THE POTENTIAL AND NEED FOR NDT INNOVATIONS

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Abstract: Usually, innovations in NDT are part of many main-stream, state-of-the-art development efforts in science and technology and applicable regulations, codes and standards often significantly slow down the development of innovative products. Fortunately, the world is changing. The formation of global markets, mobility of production, and effective international scientific networks are accelerating the dynamics of innovations pushed by a new dimension of application demands.

In this presentation, we outline these challenges for NDT scientists and engineers along the value-added chain of producing and operating technical products and systems. We start with the contribution of NDT to the development of new materials and the control of production processes by integrating smart-sensors with feedback capabilities. We also discuss the impact of new maintenance and lifetime-extension management strategies, such as risk based applications and health monitoring. The growing demand for techniques that support human activities to make life safer and more secure also poses challenges and presents opportunities for new contributions from the NDT community. We conclude that the market is open, growing, and ready for NDT scientists to move forward and meet these demands.

Introduction: By pushing forward we can take advantage of new technologies and new sensor physics that offer unique opportunities for the development of new methods and techniques, resulting in new NDT products. We consider the use of micro-technologies, including structures with limited dimensionality and integrated computing power, as essential. We present examples of sensor-on-chip technologies, smart-sensors, and system-integrated NDT. Computing provides an advanced and precise understanding of the physical principles of NDT through modeling and simulation. NDT will become more reliable, adding quantitative results of which material and component designers can take advantage. We believe that these improvements will bridge the gap of modern fracture-mechanics and NDT for an advanced component assessment and lay-out. NDT has approached the nano-dimension since nano-structures determine material properties and functions. However, the given examples also demonstrate the challenge of transferring scientific and laboratory results into the industrial practices of the NDT community.

To become more effective, NDT scientists and engineers have to respond to the new concepts of cooperation networks. We have to expand our abilities for system engineering to understand the demands and to organize the required qualifications and technologies. A new dimension is added by the globalization of markets, products, and technologies. We will use existing design and technology platforms to create new NDT techniques and applications that are transparent and internationally accepted, but specific in respect to the domestic market. Consequently, we need long-term international partnerships that will also accelerate the innovation dynamics by combining available knowledge and resources.

We appreciate the valuable and productive cooperation between the organizations contributing to the presentation.

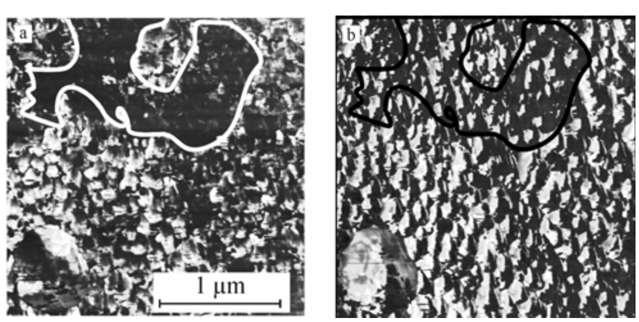
Global Framework – Global Partnerships: Ongoing globalization of markets, technologies, and production is challenging the NDT community for new effective international structures to meet new requirements pertaining to quality, safety, and reliability while minimizing production and life-cycle costs. This is reflected in the NDT community through the harmonization of standards (safety, quality, security) for global products and technologies applied and through integrated networking. In science, public research centers try to cope with this challenge by establishing integrative knowledge pools. Thus, the World Federation of Nondestructive Evaluation Centers (WFNDEC) was founded at Snowbird, Utah, in July of 1998. Partners from Argentina, Belarus, Brazil, China, Germany, India, Korea, Poland, Russia, South Africa, Taiwan, Ukraine, United Kingdom, and the USA may organize cost-effective ways to pursue pre-competitive, cooperative NDE research including opportunities for exchanging faculty, students, and scientific personnel. Some valuable support is granted by the International Committee for Nondestructive Testing (ICNDT). ICNDT, as a non-profit organization, is contributing to the international progress in science and practice of nondestructive testing, supported by national NDT societies and their international federations. Special working groups have already been organized targeting harmonization of certification, internet communication, standards for technical procedures (such as equipment calibration), education programs and research support.

In the same spirit, the authors are enjoying their partnership that benefits from sharing resources and knowledge. We are aware that partnerships, information and adaptability are needed to contribute to the highly-dynamic global innovation system (1).

Problems: NDE Science and Engineering is experiencing problems that require new tools. Only a few of these problems will be highlighted, such as the use of Micro- and Nanotechnologies, modern computing and information systems that also result in new engineering concepts. In addition, our societies have to tackle problems caused by significant structural and cultural changes such as maturing societies and terrorism.

Limitation of Dimensions: Engineering has already exceeded the common range of tangible dimensions. We are enjoying products based on the progress in Nano-Technologies in our everyday life. However, problems concerning product quality, safety, reliability and life-time are unchanged.

A View into the Nano-World: A direct approach is the high-resolution NDE that allows imaging of Nano-Structures. We can probe the nano-world using nano-scopes such as Force Microscopy. The reusability of samples and NDE-like applications, characterizing materials and structures might define the difference between Microscopy and Micro NDT.
The development of the Atomic Force Microscopy (AFM) enabled us to execute experiments on a nano-scale. Next to the operation modes allowing topography measurements, e.g. contact mode and tapping mode, other techniques have been developed. With help of AFM-based techniques it is possible to image other properties, such as friction (Friction Force Microscopy), elasticity (Force Modulation, Pulsed Force Mode, Ultrasonic Force Microscopy) and magnetic (Magnetic Force Microscopy) and ferroelectric domains (piezo-mode techniques). Atomic Force Acoustic Microscopy (AFAM) and Lateral Atomic Force Acoustic Microscopy (Lateral AFAM) are dynamic modes of AFM that combine the high resolution of AFM with the enhanced sensitivity of a vibrating cantilever to elastic properties of a sample surface. AFAM and lateral AFAM can be applied in spectroscopic and in imaging mode (2). In the spectroscopic mode, the bending and the torsional contact resonance frequencies are measured, from which the vertical and lateral contact stiffness can be determined. In addition, adhesive and friction forces have a pronounced influence on the shape of the measured contact-resonance spectra. In the imaging mode, the AFM cantilever vibrates at a frequency close to the contact resonance frequency and the amplitude of the vibrations changes with the local tip-sample contact stiffness. Using the amplitude of cantilever vibrations as contrast provides qualitative images of changes in the tip-sample contact stiffness. The bending and torsional modes can also be excited in the so-called piezo-mode. Analyses of cantilever vibrations, originating from this mode, provide information about out-of-plane and in-plane piezo-activity, for example in ferroelectric domains, see Figure 1 (3).



a) b)

Figure 1: The ultrasonic piezo-mode images obtained on a PTC sample, annealed at 650 °C; this sample was fully crystallized. The bright islands separated by dark areas can be distinguished in the image obtained at the first bending contact mode (a). When the same area was imaged with a torsional mode, an additional structure appeared whereas the bending mode showed no contrast (b). This proves the presence of in-plane oriented domains in the PTC film annealed at 650 °C.

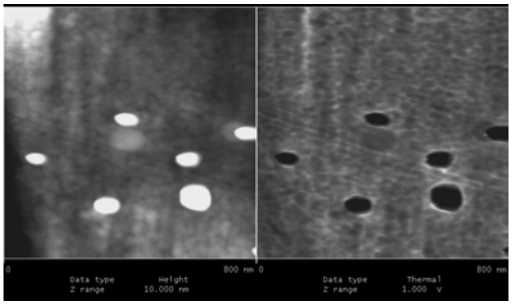


Figure 2: AFM (left) and UFM (right) images of nano-precipitations in Al 7075-T6 [4].

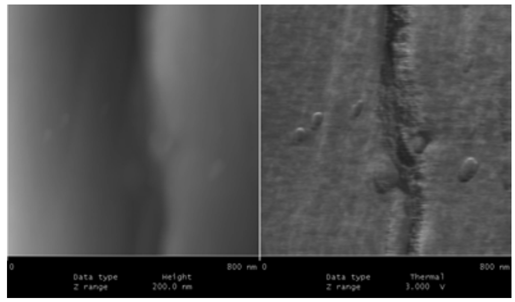


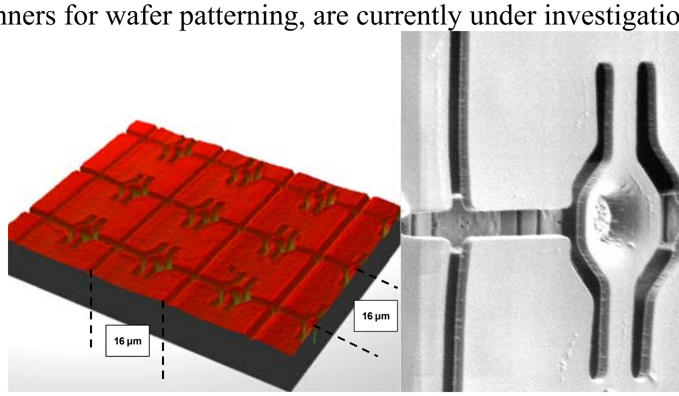
Figure 3: AFM (left) and UFM (right) images of interaction of a crack and nano-precipitations in Al 7075-T6. The crack path is modified by the two large precipitations [4].

Gunier Preston zones and nano-precipitates are imaged at monolithic samples of hardened Al alloy (see Figure 2). This material was selected as a model substance on nano-reinforced composite material. The interaction between such precipitates with propagating cracks (as shown in Figure 3) can be initially studied using this method to understand the fracture behavior of nano-materials (4).

Inspection of Micro-Systems: The increasing number of new products manufactured in micro-system engineering and the growing number of industrial applications require new approaches to monitor the functionality of products like micro-fluidic devices or micro-opto-electro-mechanical structures (MOEMs).

Definite mechanical properties and stability of metallic parts of MOEMs are important for their reliability, especially for long-lasting and high-power applications. Reduction of the component sizes requires a considerable modification of the material properties (5). For example, a qualitatively new mechanical behavior was found for micro-structured metallic systems like Al- and Cu-strips.

Starting to strain such strips, they exhibit a behavior like a quasi-linear elastic chain coupled to a two-dimensional viscous media until the strain limit is reached and from which point on conventional 3D-elastic-plastic properties apply. The consequences of this behavior for mechanical stability, e.g. of micro-mirrors used in spatial light modulators of mask-less scanners for wafer patterning, are currently under investigation.



a) b) c)

Figure 4: Micro-mirror-chip in ceramic frame (a), white light interferometer image of the mirror array (b) and FIB (focused ion beam) image of an Al-blade at the hinge section (c).

To improve the metallic components of micro-mirrors to meet the requirements for their practical usage, NDT methods can provide valuable information, e.g. for the development of mirror materials. AFM- or FIB-inspections were used to evaluate the surface RMS and the mirror blade topography (see Figure 4). X-ray techniques were applied to analyze texture, stress and grain size (5) and nondestructive evaluation of structure relaxation was performed using resistance measurements (6). With the help of Laser vibrometer, the eigenmodes and short-time dynamics of mirror blades were investigated and provided valuable information on the switching characteristics of spatial light modulators (see Figure 5).

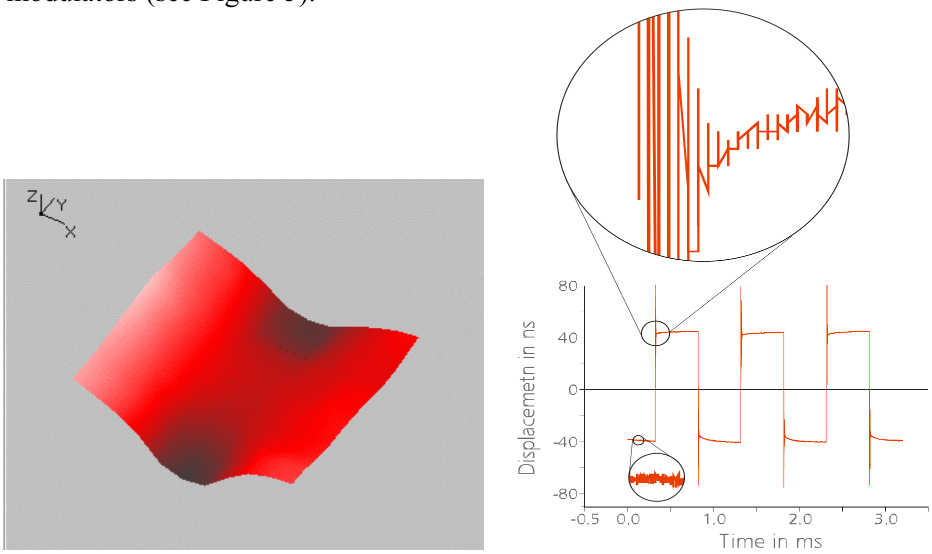


Figure 5: Butterfly mode (868 kHz, left) and short-time switching behavior (right) of an individual mirror blade detected by the Laser vibrometric microscopy.

Tools: Micro-Systems are challenging NDE inspection problems, but also provide valuable tools for innovative NDE techniques. Two trends will change NDT techniques – the use of new sensor principles and the integration of sensor, signal processing and computing into one micro-system.

New NDT Sensor Technologies: By reducing one or two dimensions of a structure down to nano-dimensions, we can design sensors that incorporate quantum physics. Thin film sensors are already used in NDT systems (e.g. GMR-Giant Magnetic Resistor) to probe magnetic fields (7).
Quantum well hetero-structures may more visibly demonstrate achievable improvements. They allow the precise control of status and motions of charge carriers in semiconductors (Figure 6), and thus, for example the efficient infrared light coupling to the quantum well (6).

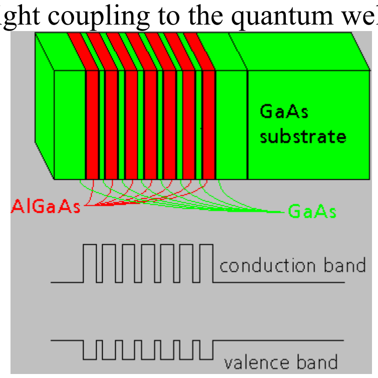


Figure 6: Schematic of epitaxial GaAs/AlGaAs quantum well layers on a GaAs substrate and resulting band-edge distributions

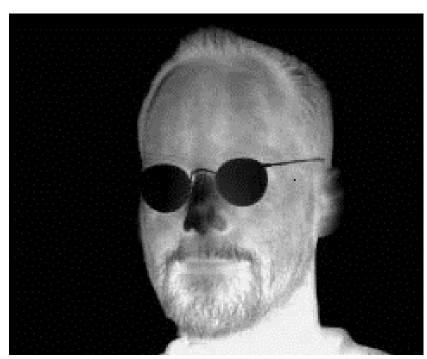


Figure 7: Image taken with a 512 x 640 pixel high-resolution thermal imaging-camera with only 7mK noise (8)

High-resolution thermal-imaging cameras based on QWIP arrays, developed by the Fraunhofer-Institute for Applied Solid-State Physics in Freiburg (7), achieve high- detection sensitivity, low noise, excellent temperature resolution and a high dynamic range (Figure 7). The maturity of GaAs-technology makes QWIPs particularly suitable for large focal plane arrays with high spatial resolution. In addition, due to the excellent lateral homogeneity, we achieve low fixed-pattern noise. QWIPs have an extremely small 1/f noise compared to inter-band detectors (like HgCdTe or InSb), which is particularly useful if long integration times or image accumulation are required. QWIPs are already successfully applied in surveillance, night vision, quality control, inspection, environmental sciences and medicine.

Computing and Communication: Due to the compatibility of technologies we will develop sensor systems with integrated high power computing capabilities. First steps are done to replace the traditional computer environment by FPGA technology. One FPGA, for example, can replace eight up-to-date PCs for high speed X-ray CT. The modified adjusted Feldkamp cone-beam back-projection algorithm could be processed through optimized scheduling of the reconstruction process (Figure 8).

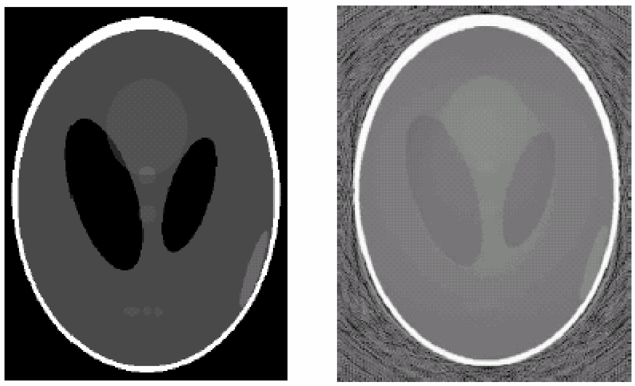


Figure 8: Reconstruction of the Shepp-Logan phantom. Left: rasterized phantom, right: reconstruction results (9).

An optimized computation scheduling will also permit sensor-system integrated signal processing in general and more specific it will allow the use of simulation codes and expert trained data banks for inverse problems, sensor-on-chip technology needs and communication support between locally distributed monitoring systems by telemetry. We have made the first steps towards robust micro-electronic devices down-scaled for sensor systems implementation. The German Association for Mechanical and Plant Engineering (VDMA) has specified Match-X (10).

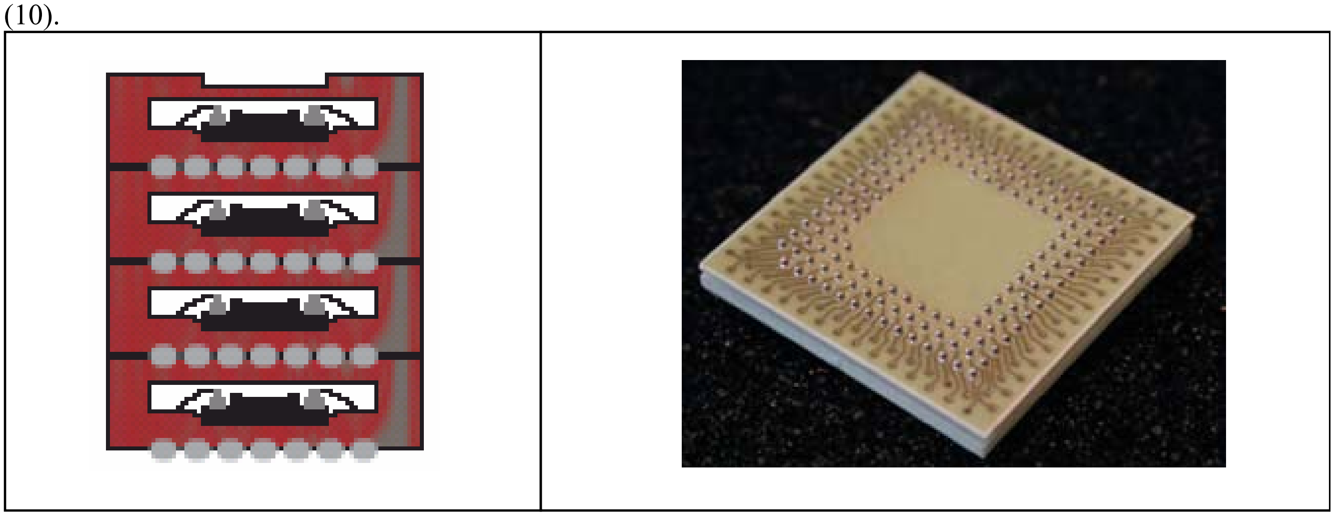


Figure 9: Principle design of a Match-X-system (left: with 4 components) and design of a single component (right).

Figure 9 shows MATCH-X components, developed for acoustic monitoring containing Digital Signal Processors (DSP) for filtering, down-sampling, FFT-calculations and correlation of processed data to component quality under inspection.

Concepts: New engineering concepts are under development for the improvement of functional capabilities in newly designed HiTe products. Along these lines, saving weight and energy consumption and increasing operational reliability of load carrying structures are the new challenges. New engineering concepts supporting these trends have emerged.

Terms, such as reliability management, health monitoring or life management of industrial plants and transportation means become more and more common and have developed as structured and defined areas of R&D and engineering.

These issues are of utmost importance for risk-management and plant life-management, or health monitoring (11, 12).

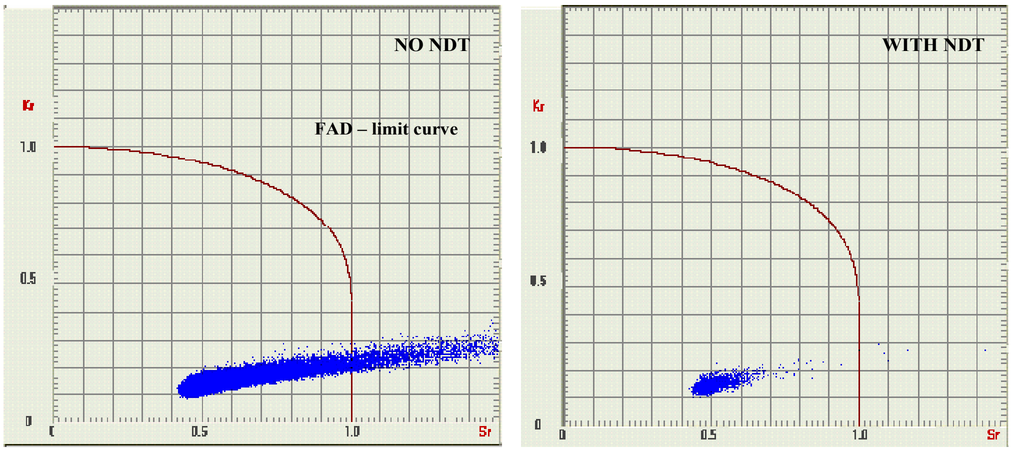


Figure 10: Effect of NDT on risk failure at 10.000 load cycles in a riveted joint (Al-alloy).

Figure 10 illustrates an example of Quantitative NDT (QNDT) and Probabilistic Fracture Mechanics (PFM) assessment of the value of applied NDT technology, where quality is defined by its POD as a function of flaw size. The example pertains to a riveted joint of aluminum alloy in an aircraft structure, and outlines the results of a probabilistic simulation of failure risk at the mid-life point of the joint with no NDT applied and compared to ultrasonic NDT applied. The increase in reliability of more than one order of magnitude is evident (Table 1). This example outlines the application of the "Failure Assessment Diagram – FAD" as failure criterion, a fracture mechanics concept commonly used and formalized in many national and international standards.

NDT	No. of Simulations	No. of detections	No. of non-detections	POD	No. of failures	Prob. of failure	Safety factor
Without NDT	1,000,000	-	-	-	5673	5,673 10-3	1.95
With NDT	1,000,000	942,887	51,113	0.9429	104	1,040 10-4	

Table 1 – Results of probabilistic NDT simulation on N the risk of failure of a riveted joint (Al-alloy) at its mid life point (safety factor 1.95).

Reduction of maintenance costs is the major driving force for developing condition-based maintenance concepts. For example, onboard networks employing smart and redundant sensor systems will be applied for the continuous monitoring of the aircraft while in use (13). Damages caused by continuous degradation or by impacts to the structure have to be quantified by analyzing the sensor signals. This, however, requires the understanding of the complex interactions of structure and physical parameters measured (e.g. ultrasonic plate wave propagation).

Detailed signal analysis for the network of active and passive sensors, modeling of the interactions of propagating waves with the structure and structural defects and modeling of the effects of the damage on the reliability of the structure are required in real-time for structure diagnosis and a decision as to whether maintenance is required or not. Networking of specialists that have the required skills might be a practical solution to solve this challenging task. Figure 11 illustrates this concept.

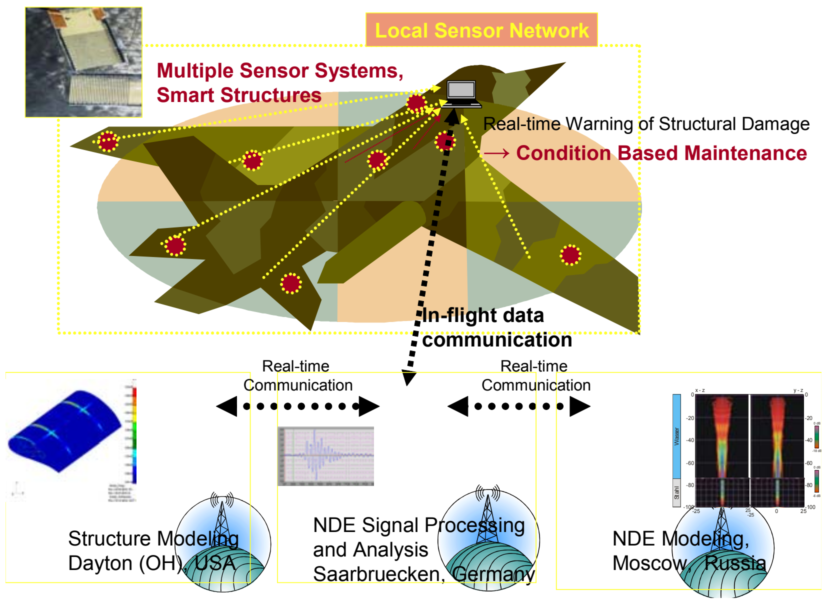


Figure 11: Concept for continuous health-monitoring of aircraft while in use

New Applications: New markets have recently evolved in the area of security applications, life sciences and micro- and nano-system engineering. Experiences, gained in conventional industrial applications, have to be transferred to new requirements. One typical example is the application of radar sensors for NDT and process monitoring. Furthermore, security is now a driving force to develop microwave technologies.

Here, the Terahertz (THz) technology is a relatively new testing technique. Only potential applications with different degrees of maturity can be found in existing literature (14, 15).

Generally, we can investigate electrically non-conductive materials in transmission and reflection mode. One advantage of the THz-technology is the ability to generate high-resolution images (sub mm-resolution) and to identify the substances by means of their spectra (vibration and rotation absorption spectra in the THz-domain). We expect the development of THz Cameras that are able to image objects at a distance of 10 to 30 meters at high resolutions. One example could be the detection and identification of explosives in letters (mail). Other examples are: detection of dangerous or prohibited substances (drugs, chemicals, biological agents, e.g. Anthrax), medical applications, food analysis, material characterization and packaging inspections. However, to make the THz technology practical we have to develop components for system design at reasonable costs (14).

Conclusion: The ever changing and dynamic world we are in presents both challenges and opportunities for innovative nondestructive testing methods and technologies. The NDT community experiences challenges to respond to the demands and to bring available technologies to use. We can only address a few aspects of modern NDE engineering, and the most important issue should be mentioned again – we are working in a global partnership for a safer world to benefit everyone.

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