4D CT enabled by Nikon's software versatility

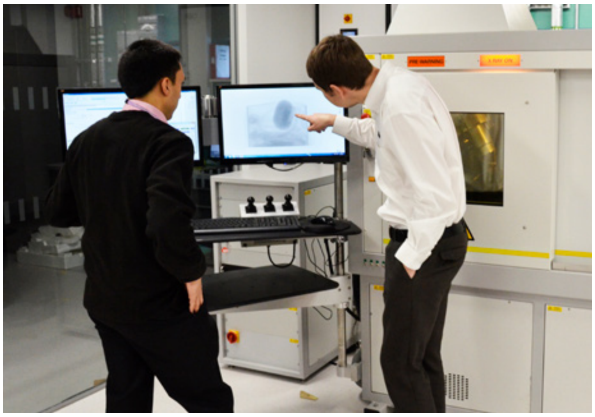
A unique feature of Nikon Metrology's Inspect-X software is that, along with its easy-to-use user interface, it also has a programmable interface. This provides the flexibility to develop bespoke CT solutions integrating third party analysis software and controlling external hardware. Researchers at the Henry Moseley X-ray Imaging Facility at the University of Manchester have used this feature to implement 4D CT for laboratory experiments. Could this open new doors for industrial environments?

Parmesh Gajjar is a Research Associate at the Henry Moseley X-ray Imaging Facility who has been discovering the possibilities of IPC and how it can be harnessed to perform temporal CT for scientific experiments on samples that change structure over time. Andrew Ramsey is a CT Consultant at Nikon Metrology with extensive experience of developing special CT applications in industrial environments. Together, Parmesh, Andrew and colleagues have recently published the scientific paper 'New software protocols for enabling laboratory based temporal CT'. In this article, Andrew and Parmesh offer an insight into how temporal CT can also be used to great effect in industrial environments. Nikon Metrology takes a look at how temporal CT can contribute to manufacturers, production plants and QA departments in achieving a digital, automated and connected production line – Industry 4.0.

IPC facilitates temporal CT

The programmable interface to Nikon's X-ray control software is known as IPC (inter-process communication). It allows the user to call individual functions in Inspect-X, from as low level as turning the X-rays on and off, to as high level as initiating a CT scan with previously stored acquisition parameters, automatically reconstructing a CT volume using stored settings, and running an automatic analysis using stored macros, while providing progress feedback throughout. The resulting IPC program can be used to implement novel acquisition techniques, increase productivity or create highly simplified user interfaces for previously cumbersome tasks.

CT is unique in allowing a non-destructive 3D examination of a material. However, there are many things that change over time. By collecting a series of measurements of the sample object at different times, we can observe changes in the additional dimension of time. This creates the



The mung bean inside of the Nikon XT H 225 can be seen on the screen.

Mung beans, which were used for Parmesh's uninterrupted time-lapse CT.

> *"The Nikon Metrology CT systems are like a gold mine. They give us the flexibility to do whatever we want to do."*
>
> *Parmesh Gajjar, Research Associate - University of Manchester.*
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powerful technique of 'temporal CT' that is four-dimensional in nature (3D + time), hence why it is also known as 4D CT.

IPC allows CT measurements to be collected automatically over a period of time, with the data reconstruction also fully automated. By scheduling scans to take place at intervals or at predetermined times, the growth or change of a specimen over time can be documented in 3D, with no further human interaction or intervention required.

Different flavours of temporal CT

Temporal CT comes in different flavours, which can be broadly grouped into two main classes: Time-lapse CT and Continuous Acquisition CT. Time-lapse CT is the 3D analogy of time-lapse photography and involves taking traditional CT scans at specific intervals; whilst Continuous Acquisition CT involves continually collecting projections of an object as it changes, and reconstructing subsequently chosen subsets of projections to form several volumetric time-series. As Parmesh and Andrew showed in their paper, the beauty of IPC is that it provides flexibility for implementing both of these classes on standard machines. This article takes a detailed look to see how each technique could provide new insight in industrial settings.
The paper titled 'New software protocols for enabling laboratory based temporal CT', written by Parmesh Gajjar, et al., was published on September 5th 2018. To find out more and take a closer look at the studies and the findings, the paper can be downloaded at https://doi.org/10.1063/1.5044393.

A) Time-Lapse CT

A temporal picture of a changing object can be built by simply taking repeated CT scans at regular intervals, in a time-lapse manner. If the sample is left alone between each scan, until changes occur naturally this is what is known as 'uninterrupted time-lapse'. On the other hand, if the sample is forced to change in between each scan, this is 'interrupted time-lapse'. If performed manually, conducting anything more than a few scans becomes a hugely laborious process. Through IPC, however, this can be fully automated, drastically reducing the need for human intervention.

Consider the in-vitro sprouting of a mung bean, or in other words, a mung bean sprouting inside of a CT machine. Parmesh uses polyimide tubing with wet tissue to create an in-vitro sample holder with a moist micro climate for the bean to germinate in. After soaking the bean in hot water to initiate sprouting, the bean was placed within the sample holder inside the CT machine (see figure 1). As the bean naturally germinates and develops, 54 CT scans are automatically taken at two hour intervals over five days throughout the sprouting process. This allows the internal changes to be visualized. Uninterrupted time-lapse scanning creates a 4D video of the bean germination, with the ability for quantitative analysis Several snapshots of this process are shown in figure 2.

Parmesh also uses time-lapse CT to visualise the 'brazil-nut effect', i.e. why large objects rise to the top of a mixture when shaken. Parmesh developed a specially designed shear-cell for shaking a mixture of glass beads ('nuts') that fits on the stage of the CT system. The cell contains two different sized glass beads. The 6 mm beads are at the bottom, and the 3 mm beads are on top. The mechanism applies a motion force to its contents at intervals, and the CT system takes automated scans after each interruption. The resulting scans can be stitched as a movie to depict the natural ordering effect that takes place as can be seen in figure 3.

B) Continuous Acquisition

The other class of temporal CT involves collecting a stream of projections continually as the object changes. Here, the spatial and temporal resolutions can be optimised together. Parmesh implements the 'golden ratio' method for angular sampling, which allows for the number of projections in a reconstruction to be changed as sample evolution occurs.

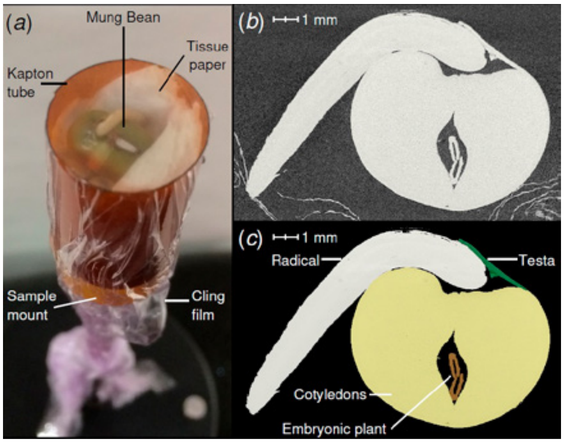


Fig. 1 (a) in-vitro set-up for mung bean germination; (b) A slice of the reconstructed volume showing grey-scale levels; (c) The same slice, colorised using a manual singe slice segmentation of the different bean parts. Figure courtesy of AIP.

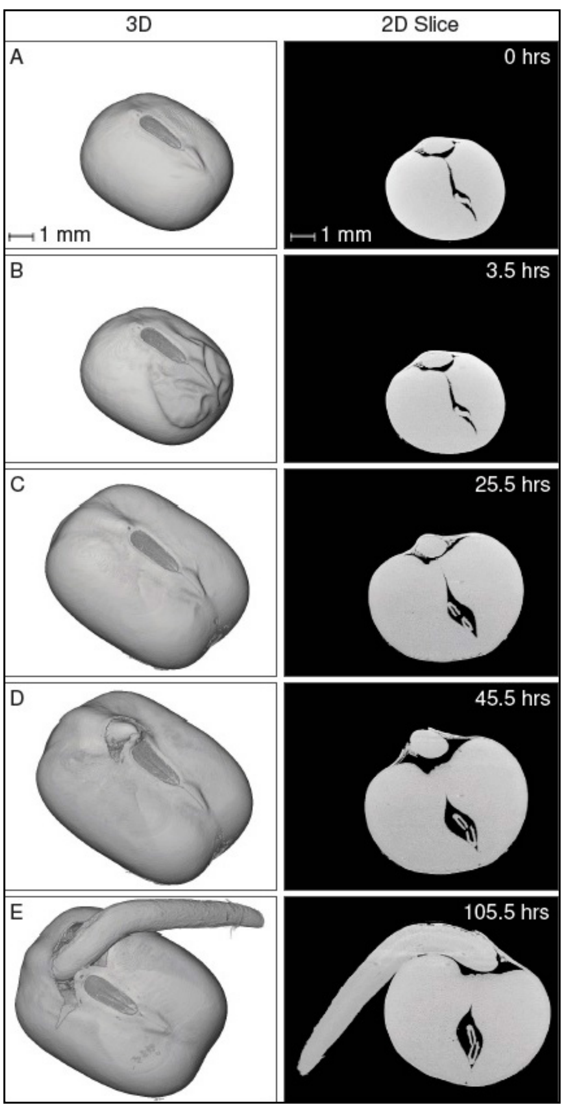


Fig. 2 3D virtual representation and 2D slices show the stages of mung bean germination at different times. Figure courtesy of AIP.

Golden ratio angular sampling ensures optimally distributed tomograms

The golden ratio (Phi / $\Phi \approx 1.618$) is an irrational number that is commonly found in nature. It is a form of optimal distribution and can be seen in the way leaves arrange themselves as to not obscure another or how sunflower seeds form in a spiral within the flower head. The aesthetic qualities of the ratio have seen it implemented throughout architecture and in many pieces of art, most notably adopted by Leonardo da Vinci in many pieces of work.

The relevance of the golden ratio to CT scanning is that it allows projection angles to be distributed optimally. Compared to obtaining projections at angles organized in a standard incremental fashion (10, 20, 30…), the projections collected in a golden ratio manner are as independent from each other as possible, allowing a full picture to be built up much faster and allowing the number of projections in a reconstruction to be changed as sample evolution occurs.

This golden ratio approach has been successfully implemented before, in MRI scans, with neuron tomography and at synchrotron X-ray facilities. For laboratory based CT systems though, it has (up until now) not been technically possible. In Parmesh's experiment, the IPC interface enables golden ratio sampling to be implemented for the first time in a lab.

Overcoming the restrictions of lab-based machines

Parmesh's experiments highlight the wide flexibility of laboratory based CT systems, and how they can be adapted to achieve greater goals than the standard practices. Parmesh describes the programmable Nikon Metrology CT systems as a 'gold mine' for researchers and manufacturers alike, as it gives users the flexibility to do whatever they choose.

Although temporal CT acquisition could be performed manually by an operator using the system, IPC allows all of the processes to be fully automated, and integrated into larger industrial setups. The fully programmable interface of Nikon CT systems allows users to write their own software and tailor their system for their own specific challenges and projects.

What impact can 4D CT have in a manufacturing environment?

The impact temporal CT could have on the manufacturing industry and QA departments now and in the future is very significant. The principles of temporal CT, and the different methods of implementation can make an enormous difference in the industrial environment. The possibility of synchronised in-situ CT scanning opens the door to tests that could never before be achieved.

Andrew Ramsey explains that for aerospace and automotive industries, the introduction of temporal CT could prove to be a very beneficial tool. For automotive and aerospace OEMs, failure is not an option. Due to the demand of unwavering quality, components, assemblies

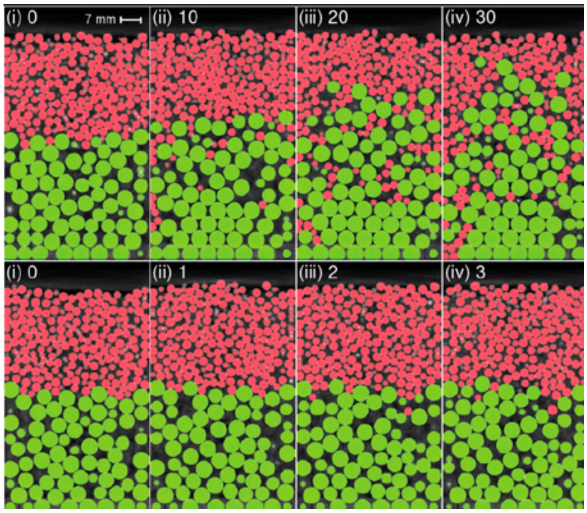
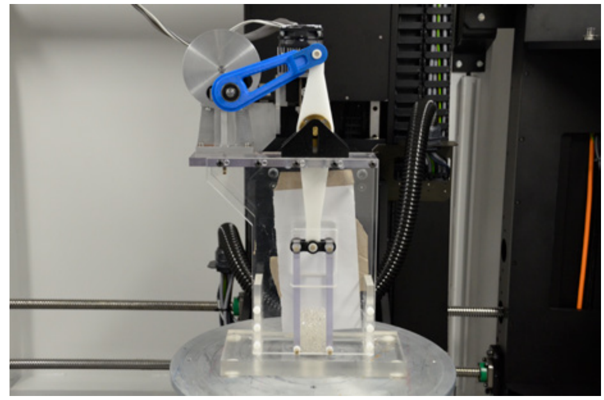


Fig. 3 (a) comprises of 4 scans with 10 shear cycles between each scan, whilst (b) shows scans separated by 1 shear cycle per scan. The small particles can be seen to percolate downwards, whilst the large particles migrate upwards. Figure courtesy of AIP.



A shear-cell specially developed for studying granular segregation using CT.

> *"For aerospace or automotive components, with accelerated fatigue of cracks in fan blades, time-lapse CT can be used to replicate years of work in just a fraction of the time."*
>
> *Andrew Ramsey, CT Consultant – Nikon Metrology.*

and mechanisms are subjected to extensive and vigorous in-situ environment and condition tests. Introducing time-lapse CT to these tests is very beneficial. It is vital for components and assemblies in these industries to be built well enough with to withstand substantial and consistent usage over a prolonged period of time. To incorporate 4D CT into these tests gives manufacturers the ultimate inspection tool to obtain fast, accurate and insightful results of their products. Complete confidence in products is what manufacturers and customers demand, and this is what 4D CT enables.

For smart factories, this technique could soon be the one-stop inspection solution of life-critical components, meeting the demands of Industry 4.0. QA departments often use CT to see inside components without slicing or destroying them. They also use various, in-situ simulations and tests of materials, components, parts and assemblies. However, the introduction of temporal CT can bring these two procedures together, to gain an unparalleled insight into the smallest details of critical components and parts under test with the tightest tolerances. 4D CT can show where, why, when and how a component has failed, providing a complete understanding, which is vital for product development, and priceless in terms of quality control. 4D CT introduces a whole new dimension of test results that can be scrutinized, taking quality control to the next level.

Consumers expect the utmost quality when investing in market leading brands and goods, and these tests guarantee that only the best items are produced. However, 4D CT excels and takes this to the next level, introducing a whole new aspect of testing and new heights for detail, accuracy and speed of in-situ testing. Manufacturers gain unparalleled insight into the conformity of every aspect, of every assembly or component.

The introduction of temporal CT is a very important revelation and it will soon be an integral part of the manufacturing process. As manufacturers develop smart factories, in keeping with the demands of Industry 4.0, temporal CT will soon establish itself as a valuable quality assurance tool in production plants, worldwide.

Figures 1, 2 & 3 are taken from the paper 'New software protocols for enabling laboratory based temporal CT', courtesy of Review of Scientific Instruments, AIP. The paper can be accessed from https://doi.org/10.1063/1.5044393

Nikon Metrology CT with Inspect-X software for software for 4D CT

Nikon Metrology's X-ray CT systems and Inspect-X software enable users to create specialized custom applications and implement 4D CT in any environment.

- The fully programmable software interface allows users to write their own code to achieve the desired requirements for unique applications
- The combination of the Nikon systems and flexible Inspect-X software enables automated in-situ studies