by Lennart Schulenburg

Recap of Part 1 and Introduction
The first part of this article introduced the basic concept of digital X-ray imaging, its components, and the commercial principles of such capital investment. Several metrics to analyze and compare processes and technologies were discussed and explained. The most important key performance indexes are overall equipment effectiveness, as a metric to describe the process efficiency, and return of invest (ROI), as a purely commercial metric to determine the feasibility of an investment. Now that the process and commercial factors are covered, we are able to move towards the even more important technical factors. It is important to keep in mind that when we are talking about nondestructive testing (NDT) equipment, quality is always the highest priority. This section of the article will provide a guideline on how to approach an investment into a new X-ray inspection system in a structured manner. Nowadays, NDT managers have a vast choice on the global equipment market, and it is easy to make unfavorable choices that lead to severe consequences in defect detectability or efficiency.

The Procurement Process
As always, good preparation and a clear concept lead to the best result. The high degree of complexity and amount of variations in modern digital radiography equipment are challenging, especially for technicians coming from a film background. To avoid classic pitfalls, it is recommended to follow a well-structured process:
1. Definition of targets
   a. Quality
   b. Throughput
   c. Available budget
2. Inquiry at a solution provider
3. Provide parts for a concept case study
4. Decision on inspection process (visual, automated evaluation, computed tomography)
5. Decision on X-ray components
6. Decision on mechanics and manipulation concept
7. Receiving budgetary quote
8. Internal ROI and compliance evaluation
9. Repeat steps 1-8 until success
10. Definition of a final procurement specification document
11. Purchase order to a selected provider
12. Design review and adaption
13. Factory acceptance test prior to shipment
14. Installation and training
15. Regular service and preventive maintenance

The next paragraphs will explain these steps in detail and guide the reader through the complete process. It is important to understand that this process should not be parallelized under any circumstances to avoid wrong choices. An organized sequential approach will lead to the highest degree of efficiency and best solution in the end. The reader should expect that the complete process can take anywhere from four months up to one year depending on the system complexity.

Definition of Targets
The first step will lay the foundations for the complete process and is of special importance. Many times, the complexity of this step is underestimated, as multiple departments need to collaborate in order to find the right answers. The quality is determined by general inspection standards, special customer requirements, or company guidelines. The following information is mandatory and should be gathered from the quality/NDT and production department:
- Quality standards (for example, EN-17636-2 or API 5L)
- Process standards (for example, NADCAP or ISO 9001)
- Company standards (for example, BSS 7044 or AITM)

It is no coincidence that the quality requirements are discussed first. Investment in new equipment should always be quality driven, and it should be ensured that full compliance to customer or industry requirements is given. Only in the next step it is important to include process engineers to discuss requirements regarding cycle time, throughput, or process integration. The throughput is defined as parts per timeslot and should be discussed between the production and quality assurance departments. The answer should not be a single number but a range defined by low production and full production. When planning a bigger capital investment, the system should have a certain buffer to adapt to production changes to prevent future bottlenecks.

The information about quality and throughput is already sufficient from a technical point of view. But experience shows that if the budget is not taken into account in an early stage, the project has a high failure probability. Therefore, the technical staff should get in touch with commercial or controlling managers as soon as possible to check free budget and investment potential. At this stage, the exact amount is not necessary, but solution providers will require a certain range to develop a concept. This saves time and money for everybody in the end.

Inquiry at a Solution Provider
There are a couple of well-established solution providers on the market that offer X-ray inspection systems. In general, it is a good idea to request several suppliers to have a good market overview. Typically, a higher degree of system flexibility and customization will provide better efficiency and inspection results. To ensure smooth communication, it is important to define an internal project manager and focal point that bundles all outgoing communication and filters all incoming information. The main points being requested at this stage are already mentioned in step one. Basically, it all comes down to the following:
- Quality requirements (as stated earlier)
- Process information and throughput
- Estimated budget (if available)

Due to the high complexity in software, hardware, and safety requirements of digital X-ray systems, it is not recommended to build an in-house solution out of single components. Doing so can result in severe consequences to quality, production output, or accreditation, or can even result in health damage. Manufacturers benefit from the past experience and existing solutions.

Concept Case Study
During the previous step, the solution provider most likely already carried out a theoretical quality and process validation. Nevertheless, especially for complex inspection problems, it is necessary to conduct extensive case studies for in-depth evaluation and proof of concept. Reputable suppliers typically offer this service free of charge, up to a certain extent! To get the most out of this step, the quality department should prepare several parts: Good parts (OK-parts), parts with typical defects (NOK-parts), and parts with artificial defects. Artificial defects are also called representative quality indicators (RQI). A typical example are precise drillings that simulate porosities. If such a preparation is not possible, the supplier will use certified image quality indicators (IQI) to prove the compliance to quality requirements.

This process is highly dependent on the inspection complexity, quality requirements, and industry, but a typical application procedure is designed as follows in Figure 1. It can be seen that case studies are carried out in an iterative way to find the least expensive hardware fulfilling the quality requirements. The outcome can be either a specific hardware setup or a...
portfolio of component combinations, each with distinct advantages and disadvantages. This process can be time consuming, but ensures that the solution will be fully pre-evaluated and fit for purpose. Reputable suppliers will offer a choice of various established manufacturers of X-ray tubes and digital detector arrays (DDAs) to choose from, depending on the application.

Definition of Process
The inspection process is determined by quality constraints, cycle time, part handling, customer preferences, and physical necessities. Digital X-ray allows a broad variety of features like automated defect recognition (ADR) (VisiConsult, 2016a) and computed tomography (VisiConsult, 2016b). It is crucial to understand that these techniques have many advantages but are not applicable or even feasible in all cases. The most common options are as follows:
- Visual inspection
- ATS – Automated test sequences
- ADR – Automated defect recognition
- Computed tomography
- Placement: in-line, at-line, off-line

Automated defect recognition, for example, allows automatic identification of flaws like porosities, inclusion, geometric deviations, completeness, and many more. Unfortunately, it requires precise part handling and an upfront system-teaching. Therefore, ADR is the perfect choice for repetitive inspection of high volume parts. Computed tomography is an imaging technique to digitally reconstruct parts and to perform 3D inspections like porosity analysis, actual-nominal comparison, or wall thickness analysis. This opens up a whole new world of high end inspections, but acquiring and computing the huge amount of data is quite time consuming compared to traditional digital radiography. This makes computed tomography the perfect choice for lab environments and development departments, but not the best solution for production checks. Additionally, the system placement can have a huge impact on the efficiency. An in-line system is directly integrated into the production line, while an at-line system is besides it. An off-line system is completely decoupled and mainly used for sample checks or development purposes. See Figure 2 for a visualization. More details on this topic will be provided in point 6,
Figure 3 Off-Line systems: (a) C-Arm system; (b) Gantry based system; (c) rotational system; (d) fixed beam system; (e) tower system; and (f) top loader cabinet.
when discussing the handling and conveyor concept.

**Decision on X-ray Components**

The two preceding steps of performing a quality case study and analyzing the required inspection process provides all necessary information to decide on the X-ray components, which consists of a DDA and an industrial X-ray tube. The case study is mainly determining the right choice through the following quality relevant parameters:

- DDA: Spatial resolution
- DDA: Contrast sensitivity
- DDA: Signal to noise ratio (SNR)
- DDA: Scintillator
- DDA: X-ray standoff (shielding)
- Tube: X-ray energy (kV, mA)
- Tube: Focal spot size

The process requirements just have an impact on the DDA choice:

- DDA: Read out speed (fps)
- DDA: Active area

The combination of both parameter groups provides a holistic description of the needed X-ray components. Most of the time the special requirements of an application and its customer specific inspection process result in a unique combination of X-ray tube and detector. In the introduction, the reader was warned not to determine a hardware setup on his or her own or too early in the process. When looking at the required analysis to make an educated choice, the reason for this becomes clear.

**Decision on Manipulator Mechanics**

After deciding on the X-ray components, the whole imaging chain consisting of generator, X-ray tube, DDA, and software is completed. The next step is to look into the mechanical side. The easiest case will be an off-line system with a basic part manipulator, which typically has the X-ray components mounted on a C-arm and a turntable for part rotation, as seen in Figure 3a. The other images show different off-line manipulator concepts like gantry based (Figure 3b), turning based (Figure 3c), fixed X-ray beam (Figure 3d), and through a manipulation tower (Figure 3e). At-line systems are basically off-line systems placed close to a production line with some kind of conveyor. Either a worker or a robot picks a part from the conveyor and places it into the cabinet. Figure 4a visualizes this approach incorporating an industrial robot.

The ultimate solution in case of high volume parts are fully integrated in-line systems as seen in Figure 4b. It is important to note that comprehensive definition of interfaces to and from the system is crucial. Typical concepts are conveyor belts, palettes, turntables, or hanging holders. Systems with this high degree of automation require precise mechanics and a controlled environment. It is suggested to request suggestions of the solution provider to benefit from past experiences and projects to avoid classic pitfalls.

![Figure 4: Automated loading: (a) through robot, (b) in-line conveyor belt system.](image-url)
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Internal ROI and Justification
This step is often underestimated by technical managers but crucial for the success of the project. Every major investment has to be presented and justified in front of the controlling department. In many cases, there are several options to fulfill the inspection requirement. Details will not be provided here, as this point was discussed in the first section of this article and is summarized in Figure 5. The used example described the choice between inspection by film, by visual digital radiography inspection, and by automated inspection through ADR in the context of a high-volume casting company. It clearly shows all choices fulfill the quality and inspection requirements, but every solution had different consequences: film – low investment, high running costs; digital radiography – medium investment, medium running costs; ADR – high investment, low running costs.

Depending on throughput, order backlog, and production forecast, there is a single best choice. These economic factors have to be taken into account to justify the investment. Soft factors like computed tomography features for development departments, fulfillment of higher quality standards, more process safety, and others are helpful as well, but the main focus should be on the return of invest. Typically, solution providers will help to generate such a calculation and can advise which solution is most suitable for the current situation.

Defining a Specification and Ordering
All steps up to now should be repeated as many times as necessary until an acceptable result for both technical and commercial departments is achieved. Experience shows that one cycle is sufficient for standard systems, and more complex customized solutions can take up to five cycles. Once the desired solution is found, the buying party has to compile a specification book. It is suggested to do this very carefully and write down all requirements and information concluded during the evaluation process. A common mistake is to keep the specification too general, which allows solution providers with lower quality to “hijack” the tender. Depending on the company policy, the result can be a system not fulfilling the requirements that were determined during the evaluation phase. The specification should be the basis for the order and the contract. It also should be subject of the final acceptance test. In more complex cases, a design review during the concept phase is suggested to ensure things are running smoothly.

Installation and Training
Projects with higher complexity are typically executed in a three-stage process. The first stage is performing a factory acceptance test at the supplier’s facility. Once general functionality is approved, a commissioning and installation date has to be set. To ensure a complication-free process, the supplier should provide a turn-key setup including an operator and a service training. The buyer, on the other hand, should ensure that the operators have the basic education to understand the used technique. This means ASNT digital radiography courses and radiation protection education. Additionally, a reasonable experience with the technology is highly beneficial.

Maintenance and Service
Typically X-ray systems need periodic maintenance every three to four months, depending on the utilization. This includes greasing of the high voltage plugs, mechanical maintenance, electrical maintenance, cooler checkup, and other processes. If not carried out professionally and regularly, the system lifetime can be reduced dramatically. Service capabilities of the supplier should be available to ensure fast recovery from system failures or accidents.
Summary
This article discussed the common process of evaluating and procuring a digital X-ray system. The reader should note that this process is by no means generic, but more an example based on past projects and experience. Every application has their special requirements influencing the process. In case of a demand, it is highly suggested to get in touch with a qualified solution provider that can support the decision makers with the definition of the technical requirements based on the application and their experience. Especially customized systems can bring a huge competitive advantage over standard units. The article also shows how complex the decision process for the right digital radiography system can be and provides a comprehensive guideline on how to master it. The third and last part of this article will focus on implementation examples and deeper technical background.

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References
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Ultrasonic beams, similar to various types of energy, attenuate when passing through different media. The amount of ultrasonic beam attenuation per unit of length in different isotropic materials simply refers to the attenuation coefficient ($\alpha$). This quantity is usually expressed in dB/in. (decibels per inch), dB/mm (decibels per millimeter), or even dB/m (decibels per meter). It is an important parameter in performing ultrasonic discontinuity size evaluation procedures in accordance with the AWS D1.1 standard (AWS, 2015). The distance gain size method also refers to this parameter when sizing a reflector inside a material using an ultrasonic beam (Krautkramer, 1990). The loss of ultrasonic energy when passing through materials depends on two main factors: first, the microstructure properties of the material; and second, on the characteristics of the ultrasonic beam involved. With regards to the first factor, the grain sizes, their orientations, the presence of any impurities at the grain boundaries, micro-porosity, and any history of heat treatment on that material can all contribute to the degree of attenuation of the ultrasonic beam. The second important factor is the characteristic of the ultrasonic beam, namely, the frequency and the beam profile (beam divergence) along its propagation path. This paper provides a simple procedure to separate these factors, and a practical way for measuring the attenuation coefficient ($\alpha$) of the part under test.

When an ultrasonic beam passes through a certain thickness of an isotropic material (see Figure 1a), it not only gradually loses energy due to the material properties, but it experiences specific losses of energy due to the fact that the beam diverges as it propagates (see Figure 1b).

Based on the double-distance law in propagation of an ultrasonic beam inside a material, after a distance equal to three times the near field distance, for each doubling of the distance on the near field scale (for example, between three and six times the near field distance), the beam undergoes a fixed 6 dB loss solely due to the beam divergence. This fixed 6 dB loss, which is not related to the material microstructures, should be separated from the overall amount of ultrasonic beam attenuation when measuring the attenuation coefficients.

Figure 1. Diagram demonstrating the travelling of an ultrasonic beam through a material: (a) a simple ultrasonic beam propagation, which begins to spread out at the end of the near field distance; and (b) the gradual loss of the ultrasonic beam, which is a combination of both material attenuation and energy loss due to the beam divergence.
As an example, let us measure the attenuation coefficient for a piece of low carbon steel at a specific ultrasonic frequency. Suppose the test part has a 20 mm (0.79 in.) thickness with two parallel surfaces. The transducer used for this test is a 5 MHz longitudinal straight contact one with 10 mm (0.39 in.) crystal diameter. Note that it is important to stay away from the edges of the part (see Figure 2a). Figure 2b graphically shows the screen of a calibrated ultrasonic flaw detector with an appropriate selected range with six reflected echoes.

We then plug the aforementioned parameters into the formula for measuring near field distance in the test part:

\[
NF = \frac{D^2 f}{4 \times V}
\]

where
- \(NF\) = near field distance (in inches or millimeters),
- \(D\) = transducer (crystal) diameter (in inches or millimeters),
- \(f\) = transducer frequency (in hertz),
- \(V\) = material sound velocity: consider a typical value of 5920 m/s (0.233 in./µs) for low carbon steel (for example, steel 1018).

This gives a near field distance of 20 mm (0.79 in.) in the test part for a 5 MHz longitudinal beam of ultrasonic in that particular piece of steel. In order to apply the double-distance law, first we identified the ultrasonic signal related to three times the near field distance. The signal labeled #3 in Figure 2b corresponds to three times the near field distance, and echo #6 corresponds to six times the near field distance. Referencing the display in Figure 2b, the gain difference in decibels between these two echoes can be easily measured through the gain option, which in this case is approximately 14 dB. From this decibel difference, a 6 dB loss is solely related to the beam’s divergence inside the part. Therefore, the actual attenuation due exclusively to the material loss is: 14 – 6 = 8 dB.

Considering the round-trip distance of the beam between two selected echoes, #3 and #6 (Figure 2a), we get: 60 + 60 = 120 mm (4.72 in.).

The attenuation coefficient of the part under test using a 5 MHz longitudinal ultrasonic beam will be the ratio of:

\[
\frac{8 \text{ dB}}{120} = 0.06 \text{ dB/mm (1.5 dB/in.)}
\]

Any changes in the material compositions or history of heat treatment on the materials will naturally have a slight variation in these calculations. The attenuation coefficient is expected to be higher when using shear waves or where higher ultrasonic frequencies are used.

The outlined procedures can be summarized in five simple steps:
1. Calculate the near field distance based on the type of ultrasonic transducer and the material under test.
2. Calibrate the ultrasonic flaw detector by selecting an appropriate display range, and get multiple back wall reflected echoes from the part. It is required for the part to have parallel faces.
3. Select two echoes after taking away three times the near field distance, for example, two echoes correlated to three times the near field distance and six times the near field distance (or four times the near field distance and eight times the near field distance). Find the decibel difference between these two echoes.
4. Subtract a fixed 6 dB from the amount of decibel difference found in step 3.
5. Divide the difference found in step 4 by the round-trip distance between two selected echoes. This ratio is the attenuation coefficient for the material under test at that specific ultrasonic frequency.

Following the same procedure for a piece of brass, for example, gives a higher value of approximately 0.14 dB/mm (3.6 dB/in.).

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**Figure 2.** Diagram showing simple set up and the receiving ultrasonic echoes: (a) an ultrasonic transducer on the part being tested; and (b) a graphic representation of a calibrated ultrasonic flaw detector display showing multiple reflected echoes.
Correction

On page 3 of the April 2017 issue of The NDT Technician, the listing of references for the Focus article “The Role of Integration in NDT Quality Assurance Chain” by Peter Brunengraeber and Ajay Pasupuleti was not printed. The references are listed below. The NDT Technician regrets this error.


Professional Connections allow companies to showcase their business cards. Check out the various products and services on display each issue to see what may be of value to you.
Michael L. Carrier is the senior nondestructive inspector at Textron Aviation. He is an ASNT NDT Level II in UT and MT, and is pursuing Level II certification in PT and VT, as well. Carrier is a graduate of the NDT program at the Southeast Community College, Milford in Nebraska, and is a member of the Air Capital Section.

Q: How did you begin your career in NDT?
A: I first became involved in NDT in 1989. I really didn’t fit the four to six year college degree mold, so I opted for a trade school to obtain a skill. There were a few people from my hometown that attended Southeast Community College, Milford in Nebraska, and I knew that it would be a good fit for me. I started my career in the petrochemical field and have advanced from there, working in the energy sector briefly and aviation for most of my career.

Q: Can you tell us about your certification and training?
A: Most of my training has been on the job, gaining hours and experience. Books can only teach you so much. Hands on experience is where you gain most of your knowledge. Theory is good to a certain degree, as it helps you understand what is going on with the particular method you are using. But most of the day-to-day functions require some sort of interpretation you can’t find in text. I do currently hold ASNT Level II certifications in UT and MT. Currently I am working toward obtaining Level II certifications in PT and VT.

Q: Describe the work you do. What are the most valuable methods in your job?
A: A typical day consists of inspecting metal bonded parts using automated ultrasonic through transmission, as well as hand-held resonance equipment for compliance to my company’s specifications. I perform inspections regarding eddy current crack detection and ultrasonic material thickness on reworked parts. Also, I inspect non-conductive coatings on aircraft to prevent damage or failure due to lightning strikes. I also perform visual, magnetic particle, and penetrant inspections on welded assemblies. The most valuable methods in my job are all of them, from VT, PT, MT, UT, ET, and RT. Each has its place, and one is no more important than the other.

Q: What is your working environment?
A: I work in a production/factory environment currently. My job consists of inspecting assemblies from the beginning of the process until the jet goes to the customer for delivery. I have had supervisory roles as well as hands-on roles. I prefer the hands-on jobs because it keeps me fresh and up to date. A technician can read all the articles about methods and developments in a certain discipline, but when you actually put it into practice, that’s when you find out if you have the skills to do the job. A former supervisor of mine, Werner Yzelman, is incredibly intelligent. He has the ability to translate his knowledge into practical applications and transfer his knowledge from the drawing board to the field. I admire him for that.

Q: What advice would you offer to individuals considering careers in NDT?
A: I would say to anyone coming into the field to get as many certifications as you can. Don’t be afraid to get dirty. Experience is gained on the shop floor and in the field. Don’t be afraid of it. Embrace it. If you try something and it doesn’t work out, fine. Just because you fail doesn’t make you a failure. If you choose this career and work hard at it, the future is limitless. It can take you all over the world. Also, you will have a skill that is in demand for most of your life. Network with anyone and everyone you can. You never know when the next great opportunity will come your way.

Michael L. Carrier can be reached at mcarrier@txtav.com. More of Michael L. Carrier’s interview can be found at http://tc.asnt.org/pro/b/practitionerprofile.
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