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Advancing X-ray micro computed tomography in Africa: *Going far, together*

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ABSTRACT

X-ray micro computed tomography (microCT) is a high resolution non-destructive materials imaging technology and is emerging as a powerful tool for industrial and scientific research applications. The aim of this review paper is to present the capabilities and potential of this technique within an African context. This is done using a representative sample: all work done at the Stellenbosch CT facility during 2018 is used as an overview of the type of work done at such a facility in Africa. Besides the plethora of academic research topics, the most important industrial applications are also discussed, which assisted to keep the Stellenbosch CT facility financially operational. This provides a wider understanding of the opportunities and capabilities of this technique and how it can benefit African researchers and local industries. The question “what is it used for?”, and more specifically “what is it used for in Africa?” is therefore answered. The availability of such X-ray tomography facilities helps to fast-track research by providing local expertise and support in Africa for advancing African science. This model is not only applicable to microCT but applies to any collaborative scientific endeavor in Africa, with success rates depending on the efficient sharing of resources, providing expert skills and advancing African science in Africa. There is an African proverb “*if you want to go fast – go alone; if you want to go far – go together*”. Clearly, African science will go far by working together in such facilities.

Introduction

X-ray micro computed tomography (microCT) is a non-destructive imaging technology, using X-rays to create 3D images, see for example [1–5]. This allows visualization and accurate dimensional analysis of the exterior and interior of all kinds of materials. Unlike the similar medical CT method used for imaging the interior of humans and sometimes animals, microCT is a higher resolution technique with a wider array of parameters and adjustments, to allow imaging of diverse material types. The technique is more time consuming than typical medical CT scanners, due to the smaller X-ray spot size delivering less photons, therefore requiring longer image acquisition times [6].

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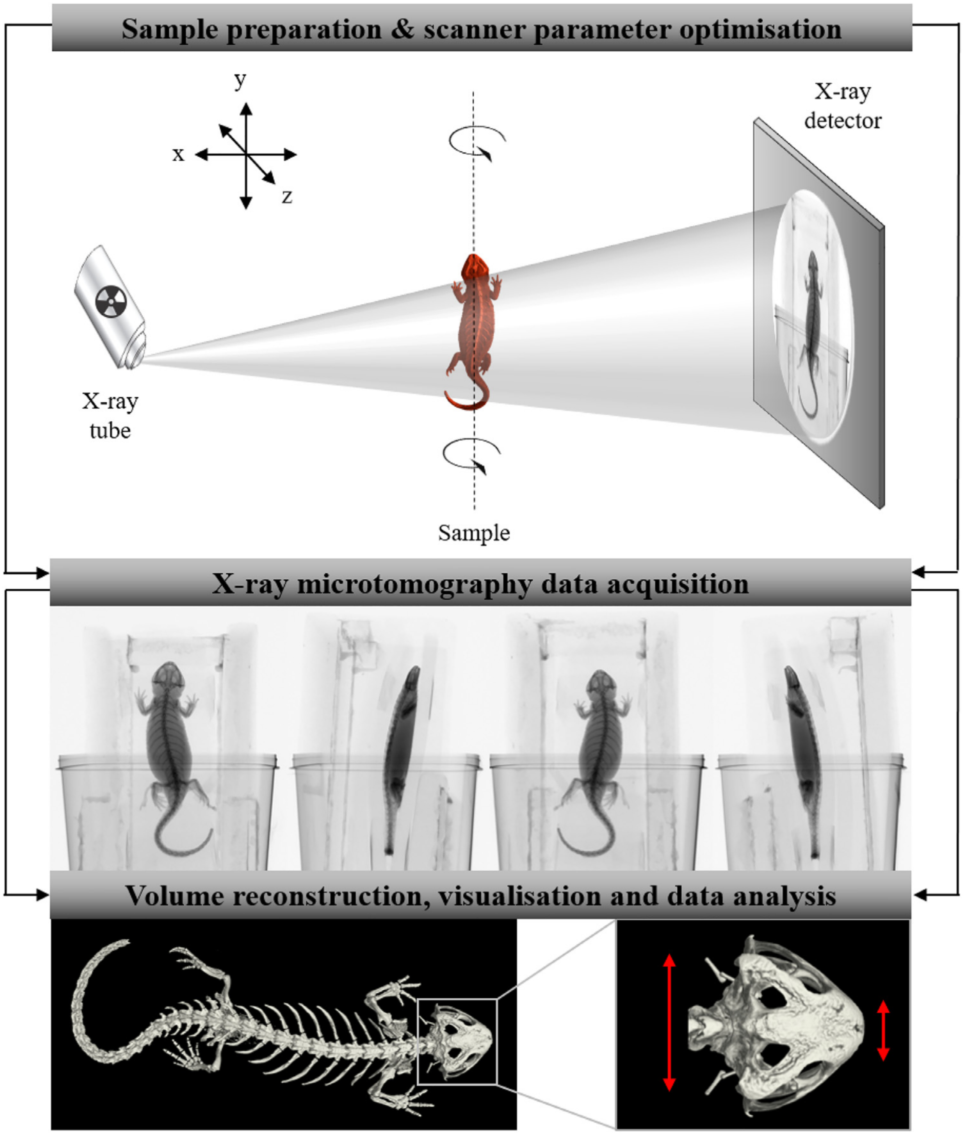

Fig. 1. Schematic of the X-ray microCT technique illustrated using a lizard as example, taken from a recent review of the use of microCT in herpetological research [3].

A schematic is shown in Fig. 1 to explain the basic concepts of a microCT scan. An object is loaded on a rotation stage which turns on an axis perpendicular to the direction of the X-ray beam. The X-ray beam is in a cone geometry emitted from a small spot, passing through and around an object and creating a shadow (or so-called "projection") image on a digital X-ray detector. Hundreds or thousands of images are recorded as the sample rotates through 360° (typically). These images are then used to mathematically generate a volumetric dataset where each three-dimensional pixel (volumetric pixel = voxel) represents the X-ray density at that location in the object - this reconstruction process is described in more detail in [7,8].

It is important to note that the "live" X-ray image (2D projection image) can be used for non-destructive testing (NDT) purposes, as a quick quality assessment. This 2D X-ray method is generally termed digital radiography (DR), especially in the NDT community and is well known for industrial testing purposes (for example to check metal castings for major voids formed during the casting process or to check electronic connections in circuit boards). Many X-ray systems commercially in use are high resolution digital radiography systems only, without any CT capability. These are lower cost than full CT systems, and are typically useful for quick inspection of objects including electronics [9], light metal castings [10,11], turbine blades [6] and even tyres and wheels, mainly for checking internal manufacturing irregularities, possible porosity and cracks. The added benefit of CT capability is the much higher detail that can be detected for the same flaw, and the associated higher confidence in the NDT test result. Not widely appreciated is the fact that most CT systems can do 2D inspections at the same or better quality than traditional lower-cost DR systems. This may be used in many instances to support industry

Table 1
Academic applications summary.

Category	Researcher affiliation	Topic of interest/analysis
Biological	Botany and Zoology Department	Lizard and snake morphology [3,28–35]
	Iziko Museums	Frog morphology
	Entomology	Beetles and larvae – tracheal system analysis
	University of Cape Town	Plant tissue
	University of Cape Town	Hermit crabs and marine biology [36–39]
	Rhodes University	Legless lizards – morphology assessment
	Botany and Zoology Department	Bird ear inner morphology
	Botany and Zoology Department	Plant root nodules – with and without bacterial infection
	University of Pretoria	Eggshell microstructure
Geological	Geology department	Gold deposition visualization
		Sulphide distribution
		Granite core petrology [40]
		Zinc core - exploration
Medical	University of Cape Town	Human hair morphology
	University of the Western Cape	Tooth and root canal morphology; also titanium tooth implants – comparative design analysis
	Africa Health Research Institute	Human lung tissue – TB lesions and lung tissue morphology
Physics	Physics Department	Accelerator target production – quality inspection of laser welds and internal target material [41]
Agrisciences	Horticulture	Disease development in fruit – apples and pears
	Horticulture	Tree branches for disease development
	Horticulture	Pomegranate fruit – post-harvest preservation
	Horticulture	Tobacco leaves
	Midlands State University, Zimbabwe	Horned melon – peel thickness and inner morphology
	Food sciences	Dough and bread analysis
	Wood science	Local wood density radial variation; also analysis of wood polymer composites; also pollination success study of tree seeds [42]
	Soil science	Permeability of sandy soils
	Agronomy	Potato density variations relating to disease
	Agricultural research council	Vineyard roots – checking insect infestation
	Animal sciences	Giraffe heads – horn analysis
Engineering	Mechanical engineering	Metal additive manufacturing parts CAD variance
	Industrial engineering	Porosity quantification of porous metal variants for flow device
	Central University of technology	Various additive manufacturing projects including process optimization and qualification [43], medical implant quality inspection, correlating porosity with mechanical properties of test parts [44], new alloys, and lattice structures [45–47]
	Vaal University of Technology	Metal additive manufacturing mechanical test parts – porosity; also powder analysis
	Civil engineering	Fibre reinforced concrete – pull-out tests [48]; concrete time lapse during setting; asphalt porosity analysis
	Chemical engineering	Metal deposition layer analysis on plates
	University of Cape Town	Ice pore structure in ice cores
Archeology, paleontology, heritage preservation	Private user	Fossil embedded in rock
	University of Toronto	Fossil embedded in rock
	University of Cape Town	Fossilized rock beds – image fossils [49]
	University of Cape Town	Fossil bones – two student projects describing bone morphology
	Stony Brook University	Hominid fossils for description [50]
	Iziko Museums	Fossil bone morphology description
	University of Witwatersrand	Fossil descriptions
	National Museum of Bloemfontein	Creating 3D models for museum user experience using 3D printed replica's

work or to allow sample selection for CT scans. For example, when 100 samples are available, and it is not clear which have some internal features of interest for a research project, DR images might help to identify the appropriate samples for full CT scans, i.e. less scans are required simplifying the data analysis, cost and efficiency of workflow. Another efficient way of using this workflow is for industrial inspection – when DR images show potential flaws, full CT scans can then quantify the size and location to ascertain better if the part passes or fails the inspection.

Sample preparation for microCT is negligible, but some important criteria are that the sample must be loaded in a low-density container or material which can be attached to the rotation hardware of the instrument. The sample must be rigidly

Table 2
Industrial applications summary.

Category	Analysis and material type
Metals	Steel cores analyzed for detailed porosity distribution as indicator for material degradation in aging industrial plant
	Light metal corrosion and identification of corrosion location in radiators and similar materials
	Analysis of laser weld seams in large parts
	2D X-ray inspection of metal part for porosity
	Analysis of large bracket with welded areas – weld quality inspection
	Light aircraft engine blocks and heads – dimensional analysis & porosity
Polymer and composites	Analysis of quality of complex production runs of packaging and preservation materials for fresh produce
	Polymer powder analysis for internal porosity, sphericity and particle size – used in commercial product
	Wax with embedded metal particles – distribution analysis
Electronics	2D X-rays of PCB's and microchips
Concrete and asphalt porosity	Asphalt porosity and permeability simulations
	Leaching of concrete – time lapse
Medical devices	Additive manufactured implants – quality inspection
	Heart valve design – leaflet thickness analysis
Additive manufacturing	Qualification tests of produced parts for porosity and manufacturing flaws
	Test parts – porosity analysis for process improvement
Failure analysis	Medical device failure analysis
	Military device failure analysis
Reverse engineering	Unique ring design
Metrology	Dimensional analysis of bottles and capping materials according to CAD specifications
	Plastic grinder analysis dimensional analysis compared to CAD and compared to prior version

attached and must not move, expand or shrink during the scan time, which may vary from a few minutes up to a few hours - typical is 1 h for good quality. Scan setup and optimization involves a process of ensuring the best possible parameters are set up for the scan which may be unique to every sample – each sample has different densities, shapes, sizes and requirements for the scan result, affecting the way that the sample is scanned in terms of system voltage, current, image acquisition time, number of projection angles, image averaging, resolution, etc. These are discussed in more detail in a review paper detailing all considerations and providing guidelines for scan protocols [12]. This aforementioned paper also discusses sources of artifacts and errors or scan problems which may degrade image quality and even result in failed scans.

MicroCT is known by many different names including CT scanning, microtomography, X-ray Computed Tomography (XCT), X-ray microscopy (XRM), amongst others. All these refer to the same basic technique, with differences in terminology often attributed to the varying resolution capabilities. On the upper end of the scale, medical CT scanning is well known and widely used to image details of the human body for medical diagnosis, and is limited to resolutions (voxel size/slice spacing) of 0.5 to 1 mm [7]. Industrial microCT (and large macroCT) range from 0.5 mm down to 5 µm voxel size [13]. NanoCT and X-ray microscopy instruments (and synchrotrons) can go down to below 0.5 µm [14]. Besides resolution, various other differences exist between commercial systems, with systems ranging from desktop to cabinet and even room sized systems, with obvious differences in the optimal size and type of samples suited to each. It is important to realize that there may be differences in image quality depending in the type of system used, the way it is used (skills and optimization process employed for parameter choices in scan itself), and the data processing itself.

MicroCT data processing is a hugely under-valued part of the process. Large image data sets can only be visualized and analyzed on relatively high-end computers with dedicated 3D data analysis software. While low-cost and even open-source options exist for 3D image analysis, the efficiency and advanced functionality of high-end software make it a game-changer for use for diverse applications, for industrial applications and for removing human bias in many analysis types. All these support its use in both academic work and industrial applications, with the latter also benefitting from standard analysis report outputs. The leading software in use in industry and academia is Volume Graphics VGSTUDIO MAX [15], with Avizo and Amira also often used in academic environments [16].

Something that is emerging in recent times is the use of standardized workflows, using entirely or semi-automated image analysis recipes for particular applications – examples of this are found in a series of methods developed for additively manufactured parts for checking microporosity and processing induced flaws in coupon samples [17–21]. The Stellenbosch CT facility uses Volume Graphics VGTUDIO MAX software for all image analysis and all users then get access to the freeware myVGL which allows to view the data and analysis performed.

The simple overview of microCT provided here is relatively brief and more details can be found in a number of recent reviews of the technique for materials sciences [22], industrial applications [9], geosciences [23], food sciences [24], biology [25], biomimicry [4], herpetology [3], concrete and asphalt building materials [5] and additive manufacturing [1]. These are only some application fields, and the aim here is not to provide a review of the technology but rather introduce the reader to the field and provide the context of the use of this technique in Africa. Readers unfamiliar with 3D data can freely access such data at the Gigascience database [26]. This particular dataset comprises microCT scans of varying resolution of a Jackson's chameleon (native to East Africa), including 3D printable surface files.

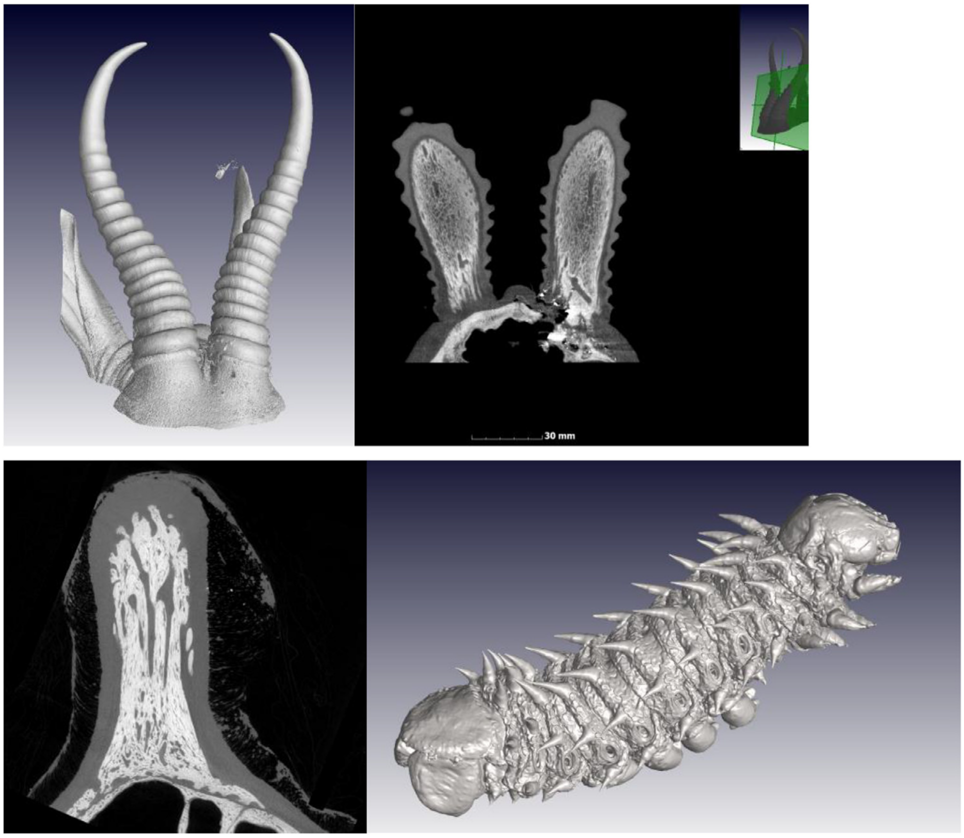

Fig. 2. Uniquely African biology – Springbok head and horns – CT 3D and slice images; Giraffe horn microstructure (slice image) & Mopane worm (3D image). Images courtesy of Prof Louw Hoffmann (University of Queensland, Australia).

Overview of applications in Africa

The main aim of this paper is to answer the question "what is it used for in an African context?" The answer to this question is not simple. The applications are definitely different than those in similar facilities in leading 1st world countries, but to explain how these are different is not a simple task. We decided to explain this by providing an overview of all work done at the Stellenbosch CT facility during 2018, both academic (Table 1) and industry work (Table 2). This overview is intentionally provided with limited details. For academic work, much of this might still be in preparation for publication. For industry work, details are limited due to confidentiality and sensitivity of some information, but enough information is provided to give insight into the type of work done. This clearly shows the diversity of applications and identifies some key trends. While 2018 is only one year, and the work type varies year by year, this provides a good overview and insight into how the technique may be used most efficiently in Africa in a local context.

Academic applications

Since microCT is an immensely powerful non-destructive imaging tool, its academic applications are extremely diverse, ranging across almost all fields in natural sciences, agrisciences, medical sciences and engineering. A prior facility description publication for the Stellenbosch CT facility outlined some of these applications in the growth phase 2012 to 2016 [27]. In this section, all academic work completed in 2018 is summarized, and some selected examples are presented. This acts as a representative "snapshot" of the work done in a mature facility of its kind. Table 1 provides a summary of the analysis types, including affiliation of researchers involved. This is followed by selected examples with descriptions of the scientific question in each case.

Biology

There are a variety of fascinating and visually impressive microCT studies in biological sciences. To provide an African perspective, we present here in Fig. 2 some local examples from recent work: a Springbok head, a Giraffe horn and a Mopane worm. All three these are uniquely African and have most likely never been scanned anywhere else in the world.

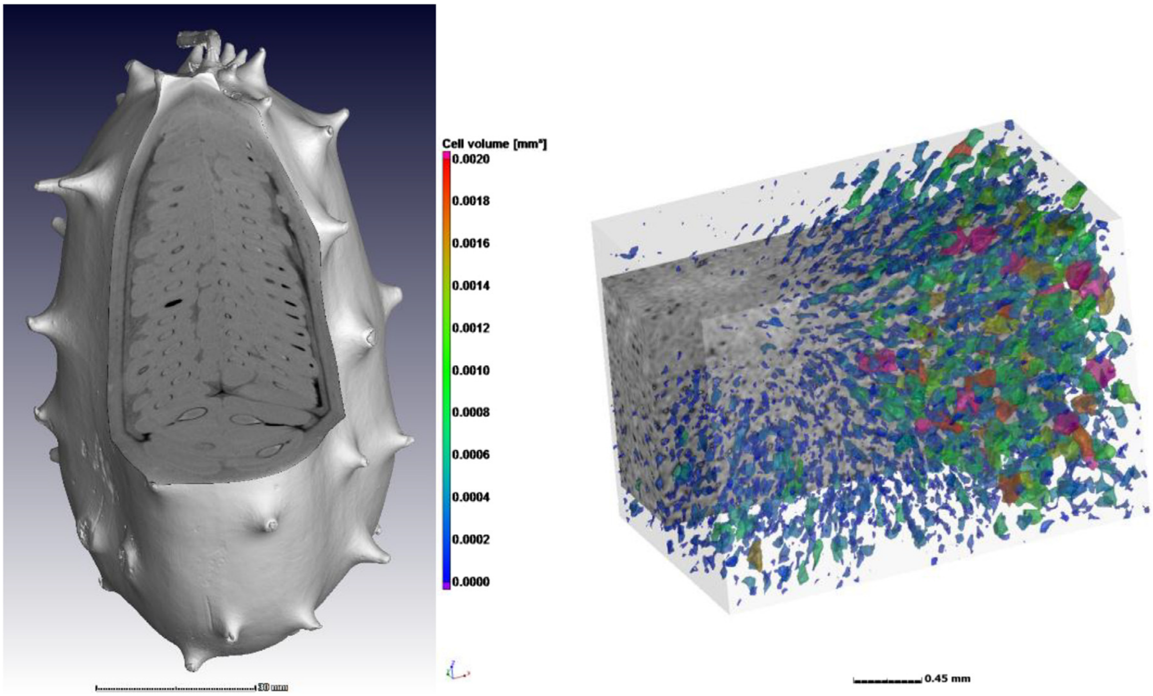

Fig. 3. Agrisciences examples: (a) a horned melon from Zimbabwe and (b) foam structure analysis in a small volume of apple fruit. Horned melon image courtesy of Dr T Muziri (Midlands State University, Gweru, Zimbabwe). Apple pore structure image courtesy of Dr Elke Crouch and Kenias Chigwaya (Stellenbosch University).

The Springbok is the national animal of South Africa and is used to represent the national rugby team; the Giraffe is a uniquely African animal and the Mopane worm is a staple food in some cultures in Southern Africa.

Agrisciences

Applied agrisciences are locally important, and various projects are especially ongoing in horticultural work – specifically looking into ways to minimize and prevent fruit diseases and disorders. Wood sciences make use of microCT for density measurements, while food sciences use microCT for porosity and texture analysis of food products. Fig. 3 shows a unique fruit – a horned melon from Zimbabwe, as well as the 3D porosity analysis of pore spaces in apple fruit.

Engineering

The varied engineering research projects are summarized in Table 1 and include primarily analysis of asphalt and concrete, and metal additive manufactured parts. Metal additive manufacturing is a fast growing manufacturing technology allowing new complex and lightweight designs which were previously impossible to realize [51]. With all new manufacturing technologies, there are steep learning curves, and microCT is extremely useful in optimizing these processes, checking for unexpected flaws and ensuring structural integrity in parts [1]. Some standardized workflows have been recently proposed and used in a round robin test of parts produced at various additive manufacturing facilities worldwide, and all tested at the Stellenbosch CT facility using the same protocols [52]. The use of such standardized and streamlined workflows assists in reproducibility and allows higher throughput and eventually lower cost structures due to the fixed method devised, and will eventually assist not only this field but many others. In addition to process improvement and quality inspection for flaws, image-based simulations (finite element modeling) on microCT data of real parts can assist in various engineering research projects to better understand the effect of various imperfections on the performance of a part.

The example shown in Fig. 4 is an additively manufactured titanium alloy part produced on the Aeroswift system – the largest metal powder bed fusion system in the world presently. This part contains lattice design which is meant to create load-bearing but lightweight structures and was intended to be a part of an experimental vehicle which contained additively manufactured components [53].

Asphalt and concrete make up another important part of engineering work but is discussed below in the industry applications due to many commercial applications of this methodology. A recent review paper discusses this in more detail [5].

Paleontology & heritage

Paleontology and archeology are fields which have embraced the use of microCT for the full morphological descriptions of fossils. Two other tomography-based research facilities in South Africa are primarily scanning fossils, i.e. the facilities at the

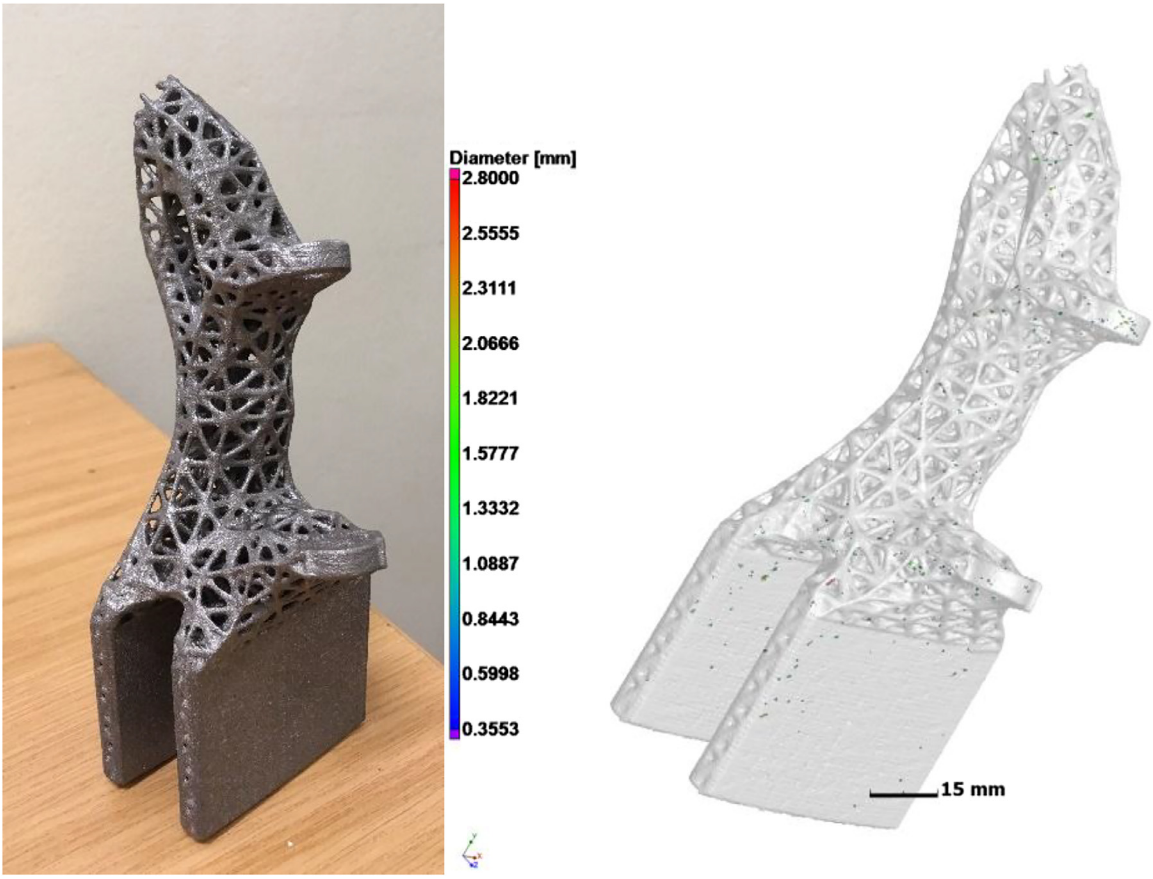

Fig. 4. Light-weight bracket produced by metal additive manufacturing, produced on the Aeroswift system – the world's largest metal powder bed fusion 3D printer developed in South Africa. Images courtesy of Marius Vermeulen (Aeroswift) and taken from [51].

University of Witwatersrand, and the facility at the Nuclear Energy Corporation of South Africa (NECSA). In both cases, large numbers of collaborators take part in microCT-based studies of fossils, many of which are hominids. It is worth mentioning that many African fossils make their way to synchrotrons for scanning. There is currently an effort to push for an African synchrotron [54], which is still in pre-funding stages. In support of such initiatives, local expertise and facilities also need to be developed prior to such large-scale investments. X-ray tomography laboratories and 3D image analysis expertise are included in this requirement. One example highlighted in Fig. 5 is the Florisbad cranium which was recovered in 1932 by Thomas Dreyer and Willeboer Venter at the Florisbad spa some 45 km from Bloemfontein, Free State Province, South Africa, and is one of the first fossil hominin skulls to be found in Africa. This specimen was scanned for the first time in 2018 at the Stellenbosch CT facility which revealed an enamel pearl [55].

In the context of heritage preservation, the digitization of museum specimens is becoming increasingly important, and microCT is one of the best ways to record a full 3D record of an object. In some cases this is for digital preservation, i.e. saving information of specimens digitally to preserve their information despite possible damage or loss to the actual specimen. In some cases digitization may assist in sharing of specimen information, e.g. in the form of "cybertypes"[3], digital equivalent of holotypes and paratypes, which can be shared easily among researchers. Finally, in some cases digitization can assist in an improved museum experience for the public. This latter aspect becomes especially useful when 3D printing replicas from microCT scans, which allows handling of the replicas for a hands-on museum experience. In some recent work, a series of museum insects including scorpions and mites were scanned to generate models for 3D printing, and these will be used to provide a museum experience for blind museum visitors to the National Museum in Bloemfontein.

Industrial applications

Industry applications of microCT are seldom reported in the scientific literature – mainly due to client confidentiality usually involved. One review paper of industry-applications is reported in [9], but this is focused on 1st world countries. Other examples of facility descriptions highlight the type of academic applications focused on [56]. The work reported here and summarized in Table 2 shows all industry work done at the Stellenbosch CT facility during 2018. No client names

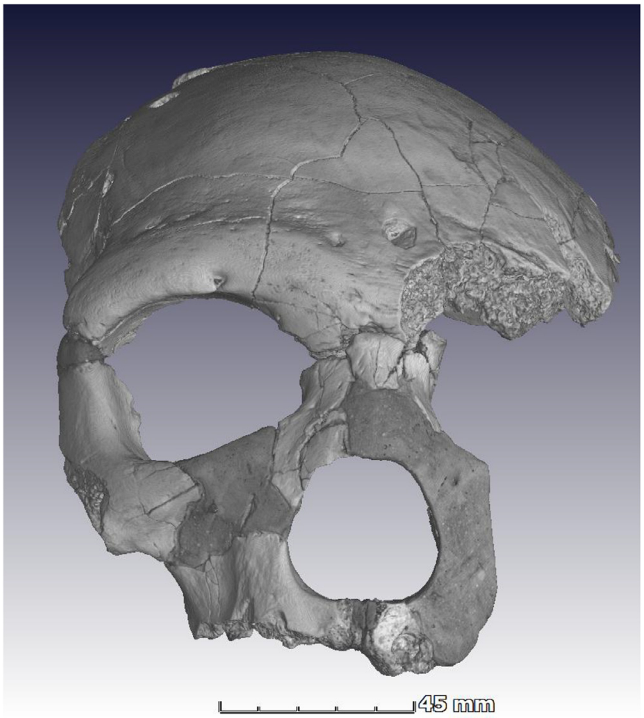

Fig. 5. Volume rendering of the Florisbad cranium from MicroCT scan images obtained at the Stellenbosch CT facility in 2018. Reproduced with permission of F.E. Grine and the National Museum, Bloemfontein.

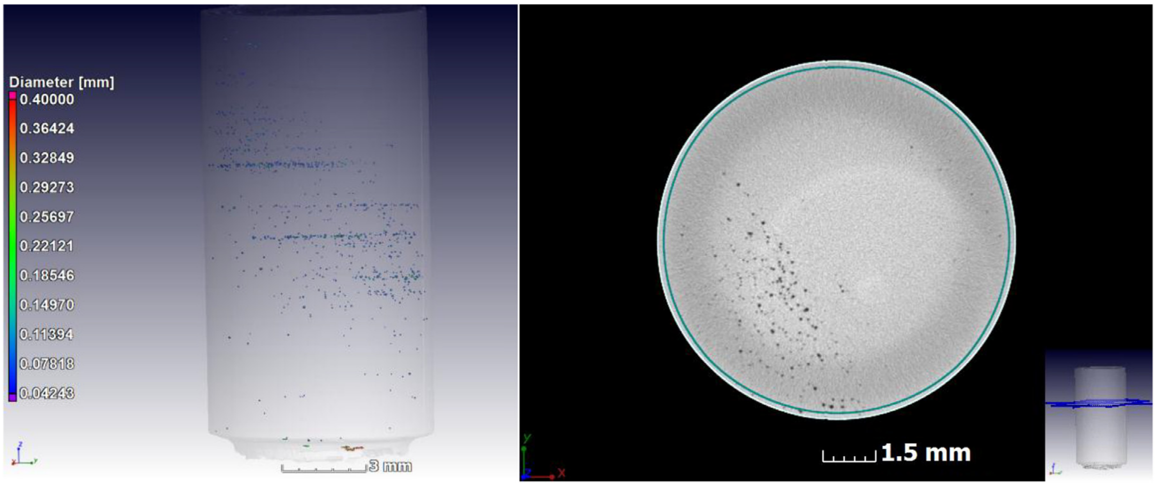

Fig. 6. An example of steel microporosity analysis for an industry client, showing (a) 3D distribution and (b) slice image (black spots are pores).

or sensitive information is shared. The selected examples which are demonstrated have been approved for sharing with limited information and the aim is simply to showcase the type of work done typically in this location, which is different from similar facilities in Europe or the United States.

Metals

One of the largest applications remains metal analysis, especially for porosity and other flaws which can be related to reduced or compromised mechanical properties of the part. An example is shown in Fig. 6 for this type of analysis, where the porosity total percentage, maximum pore size and its 3D distribution is important. This is a steel core sample of 8 mm diameter. This sample size is required to obtain high resolution images - in this case, 10 µm voxel size. The presence and distribution of the pores are important in this application.

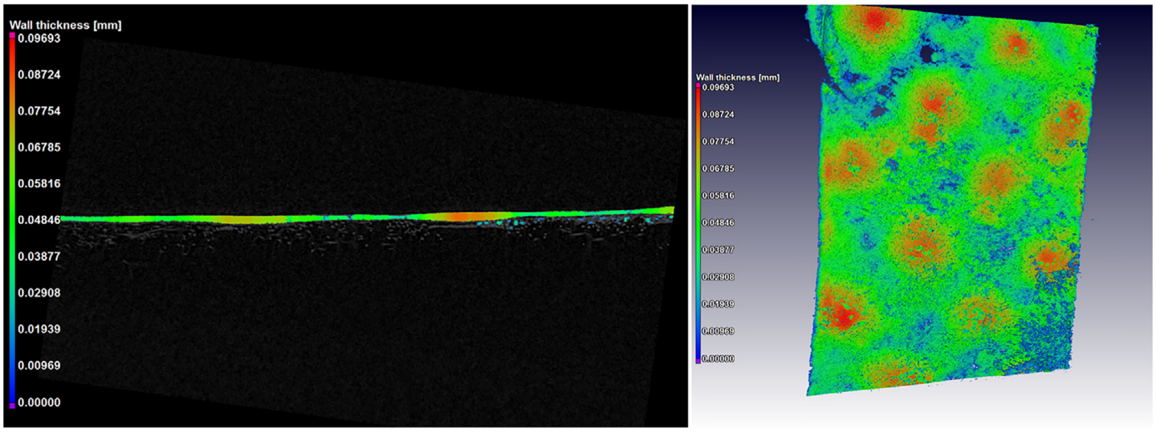

Fig. 7. Sheet-like packaging material analyzed for thickness distribution – showing variation in this case (a) slice image and (b) 3D image.

Fig. 8. Example of flaw detection in welded zone of an aircraft engine-mounting bracket.

Packaging material

Some packaging materials are critical to ensure product lifetime such as in the case of fresh produce. The example shown here is one where a preservative is embedded in a sheet-like material. The quality and integrity of the material hosting the chemical preservative is of high importance. MicroCT was used to assess the structural integrity and performance of this material under different environmental conditions, which can be used to improve product quality as demonstrated in [57]. Fig. 7 shows a cross-sectional and a 3D view of the sheet-like material with a thickness analysis showing thickness variations – these thickness variations should remain within certain specifications.

Aerospace

Due to the criticality of aerospace components, microCT is the preferred test method to ensure lack of major flaws. The example shown in Fig. 8 is a welded bracket approx. 600 mm wide, circular in shape, with numerous weld zones that need inspection for inclusions and pores. This bracket is designed to hold the engine of a light aircraft and needs careful inspection. The figure shows a large pore (black dot), and this bracket was scrapped in this case due to this and other flaws found.

Civil engineering

The analysis of large connected pore spaces in asphalt allows for permeability analysis which is useful for civil engineering firms when investigating quality issues with asphalt (road) surfaces. The analysis is standardized using a 70 mm core sample, allowing direct comparison between different types of asphalt surfaces. This is described in more detail in a recent review paper on the topic [5]. In Fig. 9 is shown the CT slice image (greyscale), the porosity 3D view and the permeability simulation shown in slice and 3D views. This permeability simulation makes use of image-based simulation of laminar flow of water in connected pore spaces, using inlet and exit planes, sealed edges and a defined pressure difference between inlet and outlet planes. This allows visualization of high-velocity flow paths, and estimation of absolute permeability values based on the pore network.

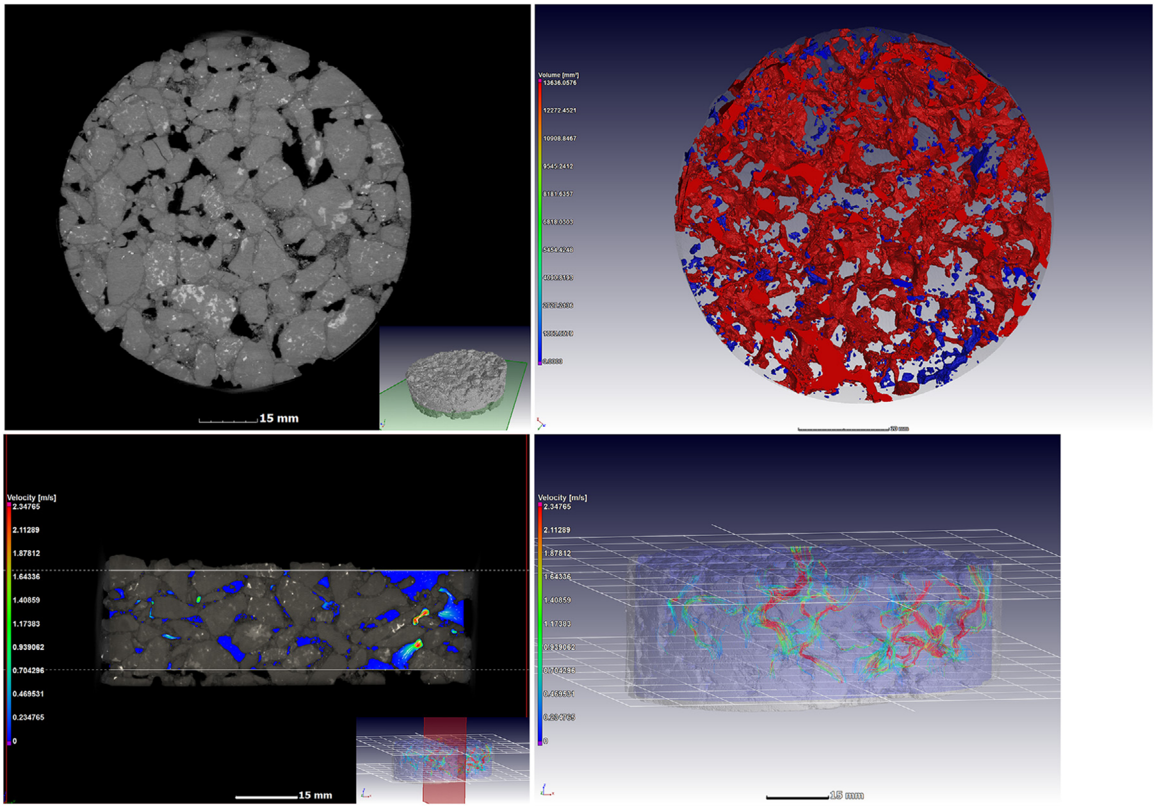

Fig. 9. Asphalt (70 mm diameter sample) for porosity (top) and permeability analysis (below) shown in both slice and 3D views.

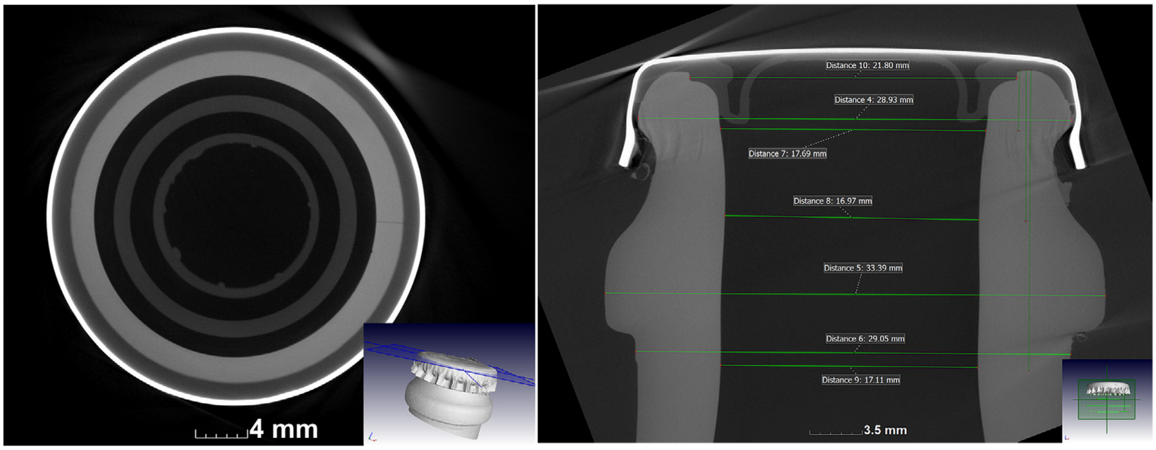

Fig. 10. Metrology of a bottle – accurate dimensional measurements against specifications.

Metrology

Metrology refers to advanced dimensional analysis, which is sometimes required to check whether a product is within manufacturing specifications. The example shown in Fig. 10 is such an analysis of a bottle neck, to inspect whether some leakage found might be due to bottle manufacturing imperfections. In this case, a small crack is found underneath the cap, which might indicate the capping process causes problems – the bottle was found within specifications.

Medical devices

Medical devices are critical and need careful inspection not only for flaws but also for manufacturing (geometrical) tolerances. In this example, an experimental heart valve was analyzed for thickness distribution, while housed inside a metal frame. This makes the scan parameters unique and challenging since the leaflet itself is not only very thin but also of a

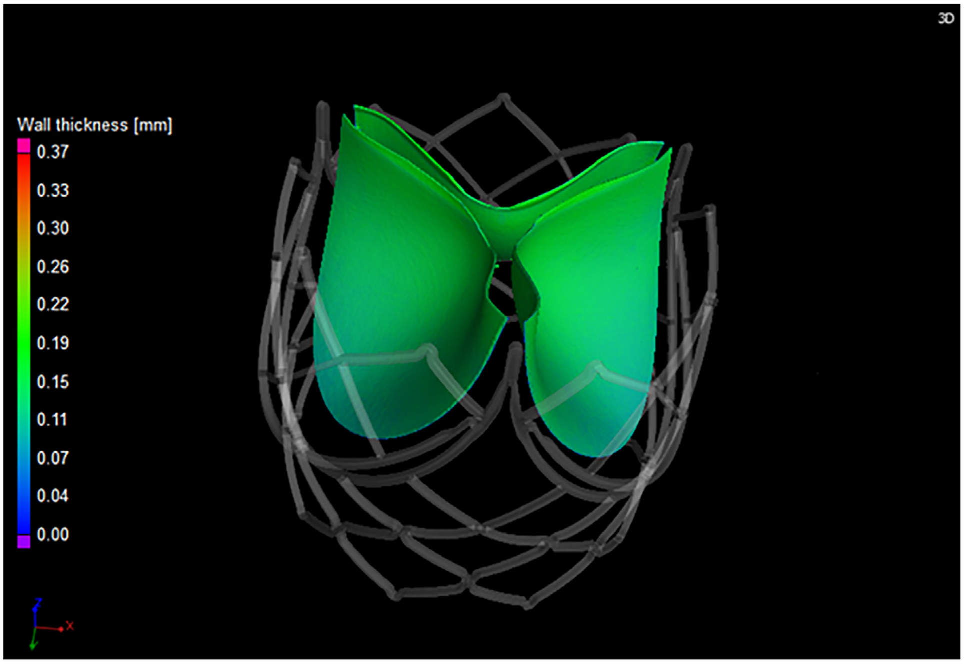

Fig. 11. Medical device characterization – a polymer heart valve leaflet thickness analysis.

low-density polymer material (much less dense than the titanium frame). Nevertheless, a thickness analysis (Fig. 11) shows the even thickness distribution in the leaflet – which ensures its good functioning. This can be used in optimizing the production and also correlating failures during testing with thickness inconsistencies.

MicroCT facilities as research “watering holes.”

Worldwide there are numerous facilities providing X-ray tomography services, some focused on industry work, but many focused on academic work. In Africa the only facilities thus far exist in South Africa, with a regular biennial conference held in collaboration between the three main facilities which have been in existence from 2011/12 – this IMGRAD conference (IMaGing with RADiation) showcases the wide variety of work done in microCT applications in South Africa and gives an opportunity for post-graduate students to share their work and build networks. Besides these facilities, some African scientists make use of synchrotrons (as also mentioned above in a previous section). There is currently significant interest in developing an African synchrotron facility [54] which builds on the recent establishment of a synchrotron, including a tomography imaging beamline in the Middle East (SeSAME) [58]. Local X-ray tomography laboratories and synchrotrons can complement one another very well – especially since local laboratories allow easier access, especially for image analysis and image processing (even of synchrotron data). Many more scans can be done at local laboratories, and when some limitation, eg. in contrast or resolution occurs, a full application for synchrotron beamtime can be done.

Local expert facilities such as these act as a watering hole, where a wide variety of researchers come together to use a shared resource, expertly maintained and offered. This concept allows highest quality outputs to most people in the lowest cost way. Also, this “watering hole” concept, where many different types of researchers meet with a shared goal and shared a resource, allows unexpected advantages of interdisciplinary and cross-disciplinary research ideas. MicroCT is not the only technology or enabler of such research “watering holes” – but microCT works well because it is used by so many different research fields. It is also something that often requires highly skilled personnel to get the best result, so operationally it works well as a watering hole. It is also very visually appealing – so can be understood widely and therefore the educational and science-communication aspect is useful. The main promotor of the watering hole concept is the ability to have expert knowledge and skills and being willing to share these resources.

Conclusions

All academic and industrial work at the Stellenbosch CT facility during 2018 was presented, and specific cases have been highlighted. Some specific points of interest, which contribute to the success of this facility locally, is the low amount of bureaucracy and ease of access to get microCT scans done, which also allows high throughput. Despite all the marketing and expected usage of geological applications, very little geological work is done at present, and none industrial (no mining companies). This is an interesting observation and might be related to the current pressure on the mining industry. Another interesting observation is a large amount of civil engineering (asphalt) samples from various industries. This might be related to the standardization employed in simplifying the workflow for this application. A reasonably large number of fossils were also scanned, despite the other facilities locally also doing this. Finally, the main workhorse method which is globally relevant, is the porosity analysis of metal parts, indicating structural integrity issues in critical parts.

This paper has shown the capabilities and potential of the microCT technique within in African context. This type of facility is one step upwards towards allowing world-class research by African researchers in Africa, making the Stellenbosch CT facility a model for future similar facilities in Africa. Not only does the facility support its own research interests but obviously a wide variety of other researchers make use of it. This leads to more high quality research and training of students than would otherwise be possible. The microCT technique is clearly one example where the watering hole concept can be applied to uplift research and technology in Africa, but collaboration and excellence is critical to its success. We hereby invite African researchers to utilize and adopt this new technology.

Acknowledgments

All users of the Stellenbosch CT facility are acknowledged for their support and contribution to our sustainability. All users are also encouraged to publish their results to assist in showcasing the huge potential of the technique in various fields. We especially would like to thank the industry users who were willing to share their examples in this paper. The equipment purchases were funded by the South African National Equipment Program (grants UID72325 and UID88057), administered by the National Research Foundation: this support is thankfully acknowledged. Opinions expressed here are those of the author and not to be attributed to the NRF.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sciaf.2019.e00061.

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