

Progress in NDT System Engineering Through Sensor Physics and Integrated Efficient Computing

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Abstract

Nondestructive testing (NDT) system engineering is comprised of different technologies, primarily measurement physics, computing, electronics, mechanical engineering and automation. Significant progress in sensor physics, microelectronics and computing in the last decade will change both the quality and application of NDT. We present examples of intelligent sensor technologies and integrated, efficient computing structures for signal processing. Keywords: Sensor-on-chip, Quantum Physical Sensing Effects and efficient scheduling of Optimized Algorithms including ill-posed problems. Our first systems designed on these principles allow for high-speed imaging with real-time quantitative assessment of inspection results. Multi-sensor systems, which communicate and combine their information for smarter processing, have also been developed. These principles will contribute to the current efforts in process integrated NDT, quantitative NDT and Structural Health Monitoring (SHM). We discuss ultrasonic inspection systems featuring distributed apertures, the use of optimized algorithms and computing structures for the processing of microwave and thermal data, and the health monitoring of lightweight structures with integrated ultrasonic sensor networks. Keywords: QNDT, Signal Processing, Imaging, Sampling Phased Array, Nano-NDT Agents, Microwave Imaging, Pulsed Thermography.

1. Introduction

Nondestructive testing systems are not mass-produced products. They are usually

adapted to specific applications such as manufacturing inspections, process-integrated inspections and in-service inspections related to service and maintenance procedures. The small number of marketable systems and the specifics of individual test requirements lead to high engineering expenditures at low and often fluctuating sales volumes.

The development of NDT systems is therefore only efficient if a development architecture, in the form of system modules that allow the integration of technologies and components previously developed for analog measurement tasks, can be used to service high sales volume markets or positive “return on investment” sales.

Examples of such markets (which can be regarded as drivers for the development of the technology of measuring systems) are medical technology, automotive electronics and information technology. Significant progress has been obtained through the availability of highly-integrated microelectronics, digital technology and modern computer technology.

Having control over thin-film technology permits the use of new quantum-physical measurement effects with sensors that are capable of being integrated into micro-electronics for signal excitation and signal processing. This technology has been termed “sensor-on-chip”.

Presented below are examples of recent progress achieved in the development of NDT systems. The emphasis is on “efficient integrated data processing” and the employment of new sensors, addressing the present range of NDT applications.

Table 1 below matches practical technologies and their application range for selected examples. In addition, the architecture of a development platform for NDT systems, which permits wide-ranging application of its modules for specific test systems, thus covering the development expenditures of the module, is indicated.

Table 1. Examples of Current NDT System Developments

	Material & Structures	Manufacturing Process Control	Structural Health Monitoring	Assistance & Security
Sensor Physics			Nano-NDT Agents	
Computing	Ultrasonic Tomography			Microwave Imaging
Robotics		Stray Flux Scanner		

In the past three years we have established development platforms for UT, X-Ray and electromagnetic test systems ^(1, 2, 3); developments for thermal techniques and microwave techniques are underway ⁽⁴⁾.

2. Ultrasonic Tomography

For practical applications, ultrasonic test systems are of great importance since these

systems can detect enclosed cracks, laminations and separations in the material volume. Although significant efforts have been made towards imaging techniques, the evaluation of test images such as A-Scan, B-Scan and C-Scan is limited to a large extent to the expansion of connected reflectors and their maximum amplitude height related to reference reflectors such as disc shaped reflectors (DSR), side-drilled holes (SDH) and notches for surface connected flaws. References to flaw type and flaw size can only be attained through indirect and often inaccurate complex analysis measurements ^(5, 6).

The application of modern Phased Array techniques principally allows for a sufficient coverage for the detection of planar flaws with oblique positions. However the scan time necessary is a considerable problem since the transducer must be excited for each individual incidence angle and the focus adjusted for each flaw depth in the volume to be examined (in principle limited to the near field by aperture size and transducer frequency). The SAFT technique (Synthetic Aperture Focusing Technique) permits for larger effective apertures but provides much less test information compared to the test information delivered by a multi-element transducer system as used in Phased Array technology ⁽⁷⁾.

The development of the Sampling Phased Array technique with the option to select and position individual transducer elements in any aperture order and under violation of the Sampling Theorem ⁽⁶⁾ allows for a fast, high-resolution reconstruction of flaw indications. The sound field can also be synthetically focused if required (for large material depths). To satisfy standard codes and requirements, the A-Scan images can be calculated and processed for any incidence angle. The images can currently be reconstructed at a pulse frequency of 10kHz allowing this technology to be used at high testing speeds.

Similar principles have been used since the 90's for medical ultrasonic diagnostic systems ⁽⁸⁾. However, funds available for this development were of another order of magnitude. Today's state-of-the-art signal processing based on efficient processing methods, optimized processing algorithms and the management of large data volumes in real-time permits the design of a development platform for ultrasonic systems ⁽¹⁾.

Figure 1 below shows the architecture of such a platform. The core components are the micro-electronics which consist of ultrasonic channels of an arbitrarily expandable number. In principle, each ultrasonic channel can be operated as an independent ultrasonic instrument.

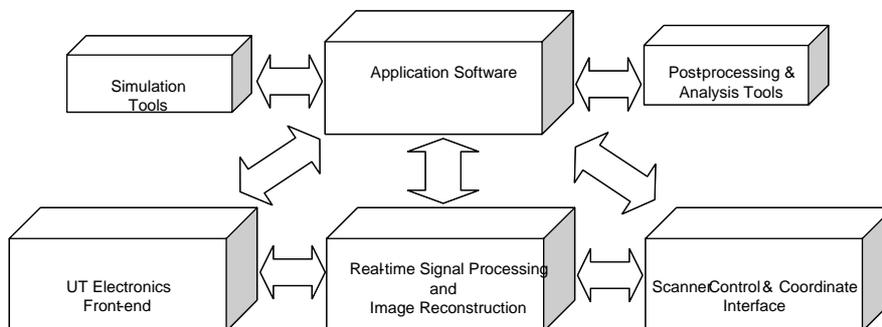


Figure1: UT Platform Architecture

Transmitting and receiving of all ultrasonic channels can be configured as required e.g. as a conventional multi-channel setup or as a Phased Array system. In the sampling mode, all time signals of the individual channels are processed into high-resolution ultrasonic images.

Figures 2 and 3 show the attainable advantages of the Sampling Phased Array technique with distributed apertures.

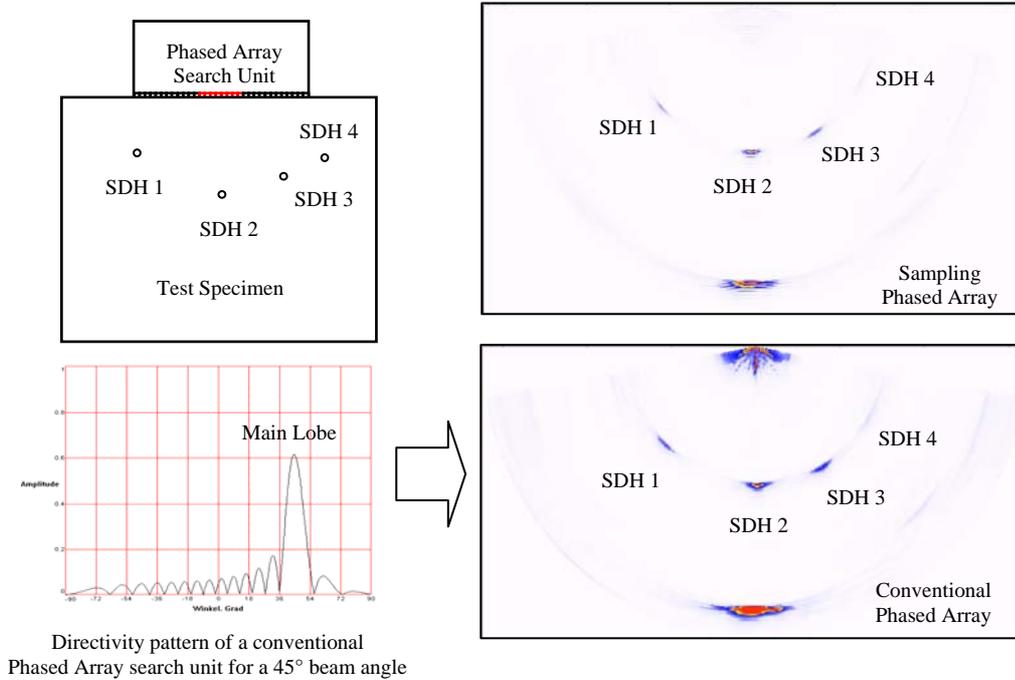


Figure 2. Ultrasonic Imaging, adhering to the “Sampling Theorem”

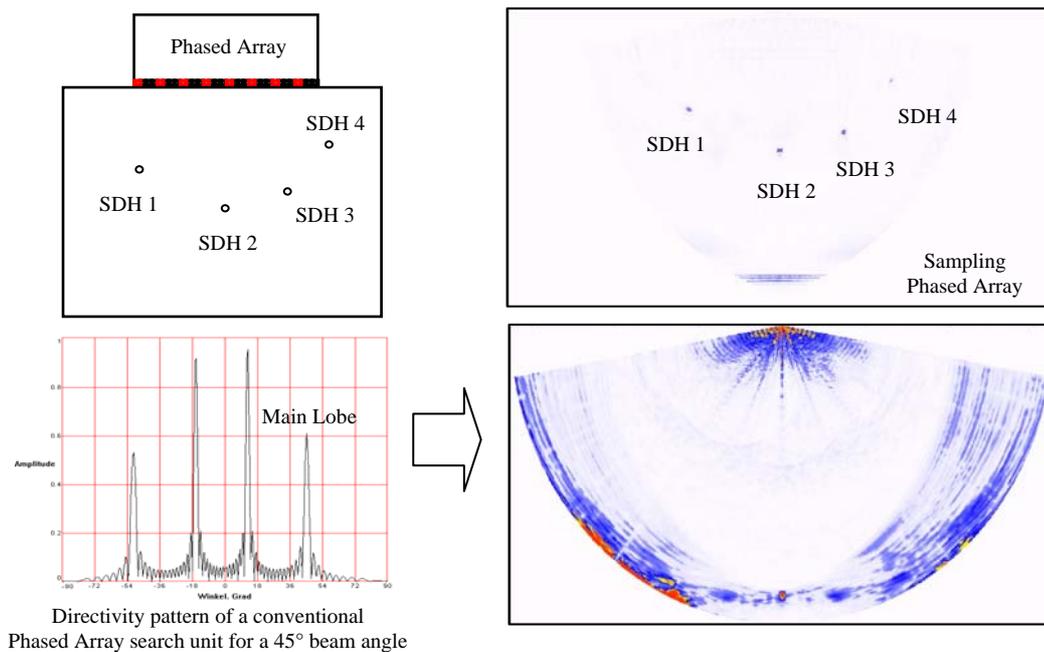


Figure 3. Ultrasonic Imaging with Distributed Aperture

2.1 Efficient Computing

Several hardware and software technologies available on the market can be used to generate these types of ultrasonic images in real time. The border between hardware and software has recently become fluid as microelectronic components increasingly grow to be “more intelligent” and contain numerous capabilities previously attributed to software components.

Tools for simulating ultrasonic propagation, image reconstruction, image evaluation and image presentation are essential for a fast ultrasonic-imaging technique using the Sampling Phased Array. Due to physical measurement requirements, all test data of all selected channels have to be acquired in parallel and must be available in a structured form for further processing. This requires fast data links since the complete package of RF data has to be transferred to the reconstruction module.

The transfer of these huge data packets of several G-bits per seconds presently requires non-standard solutions such as “Multi-Link G-bit Ethernet”, “Routed Fiber-channel Link”, or “Multi-channel LVDS”. These methods can be used for device-to-device and on-chip upstream/downstream data transfers.

The use of look-up tables permits the simplification and acceleration of the image reconstruction process but requires larger storage capacities. An architecture with distributed memory, supporting “ping-pong” read/write operations, is a relatively robust solution. This architecture avoids the blockage of reconstruction calculations during memory operations.

Two promising approaches for real-time ultrasonic tomography are currently being considered: Graphics Processing Units (GPU) and Field Programmable Gate Arrays (FPGA).

2.1.1 Graphics Processing Units

Graphics processing units are high-performance devices with a number of on-board texture processors (TP). Each processor includes a texture memory and streaming multi-processor units (SM). Each streaming multi-processor contains a command cache, data cache, command processor and a multi-processor shared memory as shown in Figure 4. Thus, by using GPUs, truly multi-threading devices are available.

A challenge for software developers is to distribute an algorithm into thread-blocks and to schedule and execute them onto the GPU. For that reason the CUDA language was developed.

In general, GPU are not real-time devices since the PCI-like bus is the only available interface for the data to be processed.

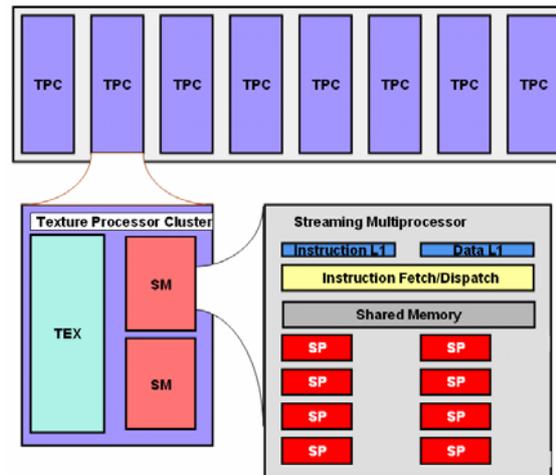


Figure 4. GPU Architecture

2.1.2 Field Programmable Gate Arrays (FPGA)

FPGAs are multi-purpose reprogrammable high-integrated chips. Nowadays, there are a large number of software-assistants available to organize almost any computational structure on the chip. The assistants include processor units, digital signal processors, data interfaces (optical, Ethernet, FireWire, PCI-bridges), on-chip cache, DDR controllers, and many more.

Because of their high flexibility, the maximal clock frequency is much lower than in GPUs. However, the FPGA user can optimize the command pipeline and a branch prediction for a given scientific task and is able to parallelize computation process. Since modern FPGAs are equipped with multiple interfaces, raw data can be received and processed in real-time.

2.2 Inspection of Anisotropic Materials

A very promising application of the Sampling Phased Array technology is the inspection of light weight materials for the aircraft industry. Carbon reinforced composite materials offer excellent mechanical properties in combination with low weight but represent one of the most complex inspection objects for ultrasonic testing.

Figure 5 shows a 3-dimensional image of a carbon fiber specimen with artificial delamination, a typical material discontinuity of such materials. The Reverse Phase Matching technique⁽⁹⁾ allows assessment of the anisotropic properties of multilayered carbon fiber structures and provides a high quality tomography image of the area of interest in real-time. Images of this quality open the door for quantitative NDT on one of the most complex and safety relevant inspection objects.

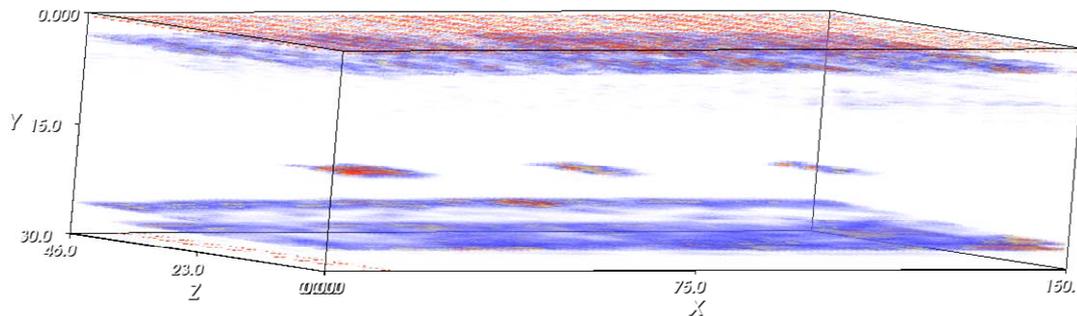


Figure 5. 3-D Reconstruction of a Carbon Fiber Structure with Delamination

The next steps to the imaging of flaw geometries require dissolving of the ultrasonic signals, which are composed of several scattering sources ⁽¹⁰⁾. The continuing progress of faster computer technology provides the necessary solution for real-time processing in the very near future.

3. Magnetic Particle Method

Magnetic particle testing (MT) is one of the most widely applied nondestructive testing methods for the detection of surface connected flaws in carbon steel (ferromagnetic) materials. A crack at or near to the test surface causes a magnetic flux leakage field, which can be used to detect and confirm discontinuities ⁽¹¹⁾.

Conventional MT procedures use the dry method where powders containing ferromagnetic particles are applied. The alignment of the powder along the crack is usually obtained visually by a qualified and certified examiner; however, automated systems employing cameras and image processing techniques ⁽¹²⁾ have been in use for quite some time.

An alternative approach for automated magnetic particle testing is achieved by the employment of magnetic field sensors, which have to be adapted to the test problem with regard to their basic sensitivity, dynamics and aperture ⁽²⁾. Handling techniques of this method are characterized by economic efficiency, robustness and reliability and short inspection cycles. This approach can involve the deployment of sensor arrays. A particular advantage of such sensor-supported flux leakage testing techniques (SensorFlux) is the ability to precisely document the inspection results for each individual test sample. In addition, a robotics-supported automated inspection technology can be customized and integrated into production-line and/or assembly-line processes.

IZFP has designed a development platform for “SensorFlux” testing systems ⁽²⁾, which permits the selection of different types of magnetic field sensors e.g. Hall sensors, Foerster probe (Fluxgate-Magnetometer) and new sensors that exploit quantum-physical effects, such as the GMR (Giant Magnetic Resistor) effect at the boundary surface of thin layers. GMR allows for a simple wiring of the sensor resulting in a small size sensor design. GMR sensors are fairly insensitive to external interference from temperature variations and electromagnetic sources. An additional advantage is the sensor’s high sensitivity (a few nano Tesla) allowing the detection of cracking at the same or better sensitivity when compared to conventional magnetic particle testing ⁽²⁾.

Parts with complex surface geometry, such as gear racks, must be frequently examined for surface connected or near surface discontinuities. Here, modern inspection procedures require the use of robotics modules that are available on the market for automated production processes. Figure 6 depicts the architecture for the integration of robotic modules into a testing system. The intelligent and interactive interfacing between robotics and inspection technique is of utmost importance for inline control of the sensor deployment.

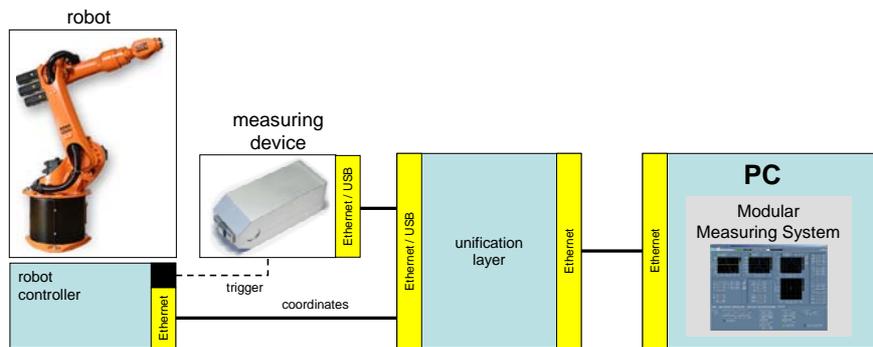


Figure 6. Architecture of Robotic NDT Systems

The use of sensor arrays permits inspection cycles at one second increments but require sensitivity balancing of individual sensors. Figure 7 below shows an example of how continuous automatic sensitivity balancing can be achieved: two sensor rows rotate over the test surface with their center proceeding linearly in the test direction. The helical path of the individual sensors lead to intersecting points, where the sensitivity of the individual sensors can be automatically balanced by comparing measured values ⁽¹³⁾.

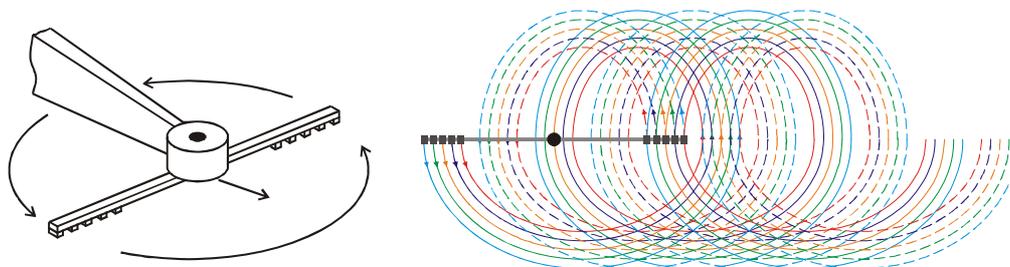
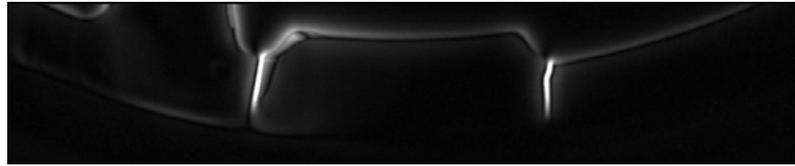


Figure 7. Principle of Automatic Test Sensitivity Balancing of Individual Sensors of a Sensor Array at Sensor Intersection Points

Figure 8 below demonstrates the results of an examination for surface cracking.



Photograph



Magnetic Flux Leakage

Figure 8. Surface Inspection Result

4. Pulsed Thermography

Pulsed Thermography (PT) testing systems are increasingly deployed in day-to-day industrial practice. These systems offer the advantage that the sensor system is not in contact with the test surface allowing use for the inspection of high-temperature parts. Furthermore, this technology can be used for a wide range of material types; specific parameters such as heat conductivity and emissivity must be considered and defined to permit the detection of the specified discontinuities⁽¹⁴⁾.

Although the physics of thermography testing methods is based on the phenomenon of heat diffusion, principles from wave physics can be applied to pulsed thermography. The heat pulses propagating in the test object are reflected at the boundary layers of the test object and can reveal discontinuities such as delamination, inclusions and cracking.

Figure 9(c) shows a typical thermography image of a PVC (Polyvinyl Chloride) plate with artificial flaws (Figure 9(a)). The test image was post-processed from 188 individual infrared images at a resolution of 256x256 pixels. The unprocessed infrared image is shown in Figure 9(b).

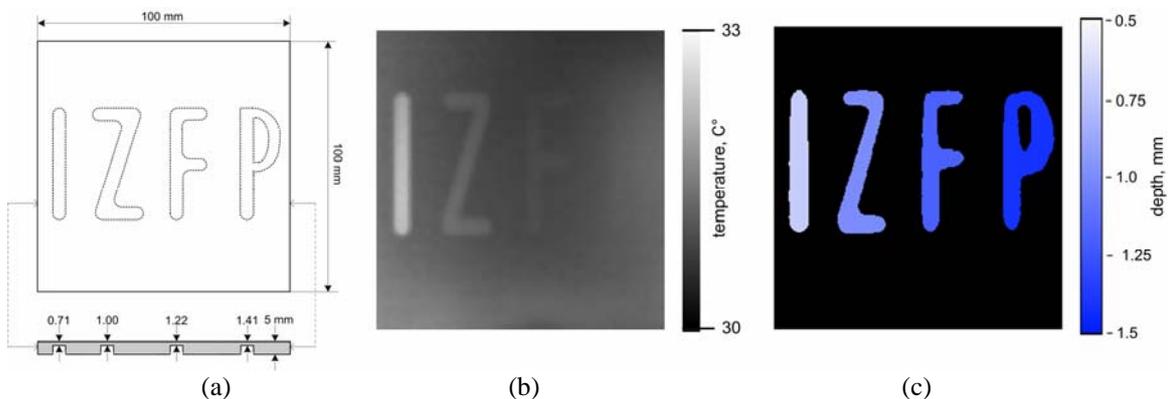


Figure 9. (a) PVC plate; (b) Thermal Image (unprocessed) from the measured image sequence (N=35); (c) Reconstructed Image of the PVC plate.

The challenge in Pulsed Thermography is the accurate reconstruction and evaluation of the actual shape of the discontinuity. Measurement conditions, heat-up and cool-down processes, available a priori information and statistics about discontinuities and tested material properties have all to be taken into account. The corresponding computational schematic is shown in Figure 10. The raw data as well as the a priori information are supplied into the computational block. A computational loop comprising of simulation and shape correction units is used to match iteratively input data and simulated data ⁽¹⁵⁾. Such a method helps to reduce miscalculations caused by external factors and eventually provides robust quantitative images, as seen in Figure 9(c).

The method presented in Figure 10 is complex and requires much more computational resources than are offered by FPGAs, for example. The iterative procedure for matching measured and simulated data does decrease the processing speed of the computation. To remedy this deficiency, a high-frequency floating-point processing approach has to be applied. An ideal solution would be distributed computing that supports multi-processor multi-core architectures. Under these conditions, the matching task can be performed independently by the individual CPU's and then synchronized by means of messaging interfaces.

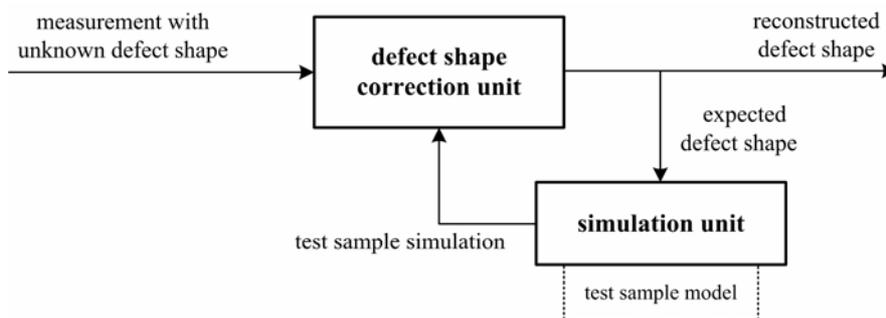


Figure 10. The structure of the iterative reconstruction algorithm ⁽¹⁵⁾.

At this time, real-time Pulsed Thermography performance is limited by the ability of CPUs to receive the data from the hardware through currently available interfaces. We look forward to working with improved interfacing technologies in the future.

5. Microwave NDT

The current state-of-the-art of microelectronics allows an economical design of microwave transmitters, receivers and antennas with wavelengths in the millimeter range. This allows the use of microwave techniques for the inspection of materials and for process control if the material dielectric characteristics are sufficient to supply adequate contrast. In combination with technologies such as optical techniques, the application of corrosion protective coatings for piping systems, for example, can be easily controlled ⁽¹⁶⁾.

Microwave NDT systems are also suitable for security related applications.

Electromagnetic waves in the centimeter and millimeter range are capable of penetrating clothing discovering dangerous and illegal objects such as explosives, weapons or drugs. However, real-time two-dimensional and three-dimensional imaging at sufficient resolution is the current challenge of system engineering. Modern approaches use multi-sensor systems based on the known principles of effective apertures. The measured data are processed by efficient synthetic aperture focusing technique (SAFT) algorithms.

An example of 2-D SAFT imaging is shown in Figure 11; a ceramic knife with plastic handle concealed under clothing.

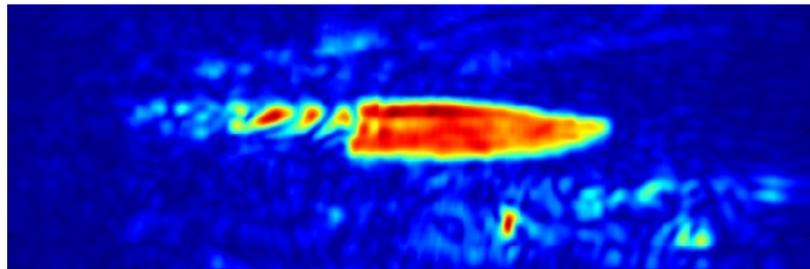


Figure 11. Two-Dimensional SAFT Imaging of a Ceramic Knife

As of today, millimeter-wave technology offers a number of sensors for NDT and security applications. These include Doppler Sensors, Frequency Modulated Continuous Wave (FMCW) Radars, Pulse Radars, and many more. A high-integrated FMCW radar, developed by the Fraunhofer-Institute for Applied Solid-State Physics (IAF), is shown in Figure 12.

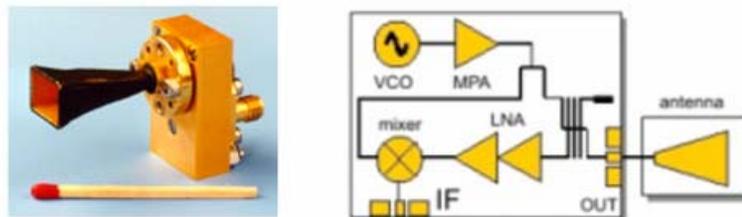


Figure 12. FMCW Radar (94 GHz), left; FMCW Radar Circuit, right

This radar includes an in-built oscillator, wave guide, mixer and connectors for external antenna and power supply, see Figure 12 (left). The sensor operates at a frequency of 94GHz. The sensor allows focusing at various distances; the synthetic aperture algorithms can be applied for the reconstruction of the volume of interest.

Three-dimensional real-time microwave imaging has only become viable through recent achievements in electronics and processing algorithms. Parallel data acquisition of multiple radar channels and the need for the reconstruction of the volume at high resolution lead to massive data streams and high computational demands.

In general, SAFT processing of microwave data is similar to the processing of ultrasonic data. The main differences are: data filtering, hardware linearization and

some additional mathematical transformations. Thus, each stage of the three-dimensional real-time microwave imaging, namely, data transmission, volume reconstruction and image processing can be done by using fast data transmission links, FPGAs and GPUs, as discussed above.

Special attention has to be paid to the visualization phase and image processing for microwave imaging. For microwave imaging the area of interest is the pattern recognition in a volume (for example recognition of hidden weapons and illegal objects) and characterization of the detected objects, for example, plastic, metal, glass, explosives, etc.. Such data processing has not been accomplished and will certainly require special engineering solutions and further optimization of algorithms and computing structures.

6. Nano-NDT Agents

Corrosion and degradation of material surfaces usually takes place due to the environmental chemistry. Recently developed techniques for decreasing corrosion rates and improving the lifetime of materials and devices are available. Some of these techniques incorporate nano-structured materials processing approaches. These include surface treatment methods, nano-composite thin film coatings, top layer coatings and thermal barrier coatings.

Generally, nano-particle based coatings can, depending on size, composition, distribution, etc., improve corrosion and wear resistance. They facilitate good adhesion of paint on metals and increase hardness and lifetime of the coatings⁽¹⁷⁾. Furthermore, nano-particle coatings often exhibit self-healing characteristic. Nano-diamond particles as well as chemical compounds, e.g. SiC, ZrO₂, Al₂O₃, SiO₂ and TiO₂ are commercially available. Nano-containers loaded with corrosion inhibitors, such as benzotriazole, can be used as an active coating, responding to changes in the local environment⁽¹⁸⁾.

Through multi-level chemical modification of the surface, nano-particles can monitor for corrosion. These modified particles (nano-agents, see Figure 13) can be deposited using chemical methods from sols (suspensions of solid particles) with dip and spray coating or with electro-phoretic deposition.

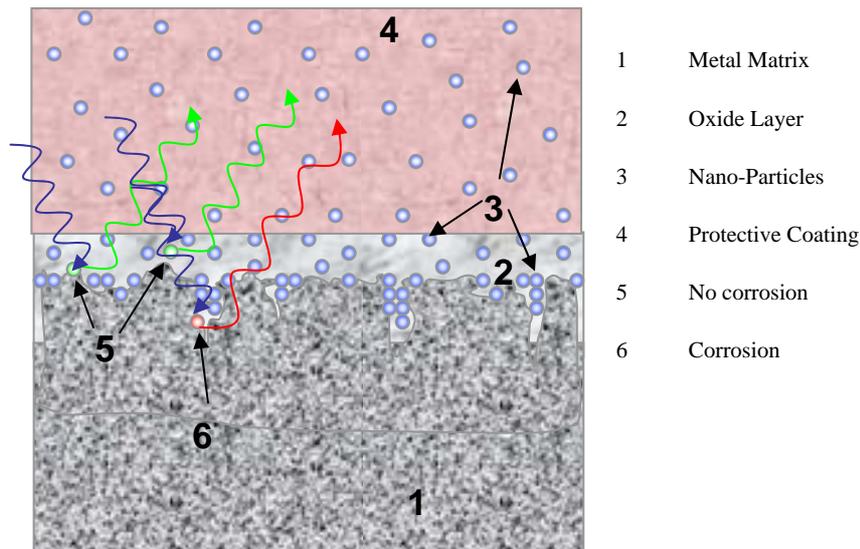


Figure 13. Self-Healing and Corrosion Monitoring using Nano-Agents.

The corrosion locally alters the characteristic parameter of the nano-agent (for instance the wavelength of the emitted light). Fluorescence signals can be easily measured with an optical measurement system. In first studies on aluminum alloys with modified nano-diamond particles, we have been able to demonstrate and prove this corrosion monitoring technique.

Thus, nondestructive corrosion monitoring and inspection can be easily performed on large-area applications such as aircraft components. In addition, this NDT application demonstrates that the “smart” implementation of NDT can also improve product quality and extend the lifetime of products.

7. Conclusion and Future Perspective

With the examples presented in this paper, we have demonstrated the tremendous benefits that recent advances in science and technology have provided for the design and development of NDT systems. All of these new technologies were originally developed for other purposes.

The NDT systems designer has the important task of assuming control over these new technologies at the right time. The right time is defined by the development risks including the development costs to make the technologies available for NDT applications. Modular structured development platforms that allow further development of individual components will be instrumental.

The ongoing “Nano-NDT Agent” project clearly demonstrates that completely new NDT approaches can be pursued for the examination of materials and components, in particular, when conventional methods and procedures are only conditionally applicable or not applicable at all.

Development costs, in our judgment, are worthwhile for preventative service and maintenance procedures, which, if neglected, may result in high replacement expenditures and costly downtime.

The current project for the development of security and access controls shows that NDT systems are suitable to help securing the human environment. The large market for systems supporting human actions and activities and protection against crime and terrorism may become the breeding ground for the advancement of NDT systems.

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