the casting object.

1.4 Functional extensions

As shown in Table 1, a great overlap exists between certain building blocks regarding the different modes and tasks involved. The demands themselves, however, are much more manifold, i.e. each casting foundry has its own individual conception of how an ADR system should work. Moreover, a trend toward greater efficiency in system evolution, e.g. in the automotive industry, and new test parts will lead to more complex algorithms for ADR. Of course, the principal steps as shown in Figure 1 are not affected, but basic functionality must be extended. On the other hand, a specialized functionality might not be needed to perform a certain task. The goal is that an X-ray inspection system includes only those functions that are precisely needed. That way it is possible for the customer to order an ADR system that consists of the basic building blocks, and to select only those functional extensions that they really need at that time: the system becomes a *customized* solution that has been *tailor-made*. When the customer has new requirements later on, all they would normally need to do is extend the functionality of their ADR system.

Some examples for extensions of ADR software are given under the heading *Functional Extensions* in Table 1. Image-processing filters are the basis for X-ray image analysis. The quality of defect recognition is commonly limited to prior knowledge of a test part's structure. There are two different approaches toward dealing with prior knowledge: The first method defines the appearance of defects as known, i.e. only the known shapes of defects are listed in a so-called 'positive list', and only defects that match this list are recognized [4]. Yet defects can have almost arbitrary shapes (e.g. shrinkage cavities), so that the risk of missing a defect bearing an unknown shape still exists. We therefore propose taking only the method that uses a negative list into consideration, i.e. all regular structures that belong to the test part are well-known, and all unknown structures that might be recognized during ADR are potential defects.

How much prior knowledge is available concerning a certain test part is important, too. There are generally methods known that work without prior knowledge, with one image or even with a number of images (n images) as prior knowledge. But even n images as prior knowledge are not able to cover all degrees of freedom when it comes to positioning a part. As X-ray images are two-dimensional, projected mappings, the effects of a tilted positioning of the test part are not predictable using a two-dimensional image as reference. Extending prior knowledge via a three-dimensional model would thus be an improvement, especially for complex test parts. As shown in Table 1, the standard for the automated mode is a filter with n images as prior knowledge. Filters with more or less prior knowledge can be chosen either additionally or alternatively as an option. Whereas the semi-automated mode is equipped with a filter set containing no prior knowledge, a filter with prior knowledge could also be optionally applied by choosing the right functional extension as shown in Table 1.

Yet another functional extension is classification according to the ASTM standard E2422. That standard is based on digital X-ray images of the same castings used as reference radiographs for ASTM E155 (see Table 1). This is a special way to extend the detailed classification of defect types mentioned in the above. With the help of a decision tree, a detailed classification is performed that results in defect classes similar to Figure 2 (see [3]).

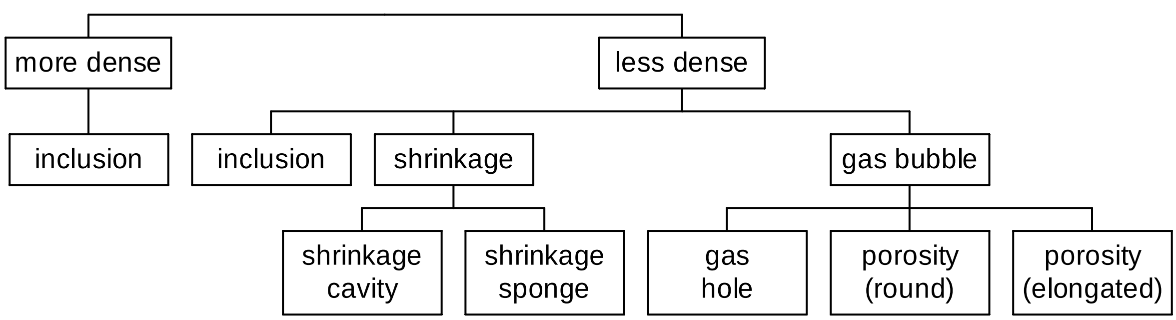
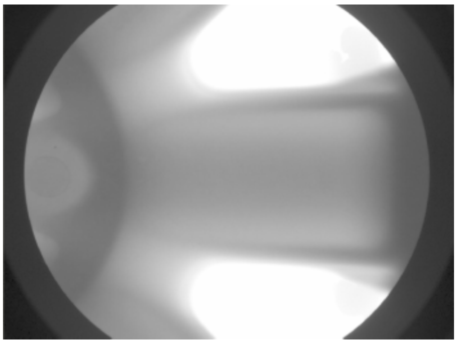


Figure 2. Decision tree of detailed classification pursuant to ASTM E2422 (cp. ASTM E155).

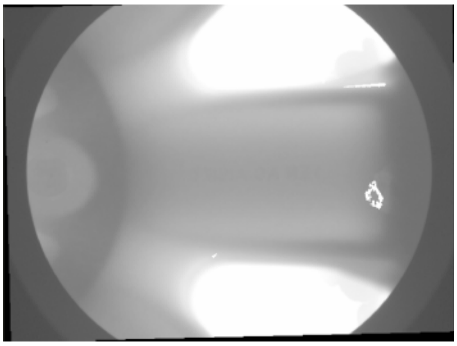
2. Results

With relation to filter methods employing a certain amount of prior knowledge about the test part's structure (see 1.4), we are now going to present results from a third-generation ADR system. An example is given in Figure 3 of how using prior knowledge can affect defect recognition. Subfigure (a) shows the reference image of a wheel spoke without defects. In Subfigures (b) – (d), we always have the same X-ray image of a spoke of the same wheel type as in (a), but a large defect has been applied to different filters for ADR. Subfigure (b) is the result of simple low-pass filtering without prior knowledge [1], whereas in Subfigure (c) the difference between the reference image (a) and the optimally registered image is shown as an example for a filter with only one image as prior knowledge. Subfigure (d) depicts the result of a filter with n images as prior knowledge, namely the Trained Median Filter [2], [3]. As can be seen in Figure 3, the filter without prior knowledge recognizes only the edges of the large defect, and detects some edges of the part's structure (b). The filter with one image as prior knowledge detects several variations between the images mostly due to positioning tolerances, but also detects the large defect (c). These results must be processed again to avoid erroneous detections. The Trained Median Filter (TMF) has found the large defect reliably in one step (d) because the TMF has an n image prior knowledge regarding the part's structure.

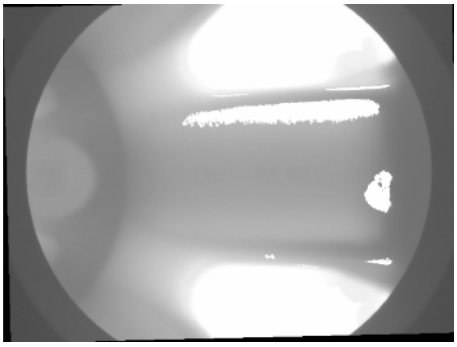
(a) Reference image.



(b) No prior knowledge.



(c) 1 image prior knowledge



(d) n image prior knowledge.

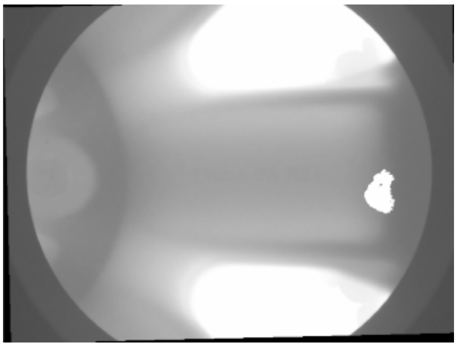


Figure 3. Defect recognition using variable prior knowledge.

X-ray inspection systems, and especially third-generation ADR systems, may be configured for different applications at distributed sites, but their look and feel is always the same. The operator is guided through the setup process as introduced in [3]. A setup screen for ADR is shown in Figure 4 as an example. A navigation tree on the left side gives an overview of actual tasks, whereas a large image view on the right side shows the results of image processing. Dynamically generated boxes for settings are placed in the space between depending on currently available functional extensions, as well as at the site of actual context.

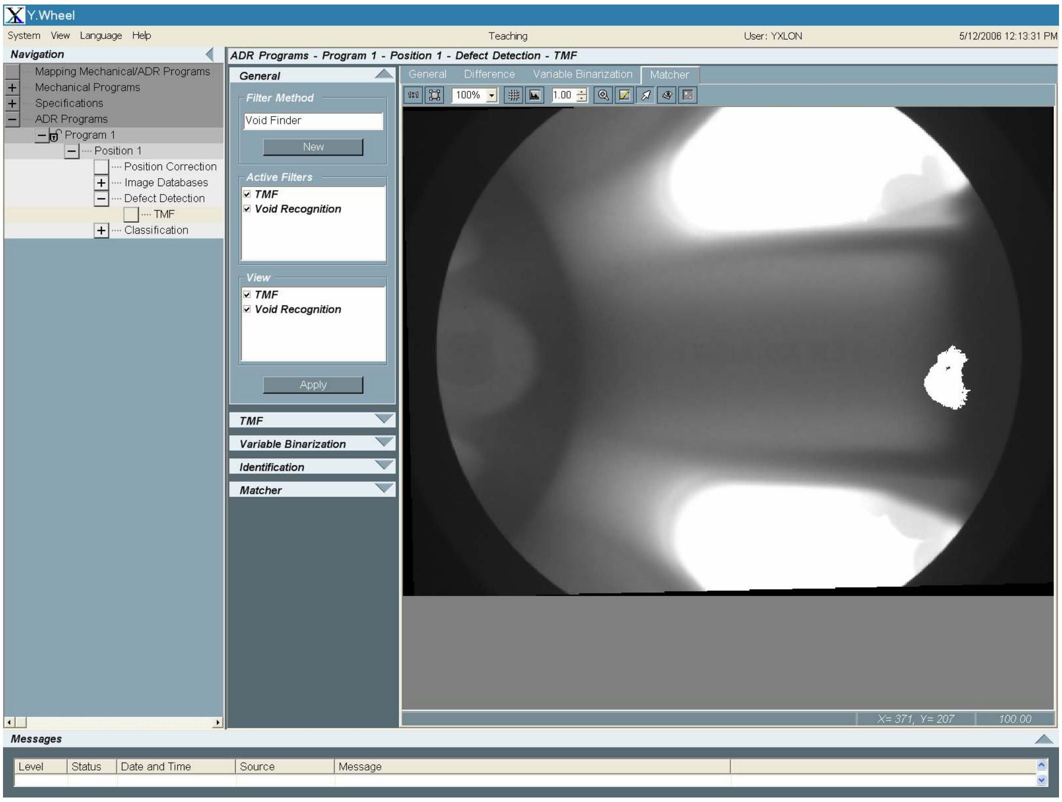


Figure 4. Dynamically generated teaching view split into navigation, settings and image view.

3. Conclusion

With the aid of software building blocks, an individual third-generation ADR system can also be configured at distributed sites. A well-configured X-ray inspection system like this can be expanded further by means of so-called ‘functional extensions’ so that it provides exactly the customized tasks and range of functions required at that moment. Moreover, this flexibility also makes it possible to satisfy a customer’s future requirements by extending the basic building blocks to include an added new functionality.

An example was given of how using more complex prior knowledge can optimize defect recognition, but of course not every application provides prior knowledge, and sometimes less prior knowledge may already allow performance of a special task. A flexible configuration of the existing X-ray inspection system is useful for these purposes, besides increasing uptime and saving costs. Concentration on the substance of an X-ray inspection system also makes it possible to build up a user-friendly graphic user interface that provides each operator with only those settings needed in the actual context.

References

[1] R.Gonzalez, R. Woods, “Digital Image Processing”, 2nd edition, Prentice Hall, Pearson Education, Upper Saddle River, New Jersey, 2002, ISBN: 0-201-18075-8.

[2] F. Herold, K. Bavendiek, R.-R. Grigat, “A New Analysis and Classification Method for Automatic Defect Recognition in X-Ray Images of Castings”, The e-Journal of Nondestructive Testing, October 2002, Vol. 7, No. 10, ISSN: 1435-4934.

[3] F. Herold, K. Bavendiek, R.-R. Grigat, “A Third Generation Automatic Defect Recognition System”, 16th World Conference on Nondestructive Testing, August 30 - September 3, 2004, Montréal, Canada.

[4] A. Stone, “What the Devil is Fully Automatic Real-Time X-Ray Inspection?”, CSNDT Journal, Vol.21, No.1, 2000, pp.6, 8-10,12.