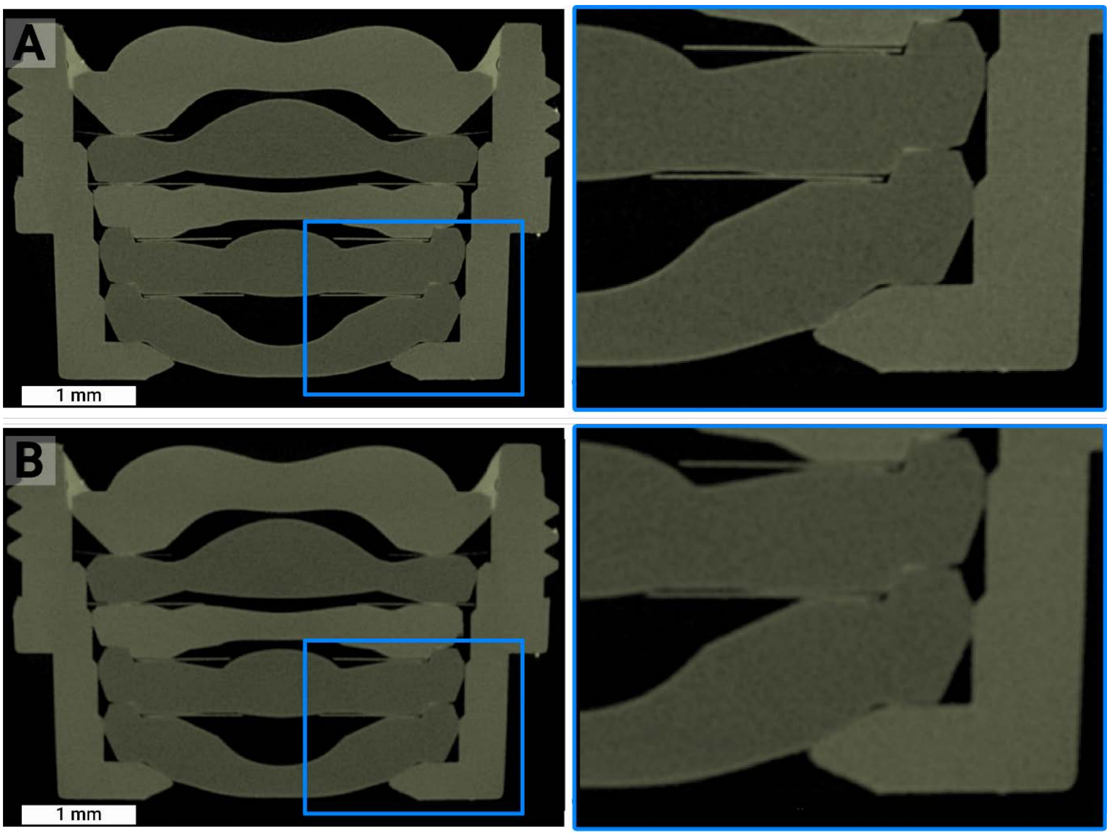
How resolution, speed, image quality and system versatility work together to provide the optimal micro-CT experience.

In recent years, the market for CT systems grew exponentially, resulting in a wide range of systems on the market — from small desktop devices with good but limited capabilities to large, flagship systems covering an extremely broad range of applications. In this highly competitive landscape, there is a large offering in the field of high (sub-micron) resolution micro-CT systems. To differentiate solutions in that landscape, manufacturers would augment the core function of micro-CT systems, namely non-destructive acquisition of attenuation-based 3D images, with additional and even novel analytical capabilities. Some examples include the ability to perform x-ray fluorescence during scans, real phase contrast imaging with grating interferometry, capturing x-ray scattering signals, or acquiring spectral data inside a micro-CT system. Furthermore, there is a growing demand to expand imaging from 3D to 4D — adding the dimension



▲ **Figure 1:** High quality scans of a phone lens assembly scanned on a TESCAN UniTOM HR system in just 26 (A) or even 7 (B) minutes using 1300 (A) and 1000 (B) projections.

of time to experiments — and many CT systems now offer cable feedthroughs for flow and signal lines, built-in connections for peripheral equipment and specialized 4D imaging tools.

However, despite an ever-expanding range of additional capabilities for micro-CT systems, the key application for micro-CT remains the production of 3D datasets of a sample's structure or composition. Whether these datasets are used to quantify material characteristics such as porosity, used as input for numerical models, or are simply being used to gain better understanding of the interior of a sample, image quality remains paramount to obtaining reliable and reproduceable results.

With the number of available instruments and a dedicated user community, micro-CT technology has evolved dramatically. Tomography devices now have better x-ray sources and detectors, and the accompanying software now boasts better reconstruction algorithms and superior post-processing and visualization tools. In this document, we provide an overview of what new technologies mean for the latest generation of micro-CT systems and illustrate how the search for the best micro-CT system for your application goes further than just comparing the maximum resolution of all systems in the market. This is amplified by the fact that today, the resolution limit of x-ray sources has reached its physical limits and all x-ray source manufacturers offer transmission type x-ray tubes, with resolution between 0.5 µm and 1 µm. Therefore, as you can find roughly the same maximum resolution with most CT manufacturers, look out for systems that maintain that high resolution within challenging conditions, such as imaging at high speed, while preserving image quality and contrast, and still offering great versatility in a system. The combination of high resolution, high speed, optimal image quality and system versatility, allows you to address the most challenging applications in a single micro-CT system. In the next paragraphs, we will explain how each of these parameters has an impact on how you perform computed tomography, how they all lead to superior results, and open up the possibility of real dynamic imaging. We hope this content inspires you to get the best out of your micro-CT system, and inspires you to tackle new challenges in your micro-CT research.

Maintaining resolution at high imaging speed increases throughput and saves on both time and cost per sample.

Of the different characteristics to assess in a micro-CT device, one of the most important to consider is imaging duration. The benefit of high, sub-micron resolution in a micro-CT system can be severely diminished if it takes days to acquire a dataset. Only when high resolution is maintained in short acquisition times of a few minutes up to a maximum of a few hours, users can truly benefit from it. Evolutions in critical scanner components, mainly on the detector side but also in computer hardware such as solid-state drives that allow faster data recording, have driven the reduction in acquisition times — from many hours to just a few minutes. Furthermore, the ability to adjust the source–detector–distance to optimize x-ray flux, means that the maximum power of the x-ray source and acquisition modes also must be factored into calculating acquisition speed. The fastest commercial micro-CT systems on the market allow for excellent scan results in less than one minute per scan and can reach temporal resolutions of just a few seconds at their maximum scan speed (Zwanenburg et. al, 2021).

Fast scan speeds provide multiple benefits, but increased throughput is probably the most important and influential one. This increased throughput delivers the ability to scan many samples in a relatively short time, thus increasing a system's availability to its users. As micro-CT devices are often present in larger, multi-user facilities, this prevents system access from becoming a major bottleneck for experiments and research progress. High throughput allows more samples to be processed in the given amount time, ensuring enough data points to draw statistically relevant conclusions. In these situations, slow scan speeds are simply not an option. And finally, fast scanners also maintain a low cost per sample, which is especially important in an analytical service lab.

Imaging speed is important for another reason. It also means that more time can be available to gather additional x-ray projection images or increase the exposure time per projection. Ultimately, increased imaging speed enables better image quality within the same or even shorter acquisition duration than a slower micro-CT system (figure 1).

Image quality is essential to benefit from a system's resolution

The importance of image quality cannot be overstated, but as it cannot be assigned a number within a specification sheet, it is also the hardest parameter to qualify. Image quality is probably the most significant factor when it comes to obtaining reliable and actionable results from micro-CT. While high resolution is paramount to enable detection of features, it needs to be complemented with a high image quality to allow for reliable analysis. This is imperative when numerical results like porosity values or absolute distances are needed. It is essential that signal-to-noise and contrast-to-noise ratios are as high as possible.

The first step in processing and analysis of 3D micro-CT datasets is often a segmentation step. This image segmentation is usually an automatic or manual procedure, where two or more distinct materials are differentiated from each other based on their grey value in the images. Because most image analysis routines require at least one such segmentation step, and all further analysis and conclusions often rely on that initial segmentation, it is probably the single most important step in image analysis. To allow for a good segmentation, it is not only important that features can be visually observed, as computer algorithms need very robust data. The better the image quality input, the more trustworthy the results from image segmentation that is executed by different users or algorithms. This is especially critical with the rise of new machine learning and AI-assisted segmentation methods, all of which rely on clean and consistent training data.

Just like imaging speed, image quality also has benefited from technological advances in electronics. Read-out noise from detectors has decreased, and more has been learned about detector implementation and fine-tuning for computed tomography (which is different for microanalysis than it is for industrial radiology). Improved acquisition modes, such as smooth acquisition trajectories rather than the traditional step and shoot approach, have further increased the signal-to-noise ratio on some micro-CT systems.

As mentioned before, we cannot ignore the fact that the resolution of a micro-CT system is one of the most important aspects of the technology. Resolution is an integral part of the image quality of the datasets that a system produces. There are indeed applications for which sub-micron spatial resolution is needed to solve the challenges at hand. However, resolution needs to be combined with enough contrast and signal-to-noise ratio to benefit from it. Only then features can be resolved and segmented with enough confidence to ensure accurate results. If the signal to noise ratio is too low at maximum resolution, the trade-off in image quality may be too great of a compromise.

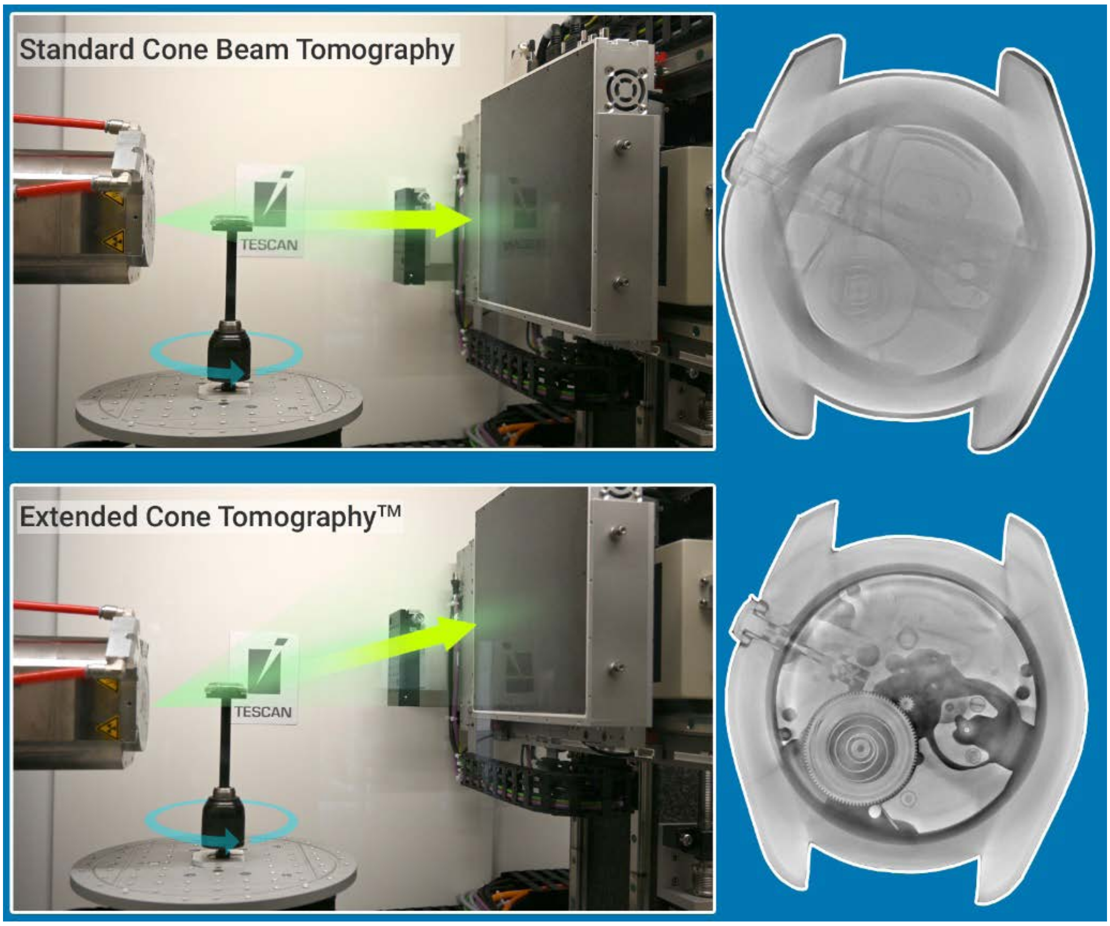
Versatility matters, because you might need it one day

Versatility of a system is what enables users to preserve resolution, image quality and scan speed for challenging samples and conditions. It also protects your investment by ensuring the needs of tomorrow are met as well as the needs of today. While rotation of the sample alone is enough to acquire a standard micro-CT 3D dataset, such systems with only this one degree of freedom are rare and only used for specific cases, like inspection of multiple identical samples in an industrial environment. Most commercial CT systems offer the flexibility to move the sample between the x-ray source and the detector (for magnification) and allow sample movement up and down (for scanning tall samples). In other cases, this is supplemented by a variable source–detector distance, often in fixed steps rather than fully adjustable steps, and/or side-by-side movement of the detector for wide-field imaging. Taking this a bit further, some devices offer a positioning stage on top of the rotation stage to perfectly align the sample over the rotation axis. This X/Y positioning is often executed by relative positioning, rather than by using motors with absolute encoders.

Versatility in a micro-CT system allows users to not only control the above-mentioned movements, but also independently change the vertical and horizontal position of the x-ray source and detector, translate the object stage perpendicular to the source–detector axis and generate acquisition trajectories using a combination of all those movements. Putting this all together, these micro-CT systems have a total of 10 or more degrees of freedom to allow absolute flexibility and accommodate very complex tomography experiments (De Samber et al, 2021).

Having this versatility is essential for performing the multi-scale approach that is typical for micro-CT investigations. After a fast overview scan of a large object, which in micro-CT may be tens of centimeters in height and diameter, a particular area or volume of interest can be identified inside the sample. At the location of this volume of interest, a longer scan is performed at higher resolution and/or image quality. Precise communication among reconstruction, visualization and scanner control software applications is needed to translate the coordinates between the initial overview scan and the subsequent high-quality scan. Absolute encoders for every motor inside the CT system assure that each component of the micro-CT system is directed to the correct location for performing the volume of interest scan. This multi-scale volume of interest workflow can be done using most micro-CT equipment, but only an excellent connection between software and hardware allows this to be an easy and user-friendly experience.

Finally, system versatility also enables non-standard imaging trajectories in addition to the standard circular acquisition scheme. These special acquisition schemes allow a user to maintain resolution and image quality, where traditional methods can't. Helical acquisition is well-known and often requested, but trajectories might be important, such as offset scanning (doubling the field of view for wide samples) or acquisition with a tilted optical axis (figure 2) where the source and detector are at a different height, to optimize transmission for large, flat samples.



▲ **Figure 2:** Reconstruction of a stainless steel watch using standard cone beam tomography vs. tomography with a tilted optical axis (TESCAN Extended Cone Tomography™)

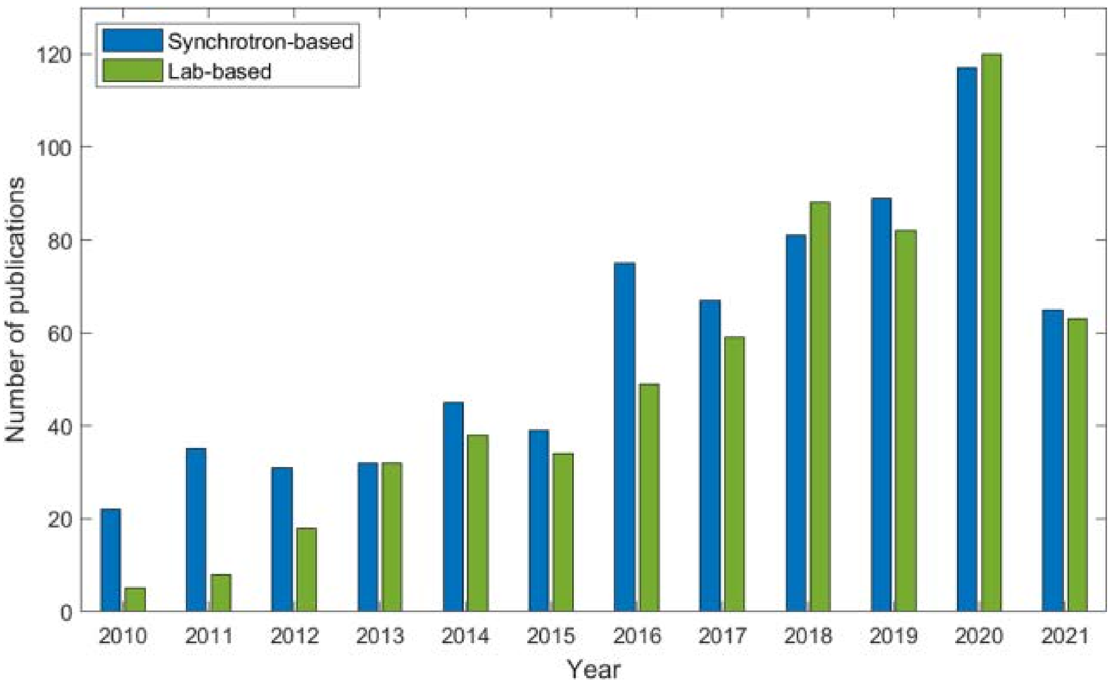
Modularity to maximize your investment

Micro-CT system versatility can be improved further by adding the option to use multiple detectors. Each x-ray detector on the market is characterized not only by its physical pixel size (pixel pitch), but also by its active area, number of pixels, energy sensitivity and scintillator thickness. Therefore, different sample types and sizes, or simply different research needs, will benefit from the use of one or the other detector. Having the opportunity to easily switch between different x-ray detectors ensures that optimal results can be reached for a wide range of samples.

Just as detector technology is the fastest evolving asset of micro-CT systems, detector modularity also guarantees that new and emerging techniques can be implemented in your micro-CT system. It means a system can be optimized for multiple fields of application, now or in the future, ensuring a long and productive lifetime of service. And finally, this modularity can upgrade a micro-CT system to include different imaging modalities, such as spectral imaging as an add-on over traditional attenuation-based CT imaging (Sittner et al, 2020).

Dynamic CT – Bringing it all together

While versatility and modularity allow scanning of a wide variety of samples, the need may come to analyze these samples under changing environmental conditions, such as mechanical stress or non-ambient temperature and humidity. The non-destructive nature of micro-CT means it has been used for time-resolved studies since its introduction. However, recent developments have made near-synchrotron temporal technology available in the lab, allowing lab-based time-resolved tomography to be dominant over synchrotron-based experiments in recent publications (Zwanenburg et al, 2021). This requires not only the speeds that can be reached at synchrotron facilities – anyone can rotate a sample fast – but also needs sufficient contrast and resolution in those very short scan times. Looking at the number of publications, the applications and the insights that are possible using dynamic micro-CT, the ability to perform fast 4D experiments in one's own lab on a micro-CT system instead of traveling to a synchrotron is fast becoming a key decision in the purchase of a micro-CT system.



▲ **Figure 3:** The evolution of the number of lab-based and synchrotron-based publications covering fast in-situ micro-CT imaging. Reprinted from Zwanenburg et. al (2021)

To be able to perform fast dynamic experiments, all components of a micro-CT system must work together in perfect harmony to produce the required result. A high-power x-ray source, combined with fast detectors are needed to keep exposure times and therefore scan times short enough to keep pace with the fastest of processes. Ample hardware connections for power and signals — preferably through a slip-ring connection enabling endless rotation of the experiment setup — and additional cable feedthroughs are needed to install complex in-situ setups inside the system. Reconstruction and visualization software need to be able to handle data acquired over multiple hundreds of sample (or gantry) rotations (Dewanckele et al, 2020). In reconstruction, it is important that a user can select the start and end of sections where interesting events take place, with full flexibility. This means that only the most interesting parts of an experiment are reconstructed, visualized, and stored, reducing storage need and processing time.

Conclusions

When evaluating micro-CT systems, think further than resolution or maximum x-ray energy. System resolution is of course one of the main parameters to evaluate during selection of an x-ray tomography device, but this resolution needs to be maintained at challenging and non-standard conditions. That's why it is important to look for what else a system has to offer, to complement the – very important – maximum resolution. Imaging speed will increase sample throughput, make the system available to more users, and will reduce the cost per sample. By optimizing the image quality, post-processing steps such as segmentation become more reliable, and therefore results derived from micro-CT scans will be more precise and reproduceable. And if you want to tackle large and complex samples or experiment with new approaches to tomography, a versatile and flexible system is of the essence.

With the optimal combination of speed, quality and versatility, complex in-situ experiments can be performed and, given that the right hardware and software tools are in place, researchers are able to perform true dynamic micro-CT experiments, bringing synchrotron-like capabilities to the lab.

Finally, consider system modularity. X-ray detectors are the fastest evolving part of micro-CT systems and selecting a system that is modular allows you to keep pace with technology by upgrading your system in the future. This way, the large investment that is a micro-CT scanner can continue to provide a return for many years to come.

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