ON THE FUTURE OF 3-D VISUALIZATION IN NON-MEDICAL INDUSTRIAL X-RAY COMPUTED TOMOGRAPHY

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Abstract: The purpose of imaging is to capture and record the details of an object for both current and future analysis in a transportable and archival format. Generally, the development and understanding of the relationships of the features of interest thus revealed in the image is ultimately essential for the beneficial utilization of that that knowledge.

Modern advanced imaging methods utilized in both medical and industrial applications are predominantly of a digital format, and increasingly moving from a 2-D to 3-D modality to allow for significantly improved detail resolution and clarity of volumetric visualization. Conventional digital radiography (DR), for example, compresses an entire object volume onto a 2-D planar image with consequent lack of spatial resolution and considerable loss of small volume feature resolution. Computed tomography (CT) overcomes both of these limitations, providing the highly desirable capability of precise 3-D detection, localization and characterization of multiple features throughout the subject object volume. CT has the further capability to reconstruct virtual 3-D solid object images with arbitrary and reversible planar sectioning and of variable transparency to clearly visualize features of different densities in situ within an otherwise opaque object.

While tomographic imaging is utilized in various medical CT, MRI, PET, EBCT and 3-D Ultrasound modalities, only the X-ray CT imaging is briefly discussed here as it presents comparable high quality images and is quite similar and synergistic with industrial XCT. Medical CT procedures started in the late 1970's (originally known as CAT Scan) and have progressed to the extent of being experienced and accepted by much of the general population. Non-Medical CT (or Industrial XCT) technology has historically followed in the shadow of Medical CT but remains today considerably less pervasive. There are however increasingly several important equipment and application distinctions. These will be discussed somewhat, but with the main emphasis on the importance of their present synergy and the future directions of 3D imaging, visualization and the emergence of new innovative applications for this unique non-destructive examination and characterization technology.

Introduction: History is replete with erroneous predictions of what the future will be like for many varied interests, including both societal and technological. Fortune tellers of various sorts and titles have remained with us over many millennia despite their high inaccuracy rate because they address a vital and fundamental question – "what does the future hold?" The difficulty of predicting the future is discovered by all who attempt to do so. A scant few of the many available "classic" technological misjudgments in future forecasting may help illustrate my point and are listed as follows:

- "The abdomen, the chest, and the brain will forever be shut from the intrusion of the wise and humane surgeon." -- Sir John Eric Ericksen, British surgeon, appointed Surgeon-Extraordinary to Queen Victoria 1873
- "There is no likelihood man can ever tap the power of the atom." -- Robert Millikan, Nobel Prize in Physics, 1923
- "I think there is a world market for maybe five computers." -- Thomas Watson, chairman of IBM, 1943
- "There is no reason anyone would want a computer in their home." -- Ken Olson, president, chairman and founder of Digital Equipment Corp., 1977
- "640K ought to be enough for anybody." -- Bill Gates, 1981

Certainly the practice of modern medicine in general, not just radiology, and the current practice of military, industrial and academic research and engineering would not exist as anything like we know it today if these and many other future forecasters had been correct. While somewhat amusing to read in retrospect, it is important to recognize that these quotes originated from some of the most intelligent, experienced and best minds of the day. They felt compelled to express their considered thoughts on the future of their respective technologies to a diverse and anxiously receptive audience. It would appear, however, that anyone, no mater how objective and experienced, can and most likely will, misread some –if not much- of what the future actually holds in store for us. Nevertheless, it is an inevitable attribute of the human species that future technology projections will continue to be advanced by many people on many subjects. Fairly recent projections published by Carrington[1,2] on the future of Medical CT Technology have become available. It is the intent of this paper, to
present some complimentary comparative projections regarding non-medical or industrial X-ray computed tomography, XCT. Also, please bear in mind that technological advancements in the XCT area are moving very rapidly and the potential competitive and/or synergistic relationships of this technology with other technologies yet remain to be beneficially exploited. Thus it is with some considered hesitation that I make the following comments in this paper. Hopefully, any subjective misdirections inadvertently advanced here will be accepted in the same open-minded spirit in which they are offered.

Results: In 2002, the USA National Academy of Engineering listed "Imaging" as number 14 of the 20th greatest engineering achievements of the 20^{th} century [3]. Of course, one of the key accomplishments included was "1972 X-ray computed tomography, Hounsfield" As in certain selected fields of medicine, Tomographic Imaging and Visualization have also gradually become essential professional tools in various non-medical arenas such as the military, industry and academia.

A brief chronological history of selected milestones in radiological imaging is shown in Table 1. Obviously, many significant items have been omitted due to current time and space limitations, but hopefully the reader can still appreciate the increasing pace of technical progress as well as the bifurcation of the technology into both Medical and non-medical application directions. A similar brief relative comparison between several of the general aspects of Medical CT and Industrial XCT technology is presented in Table 2. Here, one begins to appreciate some of the significant differences between these two x-ray computed tomography facility and application areas. XCT is a unique non-destructive examination modality that provides a direct imaging or visualization of the interior of otherwise opaque objects. Health care applications are limited by acceptable patient radiation dosage whereas most non-medical applications are dosage independent and quite large objects ($\geq$ 10E06 cm^3) of modest density can be examined with commercially available high power equipment of 9 to 15 MeV. Essentially, non-medical XCT applications are generally characterized by lack of dosage limitations, higher density engineering materials and frequently, subject object dimensions larger than a human subject; factors which require higher power facilities for greater penetration with equal or greater feature resolution and visualization capabilities.

Table 1. Brief Chronology of Selected Milestones in Radiological Imaging History

DATE	RADIOLOGICAL IMAGING MILESTONE
1895	Wilhelm C. Roentgen discovers a "new kind of light," which he names "x-rays." Receives the Nobel Prize in Physics in 1901.
1900	Thomas Edison developed Intensifying screens.
1913-1960	Commercial Medical & Industrial X-ray films developed – from cellulose nitrate to cellulose acetate to polyester base films.
1972	***X-ray computed tomography, Hounsfield.*** Receives the Nobel Prize in Physics in 1972
1983	Fuji introduces first commercial Computed radiography system with laser printer
1998	GE, Toshiba, Marconi, and Siemens all unveil versions of quad slice CT scanners with sub

2002	Eight- and 16-slice CT units begin shipping.
2003	GE Healthcare's HiLight Matrix II detector allows LightSpeed Pro[16] to deliver routine thin-slice imaging at 16 x 0.625mm and 16 x 1.25mm acquisition per rotation – in all scan modes and all scan speeds, including routine cardiac. microVoxel™ imaging collects cubic data sets of the smallest practical volume – delivering superior image quality in 3D and multi-planar reformatting (MPR)– for true isotropic resolution. [http://www.gehealthcare.com/rad/ct/products/light_speed_pro_16/detecting.html]
2003	Toshiba Aquilion 32 CT multi-detector system's hybrid 64-row Quantum Detector is capable of producing 32 simultaneous slices of 0.5 mm, or 1 mm with each gantry revolution for a total Z-axis coverage of 32 mm. The entire scan range can be acquired in 19 seconds with isotropic images. [http://medical.toshiba.com/clinical/radiology/aquilion32.htm]
2004	*Siemens SOMATOM Sensation 64, cleared for the US market in April, provides 64-slice sub-millimeter imaging per rotation for unprecedented sub-millimeter volume coverage, and the world's fastest gantry rotation time at 0.37 seconds. The new system delivers optimal image quality in cardiac, neurology and body imaging applications with a spatial resolution of 0.4 mm.* [http://www.medical.siemens.com/webapp/wcs/stores/servlet/PressRelease]
2000	ASTM Standards for Industrial Computed Tomography [5,6,7]
2002	Several NDE Conferences featuring XCT developments (see for example, U Ewert's paper, [8])
1997- 2004	Ballistic Impact Damage Visualization in metal and ceramic targets via XCT by Wells et al., [9-12]
2004	Advanced Research and Applications Corporation (ARACOR), a manufacturer of x-ray imaging systems, has placed into initial operation at the Ford Motor Company a state-of-the-art 9-MeV industrial x-ray computed tomography system, the ICT 1500, and a 9-MeV real-time radiography x-ray source. [http://www.aracor.com/pages/ford.html]

Table 2. Relative Comparison between Medical CT and Industrial XCT Technology

Medical CT Scan	**Consideration**	**Industrial XCT**
Patient isTranslated, X-ray Source/Detector Combination Rotates	Relative Motion	Object can be both translated and rotated and X-ray Source/Detector Combination may be moved
Tissue, Blood, & Bone	Subject Density Range	Polymers-Wood-Concrete-Ceramics-Metals-Composites
Normally < 200 KeV	Energy	Up to 15 MeV available

Limited For Subject Safety	Dosage Level	As Much As Needed
Commercial Equipment Philips – 16 slice CT scanner Toshiba – 32 slice Siemens- 64 slice (2004)	Simultaneous Multiple Slice Capabilities	Typically sequential multi-slice methodology BIR, Aracor, ...
Quite Advanced in 2004 Many commercial SW packages available	Complex 3D Visualization Capabilities & Software Development	Quite Advanced in 2004 Several commercial SW packages available
~ 1-2 mm for human subjects	Nominal Resolution	< 0.5 mm for engineering-scale objects (meso-tomography) and ~ 10 to 20 microns for small objects (micro-tomography)
Widespread Yes Yes Yes	General Acceptance - Broad Tech Community Peer Community General Public	Relatively Limited Limited but slowly growing Partially by NDE, Design & Mfg Mostly Uninformed
Ubiquitous – Available at Medical Schools & Radiological Training Courses	Education & Training	Mostly Vendor and hands-on at University & Industrial Facilities
Large Commercial PACS systems available and rapidly being implemented in Healthcare communities	Status of Record Systems - acquisition, monitoring, storage & retrieval	Less well developed and implemented image DBMS integrated with overall Technology & Knowledge Management
Plentiful Radiological CT (eg. www.auntminnie.com)	Web Info Available	No Central Non-Medical XCT Website – Considerably less availability and quite scattered
Ubiquitous – Available at Most Hospitals in USA	Facility Availability	Several smaller ≤420 kev facilities available; Larger Hi-power (>2MeV) facilities are relatively much more scarce
Expensive	Capital & Facility Costs	Very Expensive for Hi Power

It is unreasonable here to attempt a more substantial review of the many intricate details of the capabilities and differences between medical CT and industrial XCT beyond those listed above in Table 2. Many references exist in the literature relevant to those details. A few contemporary examples of Medical CT images are shown in Figure 1 as a brief exposure to those not yet aware of such medical CT capabilities. Similar contemporary non-medical, Industrial XCT images are likewise shown in Figure 2 to indicate both the image quality as well as the broad selected industrial application areas from sawmills, to automotive to aerospace. Certainly there are many other non-medical applications area that could be added as well.

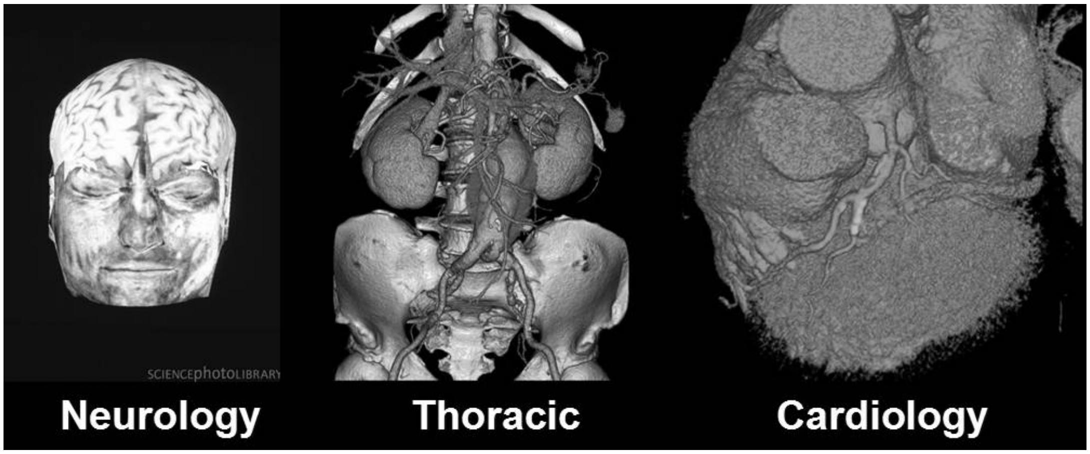

Figure 1. Contemporary Medical CT Images indicating current capabilities

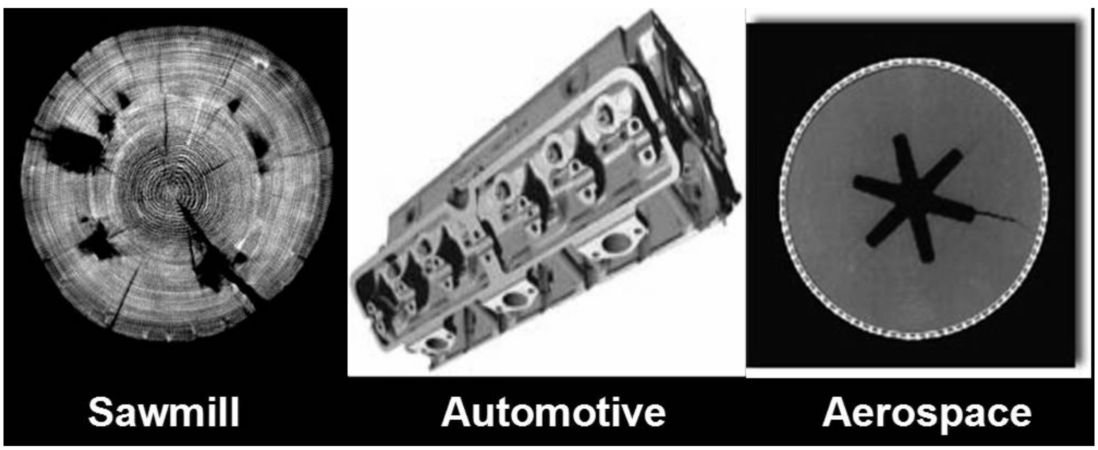

Figure 2. Selective Contemporary Non-Medical, Industrial XCT Images

Discussion: A distinction is made here in this paper between the use of the terms "imaging" and "visualization". By "imaging" we are referring to the process of simply creating a virtual image of a physical subject and/or its detailed structure or substructure. The term "Visualization" is used to denote not only that imaging process but also incorporates the intellectual comprehension of the physical relationship or significance of the features contained in a respective image. For example, imaging occurs in a 2-D digital radiograph, DR, frequently without the observer being able to visualize the full nature of the observed image details since there is a inherent lack of depth perception. Often in the case of many 2D XCT scans or even 3-D tomographic images, the ability to mentally comprehend the relationships or significance of the observed details is difficult or impossible to visualize without further "image processing and reconstruction", as well as requiring the use of significant objective and subjective knowledge-based reasoning. A simple example will be used to help illustrate this point in Figure 3 where a schematic representation of an interesting interrelationship among data, information, knowledge and imagination can be seen. With increasing value added, subject data becomes processed information which in term may be evolved into intellectual knowledge. Data may frequently consist of images alone that, although of limited utility, may optimally result in some intrinsic problem insight when reviewed with adequate imagination. Information combined with imagination may optimally result in deductive and/or inductive reasoning. Ultimately, the most desirable "Creativity and Visualization" occur more readily in scientific and engineering problem solving through the preferred combination of knowledge-based understanding and aggressive imagination. Perhaps, Albert Einstein said it best with this quote "…. *To raise new questions, new possibilities, to regard old problems from a new angle requires creative imagination and marks real advances in science*."

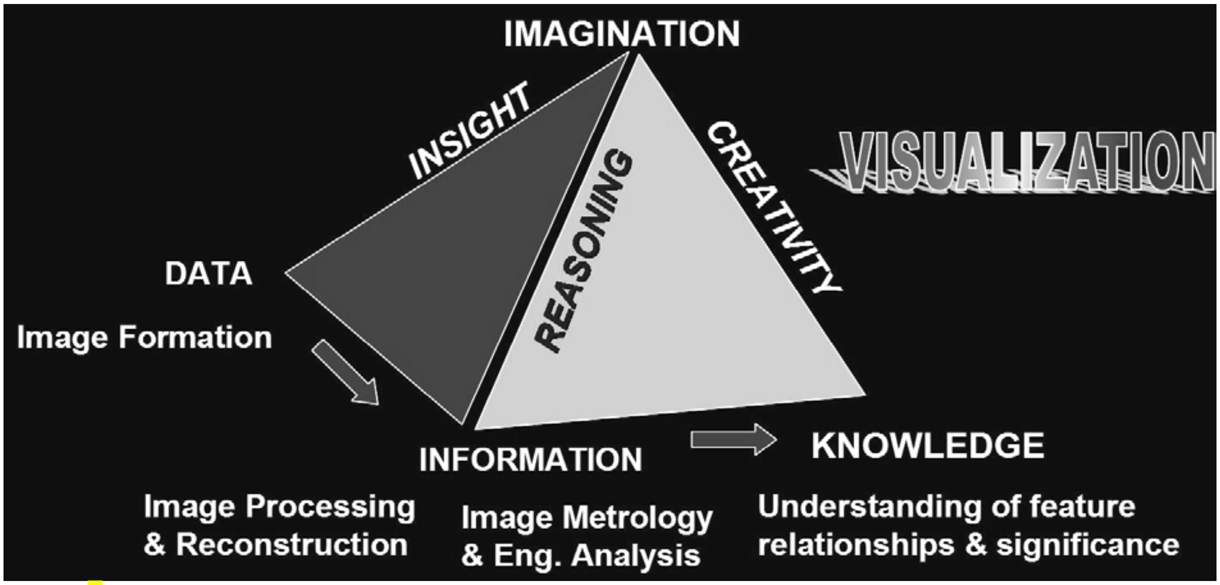

Figure 3. Visualization Schematic Perspective with XCT accentuating the importance of knowledge-based understanding and imagination to develop the intellectual comprehension nature of visualization.

Additionally, Mark Twain [XX] said …. "*You cannot depend on your eyes when your imagination is out of focus.*" Imagination remains a critical requirement throughout the complex XCT visualization process. Imagination is a generally under-appreciated intuitive attribute which has not yet been provided by modern computational methods. Furthermore we must yet advance beyond the imagination, creativity and visualization shown in figure 3. We need to be much more innovative in applying these ever improving technological capabilities to the application and solution of more expansive and complex engineering and scientific challenges.

One example of an innovative and embryonic application of this technology in which the author has been involved is in the non-destructive high resolution characterization and damage assessment of ballistic impact target materials with XCT [9-12]. Impact damage targets have been examined in greater detail with results demonstrating considerably improved quantification and visualizations of actual damage features, much of which was previously unreported. It now appears that XCT may serve as a new visualization and analysis tool to assist in the development and verification of improved ballistic damage and penetration computational models.

Another non-destructive application area that is starting to emerge is the use of XCT as a baseline 3D visualization "reality" standard for comparative validation and calibration studies with other traditional and more field-portable NDE modalities with less resolution and direct visualization capability. Thus it appears that the real future of the industrial XCT technology area will be as strongly dependent upon the practitioner's imagination, innovation and success in its application as well as upon the continuing commercial availability of improved and affordable software and hardware.

Conclusions: In a brief presentation such as this, much relevant and interesting information must, unfortunately, be excluded due to space and time constraints. However, the purpose here is not one of a comprehensive review of the subject, but rather a brief snapshot and projection of possible future directions yet forthcoming. Some highlights of these considerations are offered as follows:

- Visualization, which includes a means of understanding or conceptualizing the relationships and /or significance of observed features, is far more important than the capability to simply image or observe same.
- 3-D visualization is rapidly overtaking the traditional 2-D DR as the prominent state of the art, but 3-D is far from the ultimate. The capability for the fourth dimensionality, temporal resolution, is growing and will soon become the standard in many applications for events of relatively slow (< 0.1 second) time occurrence such as the human heart beat. Eventually in the next decade or less, we may see the real time capability of quality imaging and visualization of high speed ballistic impact events occurring on the micro-second scale.
- Affordable personal computers –not large supercomputers or even very high end workstations – will have multiple 64 bit chips (and then 128 bit chips and so forth) to make image acquisition and reconstruction calculations much faster than presently available. Concurrent advancements in acquisition and reconstruction algorithms will also be necessary and will be forthcoming.
- Computer hardware advances will continue assist in the future advancement of XCT with the introduction of multiple Gigabyte RAM to permit the rapid parallel processing of much larger XCT scan and reconstruction files than common or possible today. Commercial voxel processing and analysis software will correspondingly experience improved capabilities in speed, imbedded image processing, virtual metrology and user friendliness.
- XCT scanning and data acquisition systems will continue to improve. Multiple-scan capability has rapidly risen in the medical field from 8 to 16 to 32 to the most recent introduction in 2004 of a 64 scan machine. The industrial machines presently lag in this regard but perhaps not for long.
- These improved scanning and analysis capabilities and the expanded usage of XCT technology also introduce further requirements for new high speed relational data bases with combined data acquisition, access, and retrieval of multiple forms of digital data. The medical support industry is currently addressing new Photo Archiving Computer Systems, PACS, systems which although a considerable improvement over prior records handing systems, still have considerable room for performance, affordability and user friendliness improvements. Non-medical systems will be required with appropriate modifications.
- Prices of all such hardware and software developments will become more affordable over time and hence, the application usage of this XCT technology will expand considerably with an accompanying increasing public appreciation of the many varied benefits (particularly in the non-medical areas) to be still realized.
- New innovative applications and frequency of usage of non-medical XCT will continue to expand in the future. One exciting concept is to utilize XCY as a baseline 3D visualization standard for comparative flaw and damage features of interest in future validation and calibration studies of other traditional and more field-portable NDE modalities. Another is in the development and verification of improved ballistic damage and penetration computational models. Such reality (not simulated) damage modeling has considerable potential application in manufacturing and serviced induced damage considerations.

- Finally, for my most aggressive prediction, I envision that revolutionary changes (as opposed to the above evolutionary) in XCT methodology will be discovered, developed and made commercially available that make possible the visualization of details of features of interest in large solid objects of 100 cubic centimeters and larger to a higher resolution scale of 1 micron or smaller.

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