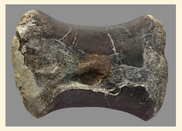
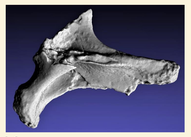
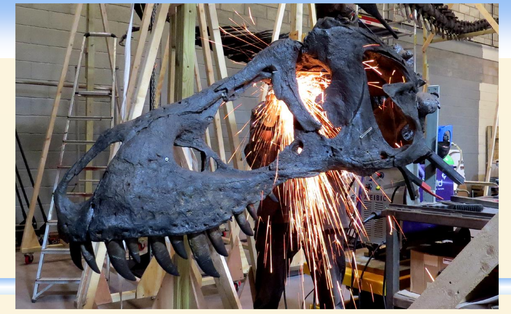
21st century Rex: maximising access to a privately owned *Tyrannosaurus rex* in the digital age.







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Abstract

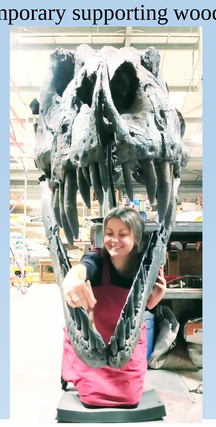
'Stan', a ~70% complete *Tyrannosaurus rex* skeleton, recently sold for 31.8 million US dollars to an unknown buyer, pushing up the price of all such skeletons way beyond the budget of most museums. Wealthy private individuals are purchasing such specimens and sometimes putting them on public display but leaving them in an intellectual limbo, unable to be studied and published. However, recently a ~20% complete *T. rex* skeleton known as 'Titus' was excavated in Montana, shipped to the UK, had casts of Stan's bones added to complete the skeleton, and was mounted and placed on display in the Nottingham Natural History Museum in a temporary exhibition (the first time a mounted *T. rex* skeleton containing real bones has been on display in England for decades). Importantly, before the mounting process began the real bones were 3D scanned in detail using photogrammetry. The resulting digital 3D models were sent to palaeontologists in America who studied them and produced a palaeopathology paper ready for publication before the mounting process was even complete. All the identifiable bones were 3D printed for display in the exhibition and permanently accessioned into the museum's collection, making physical as well as digital replicas of the bones both accessible and publishable.

Mounting the skeleton

It took a year for Nigel Larkin to mount this 12m long 3.5m tall skeleton in his workshop in Shropshire (Fig 1).

He had to assess and conserve the bones that comprised the ~20% complete skeleton and merge them with polyurethane casts of bones from a complete set of a replica skeleton of 'Stan', one of the most complete *T. rex* specimens ever to have been found. However, the casts of Stan were a shiny homogenous plain brown colour. They had to be scrubbed with wire brushes and acetone to remove the shine, then Gemma Larkin painted all of the casts to match the fossil bones of Titus (Fig 2).

He made the armature from sections of steel either welded or bolted together after being cut, heated and bent to the required shapes. Getting all the bones in their right positions relative to one another so that the mount could be designed was quite a juggling act, involving gantries, webbing, ropes, pulleys and temporary supporting woodwork (Fig 3).



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The armature had to be made in sections so that the mounted skeleton could be dismantled, crated, loaded on to lorries and transported to the Nottingham Natural History Museum at Wollaton Hall. Here, the skeleton was carried up stairs and through narrow doorways into the Willoughby Room where it would be reassembled and put on display for the next year or so. A team of people took a week to rebuild the skeleton. A plinth was constructed over the metal base.

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Photogrammetry and 3D printing

Before the mounting of the skeleton could begin, all of the fossil bones and bone fragments were recorded in great detail with 3D photogrammetry scanning by Steven Dey of ThinkSee3D, a specialist in 3D imaging for heritage institutions. Photogrammetry is a computational method which transforms multiple digital photographs of an object, taken from many different angles, into a high resolution 3D digital model. Photogrammetry is particularly suited to 3D modelling highly textured objects like bones and fossils and for this reason it was chosen as the method to 3D scan the Titus specimen.

Several hundred digital photos must be taken from a range of angles in several orbits around the target to achieve a high resolution and accurate photogrammetry model. Photogrammetry software uses points on these photos to calculate the position of the cameras in 3D space relative to the target object and then through a process of depth triangulation, across thousands of points, builds a detailed digital 3D surface which is meshed into a closed hull 3D model. The original photos are then projected back onto the 3D surface to give a very detailed colour surface texture. To do this precisely and efficiently, the use of a mechanised turntable with an automatic camera shutter release was used attached to a full frame Canon DSLR camera (Fig 4). The bones were prepared for scanning and handled by Nigel Larkin.

A set of 300 to 400 photos of each of Titus' bones was taken and processed in the photogrammetry software (in this case Agisoft Metashape). The outputs of the work were two sets of 31 models; a high resolution set with 5m polygons and a lower resolution set with 1m polygons (for online sharing) both sets had 8K photo textures.

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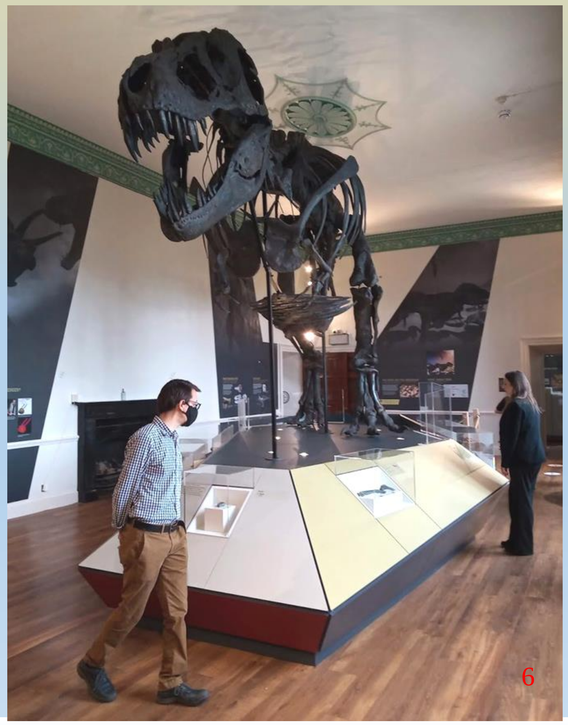
The finished models were metric scaled using Blender 3D (using scales in the 3D scene) and then loaded into Sketchfab for 3D model viewing online: https://skfb.ly/6ZCLv

The final 31 low and high resolution digital models were of a very high quality and showed lots of fine details (Fig 5). This enabled Dr David Burnham, a professor of Paleontology at the University of Kansas and Dr Bruce Rothchild, a world-reknowned expert in Biomedical Engineering at the Carnegie Museum of Natural History in Pittsburgh, to undertake the pathological and taphonomical research on Titus even though they were unable to physically handle the bones in person due to international Covid travel restrictions.

Physical replicas of all the real bones were 3D printed in colour in gypsum by ThinkSee3D for use in the exhibition so that the public could see exactly which bones had been found in the excavation in Montana. These were exhibited in display cases on the plinth around the specimen (Fig 6).



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Curation of the material

As well as being put on display for the duration of the exhibition, a set of 3D printed replicas of the original *T. rex* bones have been permanently accessioned into the Nottingham City Museums and Galleries service under the accession lot number NCMG 2021-7. The individual replicas will next be documented and allocated specimen numbers in the Nottingham Natural History Museum's (NOTNH) collection, where they will remain in perpetuity for future reference and study. The exhibition '**Titus: *T. rex* is King**' will run until the end of August 2022.

Discussion and conclusions

Unusually, right from the outset the owner of this *T. rex* skeleton was keen that although ownership of the physical specimen would remain in private hands, the skeleton should be on public display and – importantly – that despite this the material should be as accessible as possible to researchers. They wanted this to be seen as an exemplar project to encourage other private owners of important fossils to go to similar lengths to make the material accessible. Recent advances in photogrammetry scanning and 3D printing meant that this could be achieved swiftly and at least one scientific paper was ready for submission to a peer-reviewed journal before the mounted skeleton was ready for display. The 3D printed replicas of the original bones are an integral part of the exhibition and will remain accessioned in the museum collections when the exhibition is over, enabling the material to be referenced in academic papers.

References and further information

- You can read a National Geographic article about Titus here: *Titus-the-T-rex-is-coming-to-the-UK-this-summer-heres-why-that-matters*
- 3D digital models of the bones of Titus on Sketchfab: https://skfb.ly/6ZCLv
- A time lapse video of the installation can be seen here: https://www.natural-history-conservation.com/2021/TitusTimeLapse.mp4
- There is a 44-page guidebook that accompanies the exhibition, 'TITUS: T rex is King'.

Acknowledgements

We would like to thank: the whole team at Wollaton Hall, particularly Rachael Evans, for their help with the project; also David Hone; Dean Lomax and Phil Rye; and the private owner of Titus, who wishes to remain anonymous.