Chapter 2
Digitizing Methods for Paleontology: Applications, Benefits and Limitations

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Introduction

Over the course of the last decades computers have evolved from a useful tool for rapidly calculating large amounts of equations to an indispensable part of everyday life. Today, cars will not run if a chip is faulty, and communication not only by phone and email, but also by conventional mail depends on computer codes. Computer generated or edited sounds and images dominate advertising, and their influence on education and especially entertainment is rapidly growing.

Slowly, computers have also found their way into science beyond the classic number-crunching applications in, e.g., climate modeling and statistical analysis. They can be useful tools for taxonomy, e.g., for cladistic analyses or for archiving and analyzing taxonomic data (see Elewa 2010). As pointed out by Elewa (2009), however, there is a bias in the use of modern computing techniques for vertebrate paleontology. At the other end of the scientific process, publication has also "gone digital", with journals such as PLoS One. The first fully online journal with a focus on paleontology is *Palaeontologia Electronia*, which started publishing online in 1998, open to any new and promising technique and data format for presenting scientific data and results (MacLeod and Patterson 1998). Authors are actively encouraged to experiment with new data formats. As pointed out by Elewa (2007), many research institutions sadly are slow in adapting to this novel way of knowledge distribution, and need convincing to accept e-publication as equal to conventional paper journals.

Because even detailed 3D objects can now be depicted and animated quickly on ordinary office and household computers, due to the high demand of many computer simulation games on 3D graphics power, an ever growing number of scientists use these powers for vertebrate paleontology. A classic method for obtaining 3D data on a fossil, prepared or unprepared, is via tomography. This is "the representation of three-dimensional structure as a series of two-dimensional images formed

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from parallel section" (Sutton 2008: p. 1587). Tomographic methods allow study both of the external shape and internal structures. Sutton (2008) details the various different techniques, as well as typical examples of their use in paleontology, so that only a short summary is required here.

The slices (or tomographs) of a tomography can either be studied directly, or used to create 3D visualizations of the fossil. They can be obtained using a variety of methods, some of which are destructive. These include the first use of tomographic study of fossils by Sollas (1904), who described a machine "which was designed to grind parallel sections of fossils at exact intervals of 0.5 mm or more" (Sollas 1904: p. 259). These sections were recorded by photography, and structures were hand-traced on the photographs. Sollas mainly applied his method to vertebrates (e.g., Sollas and Sollas 1913), other researchers adapted and used it on a wide variety of fossils (e.g., Simpson 1933; Ager 1965; Kermack 1970; Kielan-Jaworowska et al. 1986; Sutton et al. 2001; Bednarz and McIlroy 2009). The study of internal structures of brachiopods became highly reliant on serial grinding after Muir-Wood (1934) first applied this destructive technique. From such photographs 3D visualizations can be created even from data decades old, as long as the serial images show consistently interpretable color or structure differences between materials, and the intervals between them are known.

With the advent of modern scanning techniques non-destructive tomography became possible. Initially, many research approaches centered on X-ray Computed Tomography (CT, described in, e.g., Hounsfield 1980; Kak and Slaney 2001), scanning specimens to make internal structures visible. While individual tomograms can be used the same way as a physical section, the extraction and visualization of internal 3D shapes is of especially interest. One of the first fossils to be studied through X-ray CT scanning was the Eichstätt specimen of the famous *Archaeopteryx lithographica* von Meyer (1861) (Haubitz et al. 1988). This study used each slice singly, and was limited to fairly rough images. The first *Archaeopteryx* body fossil ever found, the London specimen, was later also scanned to gain information on the brain and inner ear (Alonso et al. 2004), which due to technical progress could be gleaned from high resolution 3D visualizations of the skull, both entire and in parts.

Today, because of the increasing availability of CT scanning opportunities (every hospital has at least one scanner), the use of CT scanning has practically become standard for specimens from which interesting discoveries are expected. Scans can also be used to plan, improve or replace preparation (e.g., Clark and Morrison 1994; Fraser et al. 2007), in which case the removal of artifacts is especially important (McLean et al. 2001), or even make preparation redundant. Still, the main use of CT data remains the study of already prepared fossils (e.g., Brochu 2000, 2003; Wedel 2003a, b; Sampson and Witmer 2007; Witmer and Ridgely 2008), used for research tasks that would be more difficult, more time consuming, or simply impossible if the real fossils were used.

There are several other non-destructive methods besides classic CT for obtaining tomogram stacks, including neutron tomography (NT, Schwarz et al. 2005) and, less suited for paleontology, magnetic resonance imaging (MRI, e.g., Clark et al. 2004). Most important, however, was the development of X-ray micro-tomography or

high-resolution X-ray computed tomography (XMT, HRXT or HR-CT, e.g., Rowe et al. 2001; Carlson et al. 2003). This technique allows resolutions down to 5 µ, compared to several hundreds of microns for the best medical CT scanners. However, medical scanners were developed and optimized for the study of humans (Hounsfield 1980), and thus machines that allow scanning of specimens up to the size of obese human adults can be found in practically any large hospital. In contrast, micro-CT scanning is limited to much smaller objects, e.g., fossil fruits and seeds (DeVore et al. 2006), or small fossils preserved in amber (Dierick et al. 2007).

The University of Texas' Jackson School of Geosciences owns a HR CT scanner, which is used to supply the university's DigiMorph project, a special web library of CT-based 2D and 3D visualizations of the external and especially internal structures of extant and extinct vertebrates (digimorph.org), housing over a terabyte of data.

Synchotron radiation X-ray tomographic microscopy (SRXTM) uses a sub-atomic particle accelerator called a synchotron to create even higher resolutions and extremely crisp images, and was applied by Donoghue et al. (2006) to study fossil embryos shedding light on the initial radiation of multi-cell life. It has also been found by Smith et al. (2009) to be an excellent tool for virtual dissection of fossil and extant plants.

There are also a variety of methods to obtain digital representations of physical objects that scan only the external surfaces. Data can be gathered by (stereo-) photogrammerty, laser scanning, ultrasound or mechanical digitizing. Even caliper measurements can be translated into a 3D shape, if a sufficient number of them per surface area are taken in a defined reference system. The data type collected by laser, mechanical and sonic scanning is at first a series of point vectors. Various ways of transcribing this information to a computer aided design (CAD) program or other software exists, e.g., as individual point objects, as point clouds (groups of point objects), as curves (series of connected point objects) or as interpolated curves (mathematical formulae derived from a series of points). Often, polygon meshes are calculated from the point clouds. A polygon mesh, or polymesh, consists of a large number of triangles (and sometimes squares) connecting neighboring points, and is an easily transferable and editable way to represent a surface or body. The surfaces extracted from CT data are usually are also created as polymeshes.

Mechanical digitizing (Wilhite 2002; Mallison et al. 2009) involves a robotic arm, the tip of which is placed where one desires to record data, so that the density of surface point data collection is to a certain degree at the operator's discretion. This allows much smaller file sizes for simple fossil shapes than other digitizing methods, without extensive post-digitizing editing.

There are a variety of optical digitizing systems, only a small selection of which can be discussed here. For small specimens like mammal teeth, a number of techniques have been successfully employed, e.g., in for creating a paleoanthropological database (Kullmer et al. 2002), for studies on Recent and fossil human skull shapes (Subsol et al. 2002) and for studies on functional morphology of, e.g., the skull and teeth of bears (Engels 2007). Optical digitizing works through the principle of optic triangulation, using CCD cameras (CCD = charge coupled

device; well known from digital cameras). The technique and mathematical methods involved are described in, e.g., Breuckmann (1993).

These and other digitizing methods each have their advantages and draw-backs, their cost and the time one needs to invest to learn and apply them differs greatly, and the potential uses of the resulting data, which depends mostly on the resolution and file size, also vary. Here, some important methods suitable for paleontology will be discussed in general terms (i.e., specific equipment or programs are not mentioned), to give a broad overview that helps researchers choose the method that best fits their intended research. Chapter 8 discusses photogrammetry and especially laser scanning in detail, thus these receive an abbreviated treatment here.

Institutional abbreviations:

GPIT – IFGT collection numbers

IFGT – Institute for Geosciences, Eberhard-Karls-University Tübingen

MB.R.### – Collection numbers of the MFN

MFN – Museum für Naturkunde – Leibniz Institute for Research on Evolution and Biodiversity at the Humboldt University Berlin

Applications, Benefits and Limitations

Digital files can take the place of the real physical object for many tasks, provided the accuracy is sufficient for the task at hand. For example, digitized ammonites can be measured digitally the same way real fossils can be measured with a caliper. However, in this case the gain from the digital file use is minimal or nonexistent. Worse, inaccuracies in the digital file stemming from careless digitizing may degrade the accuracy of the measurements, lowering the quality of any work based on the data. Digitizing a fossil just because it can be digitized is usually a waste of time, effort, and money. At the beginning of every project involving digitizing a detailed assessment of the digitizing requirements must be conducted, based on the intended use of the resulting files, with the specifications of the digitizing technique for accuracy, time required, and cost taken into account. Thus, before a discussion of the technical details of various digitizing methods for paleontology a few basic questions need answering: Why should anyone digitize a fossil? What can we use digital files for? What can be digitized, and which objects are not suitable? What are the advantages of using digital files for specific tasks, and what are the limitations that must be kept in mind?

Research

The most obvious use of a digital file is scientific research. The simplest form is the direct scanning of complete specimens as mentioned above for *Archaeopteryx*. Another typical example is the use of digital files of vertebrate bones in biomechanical studies (Stevens and Parrish 1999, 2005a, b; Hutchinson and Garcia 2002;

Hutchinson et al. 2005; Christian and Dzemski 2007; Mallison 2007, 2010a, b, c; Sellers et al. 2009). Real fossil bones of large animals are simply too heavy to handle easily, some (sauropod longbones and vertebrae) requiring two or more people to lift. If a task needs only the general shape of the bone, not internal structure, high resolution surface texture and color, it can be performed using CAD software and digital files. This saves time and also protects the fossils, because they have to be handled only once, for digitizing. For example, the digital files of GPIT/RE/7288 (GPIT 1 in the literature), a nearly complete individual of the prosauropod dinosaur *Plateosaurus engelhardti* von Meyer 1837 are available for researchers worldwide for study. I created and used them initially to create a virtual mount of *Plateosaurus* (Mallison 2007, 2010a, b). The next step involved "playing" with the articulated bones to determine the motion range of all joints (Mallison 2010b). This task was greatly aided by the fact that I did not have to create supports for the 239 separate bone files, but could manipulate them on the screen in any way I wanted. A major advantage of digital files is the ability to simply save any configuration at any time, and to compare different configurations directly next to each other. Today, scientists all over the world need only write an email to the Institute for Geosciences Tübingen curator, and can obtain the digital bone models for their own research via download.

Digital data in the form of complete vertebrate skeletons, either as complete scans of mounted specimens or as digital skeletal mounts, can be used for estimates of the volume, total mass, mass distribution and center of mass position of extinct animals. For example, Gunga et al. (2007, 2008) used scans of complete mounts of the sauropodomorph dinosaurs *Plateosaurus* and *Giraffatitan brancai* (Janensch 1914) (see Chap. 8) to create 3D volumes representing the reconstructed shape of the living animals, from which all the listed parameters could be calculated. In my own research I used the same model creation tools not on a scan of the existing skeletal mount of *Plateosaurus*, but on the virtual skeleton I built (Mallison 2010a, b in press). A less comfortable but also significantly smaller data base could also have been employed, consisting of artificial bone files created by (e.g., mechanically) digitizing one element of each type (one dorsal vertebra, one anterior dorsal rib, one posterior dorsal rib, one caudal vertebra, one tibia, etc.) and scaling copies to measurements of the other bones. Provided the elements of each group of bones used have sufficiently similar shapes, this is a "cheap&dirty" way to obtain a quite reliable representation of a large and multi-part fossil for relatively little digitizing time.

Digital files can furthermore be used for all kinds of shape analyses, including full surface representations or just selected data points for morphological landmark studies (e.g., Lohmann 1983; Bonnan 2004; Brombin et al. 2009; Bushman and Cornell 2009), using for example Procrustes analyses (Bookstein 1991; Mardia and Dryden 1998; Gower and Dijksterhuis 2004). Such analyses are helpful in paleontology, but also play an important role in medicine (e.g., DeQuardo 1999; Krey and Dannhauer 2008). Interestingly, if the intended landmarks are theoretically well-defined, they are easy to pick out for humans, so that different operators can gather data for one study (Brief et al. 2006). This could allow combining data from collections world-wide by email, without requiring one person to undertake expensive travels. Complete surfaces

can be compared using techniques similar to those employed to test the accuracy of digitized data in (Mallison et al. 2009), which creates maps of shape differences.

An important advantage limited to the rock penetrating tomography techniques is the ability to retain the spatial associations between fossil parts that are normally lost during preparation (Sutton 2008). This can be especially important in connection with attempts to determine taphonomic deformation or puzzle together badly fragmented specimens. Furthermore, penetrating techniques allow the study of internal structures, easily the greatest contribution to paleontology by any digitizing technique. There are by now countless examples, including all kinds of fossils (Luo and Ketten 1991; Brochu 2000, 2003; Wedel 2003a, b; Alonso et al. 2004; Schwarz et al. 2005; Falk et al. 2007; Sampson and Witmer 2007; Witmer and Ridgely 2008; Balanoff et al. 2010; Fink and Humphries 2010).

One of the most difficult tasks in paleontology is the retrodeformation of fossil shapes, the attempt to reconstruct how a fossil was shaped before taphonomic or sedimentological processes, or worst of all metamorphosis, altered it, resulting in the loss of biological information (Hughes and Jell 1992). If the damage is solely brittle, resulting in breakage into pieces, the fossil must be puzzled together. This process can be time consuming and cumbersome, especially when parts are missing, and it is usually questionable whether there really is solely brittle deformation (Boyd and Motani 2008). Much worse is plastic deformation that alters the shape of the fossil, or a combination of both breakage and deformation. The topic is of extreme importance for comparative studies of systematics, phylogenetics and morphology (Angielczyk and Sheets 2007; Boyd and Motani 2008), and various techniques have been suggested for retrodeformation (e.g., Wood et al. 2003; Srivastava and Shah 2006; Shah and Srivastava 2007), including digital methods for 3D "jigsaw puzzling" (Zollikofer et al. 1995, 2005). For example, Ediacaran fossils were all soft-bodies, and depending on their orientation during flattening can be preserved as distinct shapes (Bamforth 2008: fig. 1-3.1), or alternatively appear similar as fossil when the living organisms differed (Bamforth et al. 2008). Additionally, tectonic deformation has significantly altered the fossils (Seilacher 1999; Wood et al. 2003; Ichaso et al. 2007), so that they now differ even more from their original size, orientation and shape. Both mathematical and photographic retrodeformation have been conducted (e.g., Rushton and Smith 1993; Seilacher 1999; Gehling et al. 2000; Wood et al. 2003; Bamforth et al. 2008); mathematical details can be found in (Wood et al. 2003). Sadly, many techniques do not work well (Angielczyk and Sheets 2007; Boyd and Motani 2008).

Taking the process of editing files a step further, instead of just removing deformation, missing parts can be replaced by scaled copies from other specimens, and small damaged areas digitally repaired. Extreme caution is required, because any repaired or composite digital file is speculative, and any science conducted using it is therefore at a risk of being less accurate than it would be if complete real specimens were used. However, digital repair can deliver best approximations that, cautiously used, may be much more useful than broken and incomplete specimens. Similarly, mirror images can be created with a single command, allowing easier comparison with other taxa if only contralateral elements are known. Additionally, digital data can be scaled at will, either allometrically or isometrically, which can make shape analyses easier.

Even reconstructions of soft tissues can benefit from digital data, e.g., the musculature of extinct vertebrates. Firstly, a digital model can be created, which, being 3D, can be much more accurate and informative than the classic 2D drawings, in which muscles are represented by lines. Cases in point are the highly details musculoskeletal models used by Hutchinson and Garcia (2002) and Hutchinson et al. (2005) of the hindlimb musculature of the theropod dinosaur *Tyrannosaurus rex* (Osborn 1905), and of another theropod, *Velociraptor mongoliensis* (Osborn 1924) as well as an Asian elephant by Hutchinson et al. (2008). Secondly, surface marks such as muscle and tendon attachment sites on bones are sometimes visible as rugosities, but most have no special texture. Almost all, however, lead to a slight flattening of the bone surface, which can be easily missed due to the colors and textures on a real bone, but are immediately visible on a shallow-angle oblique view of a (texture-free) digital file (Fig. 2.1).

In addition to body fossils, other structures of interest to paleontologists can be digitized as well. Some ichnofossils have complex 3D shapes that are difficult to

Fig. 2.1 High resolution laser scan based digital file of the left femur of *Kentrosaurus aethiopicus* (MB.R.4800.36). View rotated from (**a**) lateral, (**e**) anterior, (**g**) medial, (**i**) posterior and (**l**) slightly posterior of lateral. Note how ridges and rugosities are well visible at shallow angles

infer from the outside appearance. Bednarz and McIlroy (2009) created a 3D representation of a phycosiphoniform trace fossil through tomography, which sadly required the destruction of the specimen. However, the model allowed new insights into the complex 3D architecture of the ichnofossil. Similarly, digitizing of ichnofossils greatly facilitates the study not only of their shapes, but also of the process of their creation (e.g., Bates et al. 2009a; Raichlen et al. 2010). Also, predictions of footprint shape can be made not simply based on a rough assumption of the posture of a fossil foot and the soft tissues on it, but from complex motion cycle simulations and detailed soft tissue models (Mallison and Porchetti unpubl. data). A simplified version of such a predicted track is shown in Fig. 2.2.

These are but a few examples of past and present uses of digitizing in paleontology. They barely give an overview, but they highlight the impact of the digital age on the science.
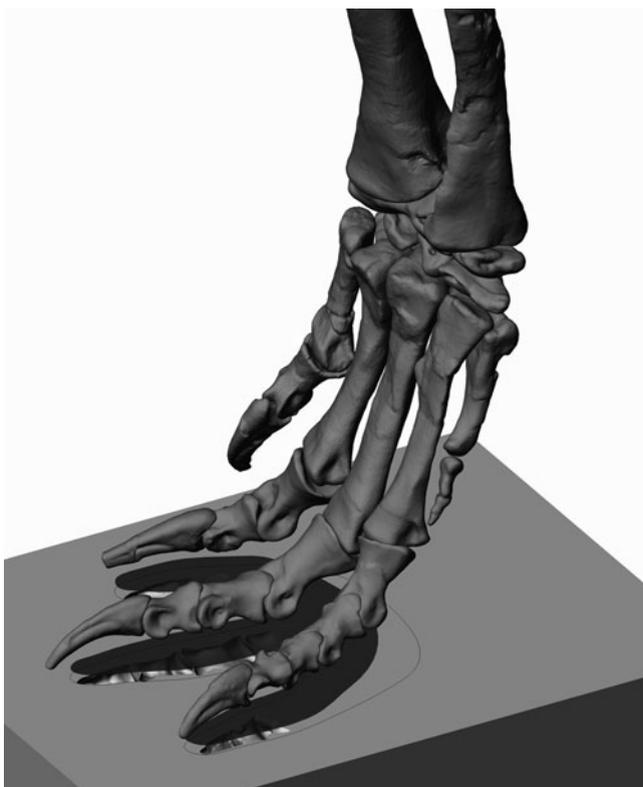

Fig. 2.2 The left foot of *Plateosaurus engelhardti* (part of GPIT Skeleton 2), digital CT-scan based files, is used to predict footprint shape. Here, solely the mid-stance position and the resulting print are shown. The *black curve* and the *dark shade* show the influence of two different soft tissue reconstructions (not shown) on the potential track. *Plateosaurus* left a tridactyle print when walking slowly; only at very high impact velocities caused by high speeds did the first toe possible touch the ground

Curation

Curators of paleontological collections must balance two main and often contrary aspects of their jobs: on one hand, the safekeeping of their precious specimens, on the other the accessibility that makes the collection scientifically useful in the first place. Additionally, some specimens usually are exhibited, both to provide justification to the public for the expense of collecting and preserving the material, and for educational purposes. Conflicts are pre-programmed, because access and exhibition result in handling of specimens, as well as exposure to dust, UV light, humidity and other potential dangers. All these problems can be totally or partly ameliorated by digitizing specimens.

Conservation and Accessibility for Research

Many vertebrate fossils, especially large bones, are rather robust and stand the occasional use by researchers without taking any damage. The other extreme are physically or chemically unstable fossils, such as a crinoid colony from the *Posidonia* Shale (Lias ε) of Dotternhausen, Germany, in the "Werksmuseum" of the Holcim Zement company that I had the pleasure to help prepare. The colony features some 20 short-stemmed crinoids on a 2 m long fossilized log. The sea lilies were mainly preserved as a mixture of pyrite and marcasite, two forms of iron sulfite (FeS_2). Marcasite is prone to react with moisture in the air and decay, the so-called "pyrite decay" (Rixon 1976; Newman 1998). Worse, sulfuric acid is produced in the chemical reaction, which spreads the destruction to other parts of the fossil and specimen labels (Stooshnov and Buttler 2001). The crinoid colony was thus potentially chemically unstable (sometimes, for unknown reasons, marcasite does not decay), and had to be kept at low relative humidity (Newman 1998) at all costs, otherwise it would crumble to dust over time. An extreme example of a decaying fossil is the early thyreophoran dinosaur *Emausaurus ernsti* (Hauboldt 1990), also from the Lower Jurassic of Germany. It has already been partly destroyed by chemical reactions caused by the wrong conservation methods being used on it, and by the decay of marcasite. It is unclear whether a re-preservation recently completed will stop the destruction. The mentioned crinoid colony is not of special scientific importance and solid enough to be casted. The *Emausaurus* fossils, in contrast, are brittle and represent the type and only specimen of a basal member of the armored dinosaurs, and they include a nearly complete skull. *Emausaurus* is therefore a prime candidate for modern touch-free digitizing methods. CT scanning can reveal both the external form and internal structures. High resolution laser scanning also preserves the external form, adding data on the coloration of the surfaces (if the scanner includes a color camera). This data can stand instead of the real fossils for many research tasks, and can be used to create 3D prints. Combining two instances of (nearly) touch free digitizing can thus preserve the exact external and internal shape, the color and some, but not all information on the details of surface structure.

Emausaurus was in fact CT scanned, for exactly these reasons, and as an aid for the re-conservation efforts (Hinz-Schallreuter pers. comm. 03/2010)

Aside from preserving fossils that decay on their own accord, digitizing can also protect other fragile fossils from destruction. A curator's and preparator's worst nightmare is a clumsy paleontologist let loose in the collection, breaking fossils by carelessly handling or even dropping them. But even the most careful researcher will occasionally damage a specimen, and some fossils are so fragile because of their delicate structure that even the most cautious handling will lead to destruction. If some research is conducted on digital files instead of the real specimens, the number of instances when the fossils must be handled can be reduced.

Furthermore, because CT scanning can reveal internal structures, it can not only be helpful for future preparation, but can aid in determining how fossils were treated during past preparation. Glued in metal armatures, as were the method of choice for mounting large skeletons, wires glued into the marrow cavity, plaster infills, etc. will all be easily visible on the scan slices, and can be created as separate 3D bodies during surface extraction, to be used as visual aids during re-conservation (Figs. 2.3 and 2.4).

Another important advantage of digital data compared to any physical object is that it can be multiplied flawlessly for an unlimited time, and can thus never be lost if sufficient precautions are taken. In contrast, even the sturdiest rock will be eroded over time, although it may take the touch of thousands of researchers to even produce a noticeable change to its external shape and appearance. Additionally, multiple copies mean that several researchers in different locations can study the same specimens at the same time, either isolated or as a cooperative effort, or work on material that is at the same time exhibited elsewhere.

Finally, not the least important advantage of digital files is that they can be transferred electronically within seconds, or at worst minutes for large file sizes. Compared to the effort and time required to wrap, package, and mail even a handful of invertebrates, this is an advantage that to computer-savvy people is a matter of course, but incredible and unfathomable for (usually) older scientist. To maximize the advantage, if digital files are lost, a new email can be sent right away, while a lost parcel with valuable fossils is usually irretrievable. The latter is the reason why so few institutions are willing to loan specimens. Digital files thus allow studying material far from its present physical locations, saving large sums of money otherwise spent on travel expenses for other uses, while safeguarding irreplaceable specimens.

Exhibition Use

The sole aspect of digital fossils usually noticed by the public is the use of digital files for duplication of specimens. Many fossils can be molded easily, and casts made from the moulds. Complex shapes or fragility make others nearly impossible to cast. For example, the neck vertebrae of *Giraffatitan brancai* (Janensch 1914) (formerly *Brachiosaurus brancai* Janensch 1914, see Taylor 2009) could not be mounted with the rest of the bones because their delicate laminae would have

Fig. 2.3 The left femur of *Plateosaurus engelhardti* (part of GPIT/RE/7288), digital CT-scan based file. (**a**) Anterior view of the polygon mesh surface. (**b**) As (**a**) but with a transparent outer surface, showing internal surfaces relating to the marrow cavity and cracks. (**c**) The internal surfaces extracted. (**d**) As (**c**) but in posterior view. Visible in (**c**) and (**d**) is a spiraling double helix structure on the internal surface caused by two intertwined metal wires that were embedded during preparation to strengthen the bone

required so many supporting armature parts that "would distract the eye of the observer so much that the details of the highly complex external architecture would no longer be very visible" (Janensch 1950: S. 97). Casting was also impossible, because of the sheer size of the individual vertebrae, as well as the fragility of the laminae. Instead, plaster models were hand-crafted for the mount in the Museum für Naturkunde Berlin, and for a re-mounting in 2007 these were molded and casted. Here, 3D printing or other rapid prototyping techniques such as CNC milling would have allowed the rapid, albeit expensive, creation of duplicates of the original bones. Detailed laser scans could have been taken of the vertebrae, and the resulting files sectioned into parts small enough for conventional CNC milling or 3D printing.
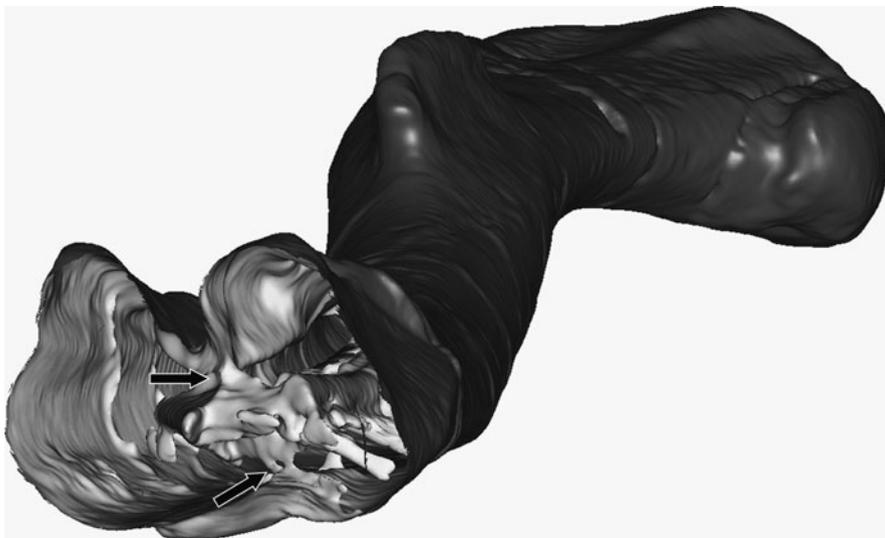
Fig. 2.4 The left femur of *Plateosaurus engelhardti* (part of GPIT 1), digital CT-scan based file, with the distal end removed. Visible are the internal structures relating to the marrow cavity, and their connection to the outer surface where less dense rock filled cracks in the fossil bone (*arrows*)

The eroded neural spines of the posterior cervicals could have been created by non-linear scaling of those of other vertebrae, and the rapid prototyping parts pre-made for easy assembly on the steel armature. Various factors caused this approach to be dropped, but a complete copy of the stegosaur *Kentrosaurus aethiopicus* Hennig 1915 was created by 3D printing. The welding of the new armature tended to blacken the bones, and welding the metal parts without the bones caused too many errors to be a feasible option. The rapid prototyping copies could be used, because it did not matter if they were damaged. Only when the armature was completed were the real bones mounted on it.

The Naturhistorische Museum Braunschweig houses an impressive example of the application of laser scanning and rapid prototyping: the sauropod dinosaur *Spinophorosaurus nigerensis* Remes et al. 2009 was scanned and a high detail copy created for a skeletal mount. While it can be argued that the public should be shown real fossils whenever possible, this can also be achieved by displaying them as found in the field, with a skeletal mount consisting of copies above, as was the case, e.g., during the special exhibit at the Naturhistorische Museum Braunschweig that presented *Spinophorosaurus* to the public for the first time. Also, the dinosaur exhibition hall of the Museum für Naturkunde Berlin sports a cast skeleton of the theropod dinosaur *Allosaurus fragilis* (Marsh 1877), of which there is not even one real bone on exhibit. Only a femur and a tibia of a closely related, but only fragmentarily know allosaurid species is on display from the Tendaguru locality that is the focus of the exhibit. Despite this, the *Allosaurus* mount is well liked by the visitors, especially because the lightweight construction allows supporting it with only a minimum of armature visible. The future will see more displays of this

kind, both because the original bones need not be exposed to the risks involved in mounting, but kept in safety, and because the original material is then much better accessible. Digital files can be used to rapid prototype bone replicas for such mounts. This is obviously also true for plaster casts or hand-made models, but both kinds of conventional replicas are often easily spotted as such, and molding large complex objects exactly has its own problems.

The flexibility of digital data is highlighted by an episode involving digital files of the wrong animal that helped re-positioning the skeletal mount of a dinosaur. *Riojasaurus incertus* Bonaparte 1967 is a prosauropod dinosaur from the Late Triassic of Argentina. When I was contacted for advice on remounting a skeleton, I was able to use files of *Plateosaurus*, scaled to the lengths given in a description of the *Riojasaurus* skeleton (Bonaparte 1971; Fig. 2.5), to test possible poses (Fig. 2.6).
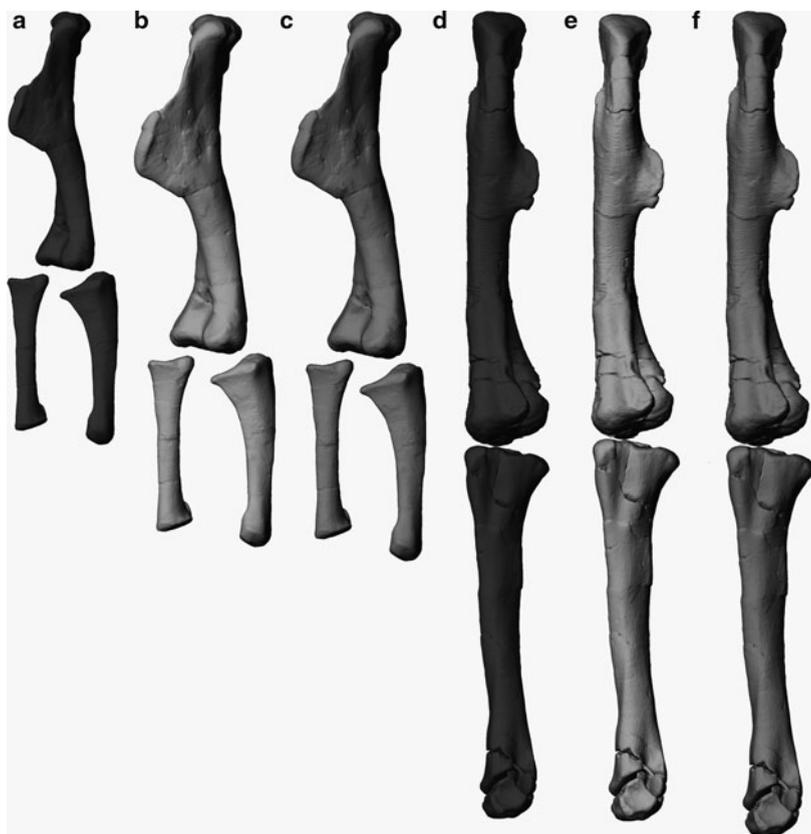

Fig. 2.5 Limb bones of *Plateosaurus engelhardti* (GPIT/RE/7288). Digital files as scanned (*dark grey*), and scaled to the proportions of *Riojasaurus incertus* for identical hindlimb length (*light grey*) and identical femur length (*medium grey*). Note the proportionally much longer humerus of *Riojasaurus*

Fig. 2.6 Virtual skeletal mount of *Plateosaurus engelhardti* (GPIT/RE/7288). *Top*: correct proportions. *Bottom*: with limb bones scaled to porpotions of *Riojasaurus incertus* (see Fig. 2.5). Note how a quadrupedal posture becomes feasible due to the different limb length ratio

Of the resulting CAD files I sent screenshots to the scientists in Argentina, who incorporated this information into their decision on how to plan the new mount (Powel pers. comm. 3/2010).

However, it is not only the actual exhibition displays that can benefit from the use of digitizing, but also the planning process. If the Museum für Naturkunde Berlin ever decides to remounts its almost complete, exquisitely preserved individual of *Plateosaurus engelhardti* for the exhibition, I can deliver measurements (length, width, height) for any desirable pose, and can plan the required armature and railing as well as the spotlights down to the smallest detail in a CAD program, using my digitally mounted skeleton of the Institute for Geosciences Tübingen's GPIT/RE/7288 skeleton, scaled to fit the Berlin specimen. The benefit is even larger if the layout of an entire hall with many skeletons is planned. Relatively little effort is required to gain rough representations of complete mounts (Chap. 8), which can then be used to test various arrangements in a CAD environment. If the mounts are planned to be changed during the renovation, as was the case for the renovation of the dinosaur hall in Berlin in 2006/2007, this can also be tested using virtual skeletal mounts, provided all major bones are separately digitized. The "quick&dirty" digitizing method of choice would be mechanical digitizing after de-mounting, but laser scans can also be used. High resolution files are even sufficient to pre-plan

an armature for a mount, so that parts like large support struts and main rods can be prepared to exact dimensions in advance.

Two other potential uses of digital files for exhibitions have, to my knowledge, barely been used in museums worldwide. Firstly, digital files can be used for explanatory videos or still images on computer screens, which are being set up in an increasing number of museums to supplement printed texts and audio guides. Additionally, instead of just showing fossils, or computer files of fossils, exhibits could cover evolutionary development of, e.g., ammonite lineages by morphing the digital file of an early species into that of a derived member of the family. We have come to be used to seeing such animations on TV, why not show them in museums, with the real fossils right next to them? A museum that remains static in an increasingly animated world, in which education in schools, universities and other venues uses modern techniques including animations increasingly, will sooner or later lose visitors, and fail to fulfill its mission of education.

The ability to edit digital data to create mirror images, composites or simply scaled copies is also helpful for creating displays, for example by creating scaled digital copies of vertebrae neighboring a missing one in a fossil, then 3D printing those copies to complete the mount.

Science Communication

Many researchers believe that their research speaks for itself, and will be duly noticed by colleagues and the public alike because of its quality. This is unfortunately untrue, and in recent years an increasing number of individuals and organizations have come to realize that public communication of science is an important aspect of scientific work. Here, digital files can be used interchangeably with photographs, but tend to have a higher impact, because journalists and the general public tend to be drawn to novel imagery. Also, as with museum exhibits, science published for the general public instead of for experts is not as limited by classic printing techniques, and TV shows especially offer the chance to use novel (for science) ways of presenting results and educating the public. Digital data has several advantages for presentation on the internet and on TV compared to classic photography or film of physical objects. Among them is the ability to make objects fully or partly translucent, and the ability to dissect them virtually by hiding partial surfaces, so that internal architecture can be shown easily. This can be done while the view is rotated, so that the 3D structure becomes easily understandable even on a 2D medium, the screen. Also, missing parts of a fossil can be reconstructed, and the process of reconstruction explained by switching the image between the scan of the real specimen and the reconstruction. The Museum für Naturkunde Berlin took this a step further in their redesign of the dinosaur exhibition in 2007. Here, the visitor can watch short films, in which the mounted skeletons are first filled with internal organs, next covered with musculature and then with skin, until finally the scenery changes to a reconstruction of the Jurassic landscape and the animals come

alive. On the basis of these clips several paleontological techniques for soft tissue reconstruction can be explained, as well as the conclusions of biomechanical studies on the posture and locomotion of the dinosaurs. In essence, the process of making a fossil "come alive" is presented in a catchy but accurate way, which would be very hard to do without the use of digitized data.

Limitations

The biggest limitation of digital data is that by its very nature it is not the physical object it represents. It only provides the data that was collected during digitizing. Weight, density distribution, color (except when laser scans are combined with digital photographs), all internal structure (in the case of external 3D shapes), high resolution details of the surface structure, smell (although very few fossils smell), electrical properties e.g., in amber, chemical properties are usually missing in the digital file. Most of this data can be dispensed with for many research tasks, but in some cases digital representations of the fossils may not be sufficient.

Also, all digital files are processed in some way during their creation. This can induce significant errors, especially when small file sizes are used, so that results derived from the study of digital files may be useless. Thus, maximum size scans (ideally the raw data) should be used whenever possible, as e.g., Witmer and Mayle (2004) found when integrating CT and MRI data on an extant pig's knee. Every study using digital files should also include a test of file accuracy, at the very least by visual inspection and comparison of the main linear measurements of original and 3D file. If digital files are reduced in size after creation, the resulting errors should be tested for by more elaborate means. For example, the laser scan based polygon mesh files of the stegosaurian dinosaur *Kentrosaurus aethiopicus* mentioned above are too large for the entire set to be handled even by large workstation computers. Using the complete skeleton for studies on the range of motion (Mallison 2010c) would have required decreasing file size to less than 25% of the original, which leads to a process I call "digital erosion". The size-reduced files resemble bones eroded by water transport, losing sharp edges, processes and surface texture. This would have changed study results, introducing errors directly caused by the use of digital files. Thus, I was limited to using partial assemblies of the skeleton at full resolution, which increased work time and caused problems when figures of the entire skeleton had to be created.

Another limiting aspect of digitizing is its cost. Any digitizing is either time intensive, or cost intensive, or both. Depending on the method the main cost factor can be the actual scanning, because of expensive tools or high worktime demands, or the ensuing file editing. For example, high resolution laser scanning requires a scanner and scanning software, a computer (ideally a laptop) able to handle the expected file sizes, and software for follow-up editing. The number of scans that have to be taken depends on the object's size and shape, the scanner type, and the

desired accuracy. Some scanners work with an object holder that rotates the object automatically, so that fewer scans are required, but this limits object size and weight. Scanning an ammonite with a diameter of 12 cm with a relatively cheap scanner took me several hours on my first try, once I had gained some experience I was able to replicate the process in about 1 h. Most of this time is not work time, because I was able to do other things while the scans were running, but the digitizing required my attention in regular intervals. The complete scanning of the *Kentrosaurus* bones one by one kept an experienced technician busy for several weeks. Afterwards, the individual scans of each bone had to be combined into one 3D surface file, a process largely automated in the scanner software. However, several files showed alignment errors, so that further editing was necessary. The time and monetary effort of scanning an entire dinosaur skeleton can only be justified if the resulting files are used repeatedly, saving time and reducing required instances of fossil handling many times.

Similarly, CT scanning is time consuming. The actual scanning is rapid, with the data transfer from the CT scanner's computer to a transfer medium being the longest part. In contrast, file extraction and editing takes much longer, and requires expensive computer programs as well as a powerful computer. Additionally, the material must be transported to the scanner, not vice versa, and fragile specimens must be adequately protected, increasing time demands and cost. If more than just the "slice" data is saved, further analyses of the raw data are possible, which again have high computational demands.

Aside from time and technical limitations, the fossils themselves sometimes make digitizing difficult or impossible. Some specimens are simply too large for some methods. Complete articulated dinosaur or mammal skeletons may not fit into even the largest CT scanners, although a handful of industrial scanners can handle specimens up to the size of a spaceship – or a hadrosaur (ScienceDaily, Dec. 3 2007; Manning et al. 2009). However, typical medical scanners are much smaller, so that even a sauropod scapula or mammoth skull may not fit through. High resolution CT scanning is even more limited, with most scanners not large enough to scan a shoe box sized fossil. Laser scanning with different scanner types can handle practically any object larger than a centimeter, but demands light reflecting surfaces. There are a number of ways to solve problems of insufficient reflexion such as coating with powder, but risk of damage may mean that they cannot be used on some fossils.

Also, there are a variety of technique-specific limitations. CT and similar techniques require differences in the density or other physical properties to exist in the specimen. If these are too small, surface extraction will fail. For example, Sutton (2008) reports that sparry calcite fossils in a largely micritic matrix could not be distinguished by HRCT and SRXTM. However, some extraordinary results have been achieved, for example calcitic fossils in limestone matrix (Dominguez et al. 2002).

Mechanical digitizing and other techniques that require physical contact with the specimens are limited to fossils stable enough to withstand touching, and care must be taken not to scratch surfaces with digitizer tips. Rough and pitted surfaces are at a greater risk, so that fragile surface features may make mechanical digitizing impossible. Also, because of the limited reach of a digitizer arm object size is

only theoretically unlimited (Mallison et al. 2009), because repeated recalibrations as required for very large objects can lead to intolerable summation of errors.

Laser scanning is often combined with digital color photography to create textures for the digital files. This is supposed to add color data, and usually works quite well. However, if the specimen or scanner is moved to capture a different view, the lighting will be altered at the contact point of the two scans. This leads to either lighter or darker colors on the photograph, so that the texture usually has artificial lines where the lightness changes radically. Also, while the color difference between neighboring areas is normally well represented, except for the mentioned overlap areas of individual photographs, the color hue and saturation are usually not recorded with a proper white balance.

Laser scanning, photogrammetry and optical digitizing (and to a lesser degree mechanical and sonic digitizing with flexible digitizer arms) requires direct line of sight to the surface that is to be digitized. With a digitizer arm that has a sufficiently small tip it is sometimes possible to reach into recesses and cover obscured surfaces that cannot be seen from the outside. However, vertebrate skulls or complexly shaped vertebrae e.g., of sauropods, can require several dozens of scans and still not be fully covered.

Digitizing Methods and File Types

The digitizing methods described here are only examples for the vast number of different techniques that have been or could be applied in a paleontological context. Human ingenuity and technical progress lead almost daily to the invention of novel techniques or novel adaptations of existing techniques, so that an attempt to list all methods is doomed from the start. I have thus selected those methods that are most common in general, and most often applied in paleontology, and easily learned. Some rarely used techniques will be mentioned in passing when methods are discussed that use similar principles.

Laser Scanning

In recent years a number of affordable laser scanners have become available that can scan a field of view large enough to contain between a soda can and a packing case. Scanners that can cover a whole mounted skeleton are discussed in detail by Stoinski (Chap. 8). The simplest scanning setups for small objects are construction kit systems, using webcams, a cheap laser, a special-made background, and free computer programs (e.g., www.david-laserscanner.com). Scanners of this size range are ideal for scanning single bones of medium sized vertebrates, while those of rodents or sauropods are too small or too large, respectively. Similarly, typical large-bodies invertebrates such as mollusks are easy to scan, while single-cell organisms are usually too small. For example, my attempts to get exact scans of

foraminifera of the genus *Nummulites* failed, although the largest individuals had diameters of several centimeters. The size range is roughly between 1 cm as a minimum thickness and 100 cm as the greatest length of an object, although larger objects can be scanned in pieces. Theoretically, the size range is unlimited, but accuracy suffers significantly when many scans are pieced together to create a model of a very large object.

High resolution scanners with an included high resolution digital color camera can cost several thousand to tens of thousands of dollars, and typically offer both a wider field of view and a greater measuring depth. The larger the field of view of a scanner, and the higher the resolution of a scan, the more expensive the scanner, and the longer, usually, the time for a complete scan.

Laser scanners collect data points covering the surface area of the object that is visible to the scanner. Thus, at least four scans are usually required to cover an entire object without gaps. Complex shapes, such as deep recesses, require a multitude of scans, and some surface parts may not be accessible to the scanner at all, because no direct line of sight can be established.

An important step in creating digital 3D data from laser scanning is correlating the separate scans into one file. Incorrect alignment can lead to serious errors in the final surface files. Some programs automatically recognize overlapping areas and adjust the scans accordingly, others ask the user to indicate roughly correlating points on the separate scans. More basic methods require special markings and manual adjustments. Placing of these reference markers properly requires planning and experience, because each hides part of the object from direct scanning, so that as few as possible should be used. However, this means that each marker should be visible in as many of the required separate scans as possible. Additionally, using fewer markers means that separate scans are all correlated and arranged to the same few points, so that there is no summation of errors. In contrast, when, e.g., scan 1 and scan 2 are aligned to one set of markers, then scan 3 to the two other via another set, then scan 4 by still another, the errors in each correlation will add up. This problem exists as well for other techniques that use combinations of several separate scans, such as mechanical digitizing.

There are a variety of portable and affordable laser scanner that can small object, up to the size of a soda can. Prices vary with the available resolution, scan size, scan depth, accuracy and quality of the software supplied, and a factor often overlooked: the ability to scan dark or shiny, reflecting surfaces. This point may seem irrelevant for paleontology – we typically do not scan volcanic glass or polished meteorites, nor metallic minerals or mirrors. However, shininess already begins with fossils consisting of any crystals visible to the naked eye, such as calcite and aragonite in many invertebrates. Mollusk shells that retain the original mother of pearl structure of their shell are also shiny. Usually, cheaper scanners have a less powerful laser. This means that they have a harder time getting a proper reflection of a surface that reflects laser light badly (dark materials) or away from the scanner (reflective surfaces). High power scanners, in contrast, may even allow using mirrors to scan surfaces otherwise hidden from direct view, as S. Stoinski and I found (see Chap. 8).

One solution to this problem is covering the object with a substance that reflects light well, and back at the scanner, and can later be removed easily and without damaging the object. Some companies sell powder-sticks or other tools for this purpose with their laser scanners. Alternatively, for larger objects, it may sometimes be sufficient to slightly alter the angle between scanner and object. Also, smooth and level surfaces can simply be covered with paper stickers. Scanning with strong external light, e.g., outside, may require shading of the object (e.g., Adams et al. 2010).

The smaller the object of a scan, the more important are correct registration of the separate scans, because artifacts resulting from alignment errors are proportionally larger compared to the total size of the object. The same is true for scan resolution; smaller objects require higher resolution. This means that objects with parts of different sizes, such as vertebrate skeletons, may require the use of two different scanners in order to create a complete digital model at sufficient resolution in an acceptable time frame.

High quality (and high prize) laser scanners allow scanning entire buildings, sauropod skeletons or mounted whales in one piece. Details can be found in Chap. 8. A problem that often occurs when very large paleontological objects are scanned is that the scan resolution cannot be sufficient, due to time and data size constraints, to allow simple meshing into 3D bodies of high accuracy. For example, a full skeleton scan of a medium-sized dinosaurs may be run at a resolution of 5 mm (distance between points), or even at 2.5 or 1 mm. Anything more detailed just takes too long. Neither resolution is sufficient, however, to create anything more than a rough model of the bone shapes. Thus, laser scanning of very large and complexly shaped objects provides data helpful for certain tasks, such as mass estimates based on digital 3D models derived from the scans (Gunga et al. 2007, 2008; Bates et al. 2009a, b). For more detailed work, the resolution is often insufficient, or the data too large even for high-end PCs. I experienced this problem when attempting to use a scan of *Giraffatitan brancai* (MFN mount) provided by S. Stoinski (see Chap. 8) to correct the minor errors in the mount before creating a 3D CAD model of the animal's external shape. The full scale point cloud crashed the PC, and meshing reduced versions did not give sufficient anatomical detail to adjust the vertebral column as desired. Working with the naked, un-meshed point cloud decimated to 50% of the points was not possible either, because it is impossible to estimate the depth of point clouds. This makes it nearly impossible to arrange elements in 3D. However, the solution to this problem is simple: more computing power, especially in the graphics card, would allow using the full resolution scan.

Mechanical Digitizing

Mechanical digitizing refers to the use of a robotic arm that is automatically or, more commonly, manually guided across the specimen, while the position of its tip is recorded as a 3D coordinate. Mechanical digitizing is on average cheaper than laser or CT scanning, and especially suitable for collecting landmark data, i.e., a number of specific points on an object, instead of a complete scan of its surface.

However, at limited resolutions, mechanical digitizing can also be used for surface representation, and the resulting files can be as accurate as those produced by low-resolution laser scanning, or files from high-resolution scanning that have been reduced in size (Mallison et al. 2009). Given the limitations in computing power of an average office computer, mechanical digitizing files have the same resolution as the largest laser scan files that can be used if larger assemblies such as vertebrate skeletons are investigated. My colleagues and I have detailed surface representation techniques for mechanical digitizing on the example on vertebrate bones, using a small, non-motorized digitizer arms (Mallison et al. 2009), thus only a short overview is given here.

Surface Representation

There are two main approaches to the accurate 3D representation of surfaces with a mechanical digitizer. Point clouds comparable to those created by laser scanning can be collected, from which 3D polygon meshes can be easily computed. In order to get complete representations of an object, digitizing from all sides is required, which demands multiple calibrations of the digitizer. For this, a coordinate set must be marked on the object, and extreme care must be taken that re-calibration after moving the object is accurate, otherwise the separate point clouds digitized from different sides will not match in 3D. The resulting errors are in principle the same that can occur when laser scan point clouds are not perfectly aligned. As mentioned for laser scanning, aligning should be achieved using as few separate sets of calibration marks as possible, in order to avoid summation of alignment errors.

The main advantage of point cloud digitizing with a mechanical digitizer is the ability to avoid unnecessary overlap between partial point clouds, and adjust digitizing density to match the surface topography of the object. Flat surfaces can be sampled at a far smaller resolution than highly complex structures. Also, because calibration is achieved by using coordinates, overlap between partial point clouds can be minimal. This leads to less data in the first place, and eliminates unnecessarily small mesh triangles in the overlap area, further reducing file size. For laser scans, the same reduction requires at least one extra calculation step, which reduces redundant areas of the full data set. Additionally, because digitizer arms usually feature several highly mobile joints, direct line of sight between the digitizer base and the sampled surface is not required. Instead, the operator can reach around the object, sampling complex surface topographies such as recesses or sharp keels in one go, greatly reducing the number of separate digitizing instances compared to laser scanning. This reduces the problem of inter-scan correlation, further lightening post-scanning calculation time. Overall, it is possible to achieve comparably accurate final files of 60–80% the site of a laser scan, with fewer scanning instances, and for significantly smaller file sizes during digitizing.

The second method for surface digitizing involves the recording of NURBS curves that wrap around the object. NURBS stands for non-linear uniform rational

B-splines, a type of mathematical equation that defines curves in 3D space that are mathematically easy to handle. NURBS modeling allows easy editing of curves and 3D bodies. The process of digitizing these curves is the mathematical equivalent of wrapping wires around the object to get a proxy for its shape, then pulling a cloth taught over the wires. The individual curves do not need to be exactly parallel, but can curve following surface structures, as i.e., the curves are not planar long as they do not cross each other. The curves also need not be closed, so that partial surfaces are created. These need to be combined into one complete surface later, as e.g., described by Wilhite (2002). Curves reaching fully around the object allow creating a complete representation of the fossil in one go. This requires that the digitizer arm can reach all the way around the object, and makes special supports necessary (Mallison et al. 2009). However, these can usually be produced at low cost. The operator's freedom to space and bend curves depending on the complexity of the topography allows dense sampling where required, and extremely limited sampling for areas with simple shapes such as scapula blades. The resulting files can therefore be much smaller than even low resolution laser scan files, so that large numbers of surfaces, e.g., entire skeletal mounts of large vertebrates, can be handled at the same time.

In principle, surface creation from NURBS curves follows the same methods as for CT or MRI scans, connecting corresponding points on stacked curves, but in contrast to MRI and CT data, the mechanically digitized curves are not flat (i.e., each curve point may differ from all other curve points in three, not two coordinates), and neighboring curves are not necessarily parallel.

Like all other digitizing methods, NURBS curve and point cloud digitizing both allow combining data from several specimens, even of different size or handedness. As long as sufficient overlapping area is available, or at least three easily identifiable corresponding point, data from one specimen can be scaled and mirrored to match that of others.

Landmark Analysis

Digitizing landmarks with a mechanical digitizer arm (e.g., Engels 2007) is simpler and faster than any other method and far less error prone. Collecting landmark data from photographs (e.g., Bonnan 2004, 2007) recovers only a 2D shape. With a mechanical digitizer the third dimension can be added, although using the full potential of the added information requires different analysis tools. As an added benefit, curves outlining the object can be quickly sketched in, while the 3D coordinates of each point can be directly exported from the digitizing program, usually as standardized formats, so that analysis programs can read them directly.

In addition to direct digitizing of landmark points, landmarks can also be selected and extracted from completed digital 3D surfaces. This method should be used with care, because of the inherent (although usually minimal) loss of accuracy.

CT and Other Tomographic Methods

Because of the size of CT scanners and similar machines, specimens need to be taken to the scanner, not vice versa. Usually, this means a trip to the local hospital, because the high cost and the demand for a separate room compliant with high safety standards due to the strong radiation produced make it impossible for most paleontological research institutions to acquire their own CT scanner. Working within the collections is thus usually not possible.

My own experience with CT scanning of vertebrate fossils has taught me that time spent preparing specimens for easier scanning and data extraction is usually time well spent. Small bones have little weight, and tend to rock on the CT scanner's slide during scanning. To avoid this they can be placed on a Styrofoam slice, into which small depressions fitting the fossils are cut. This not only allows error-free scanning, but is also a good method for avoiding damage during transport. Additionally, the density of Styrofoam is so low that extraction of the bone shape via a low threshold is possible. This means that even specimens of low density, such as carbonized plant fossils, can be separated from the surroundings easily, while separating them from the CT scanner's slide may be difficult. A Styrofoam slice that fits through the scanner allows scanning many small specimens in one scanning instance, saving time. In this case it is advisable to place a small identifier next to each specimen, of a sufficient density that it is well visible on the tomograms. I often used a metal wire bent into the shape of a number. It is thin enough not to create large artifacts, and allows identification of each bone based on a list I made when placing the bones on the Styrofoam tray.

When scanning is complete one should always ask the operator of the scanner to conduct a quick visualization of some of the data, in order to test if the scan worked as planned. In the unlikely case that something went wrong (e.g., the slices cannot be auto-aligned), the operator can re-export them from the raw data, or repeat the scan right away. Similarly, care should be taken that the data is properly named and identified in the scanner software, to avoid confusion. Additionally, when using a medical scanner, two copies of the data should be made, or an agreement reached with the scanner's operator that the raw data is kept for a day or two until one has had a chance to store a copy of the data elsewhere.

Digital File Handling and Editing

General Remarks

When dealing with digital files a few simple rules should always be adhered to. These are:

1. **Keep all data!** Raw scan data and all important intermediate steps of file editing should be kept, so that sources of errors can later be traced and corrected.

2. **Keep records!** All digitizing steps should be detailed in an accompanying file so that others can later reproduce all steps of data acquisition and file handling.

3. **Name properly**, and **include as much information as possible!** File names must include the catalogue number. Additionally, information on the genus, species and (if applicable) object type as well as important editing steps should be included. For example, a polygon mesh file of a *Plateosaurus engelhardti* left femur that was smoothed and reduced to 80% polygon number could be named Plateos_engelh_GPIT/RE/7288_sinFemur_SM_80perc.stl. "Speaking" names are especially important for files combined from several specimens, which should then include all catalogue numbers. It is not sufficient to include such data within the file, as annotations, or in accompanying text files, because experience tells that other researchers will not be able to use the exact same file formats, and most in-file notes are not included when exporting to other formats. Accompanying files are nice and helpful, but may get lost or be ignored.

4. **Never edit original files!** It may sound stupid, but if one opens a file and edits it, chances are high that one will forget to use "save as" and instead save over the original file, altering it. Make copy first, then edit the copy.

There are two main types of input data for surface creation discussed here, point clouds and NURBS curves. NURBS surfaces are created in one easy step in the CAD program, and need not be discussed further. Point clouds fall into two main categories.

1. Point clouds from laser scanning / mechanical, optical or sonic digitizing: these always depict the exterior of an object and come as partial point clouds that need to be registered to create one file.

2. Point clouds from CT scanning: these are already properly registered, and can, depending on the data extraction settings, portray external and/or internal structures. Usually, one never handles these files a point clouds, but uses the CT extraction software to directly create a surface, most commonly a polymesh file.

Surfaces from Laser Scanning/Mechanical Digitizing (Point Clouds)

Laser scanning typically delivers point clouds, and mechanical digitizing, as well as a number of other methods, can also be used.

The easiest way of turning a set of scans into a surface file is meshing as a polygon mesh (Fig. 2.7). Most scanning programs include this option, but it is often not without problems. Firstly, many scan sets are not correlated exactly enough to avoid small surface errors. Additionally, if the correlation is not fully automatic and uses markings and user input, scans are often correlated with overlapping areas aligned parallel, but not intertwined. If the distance between the two point clouds is
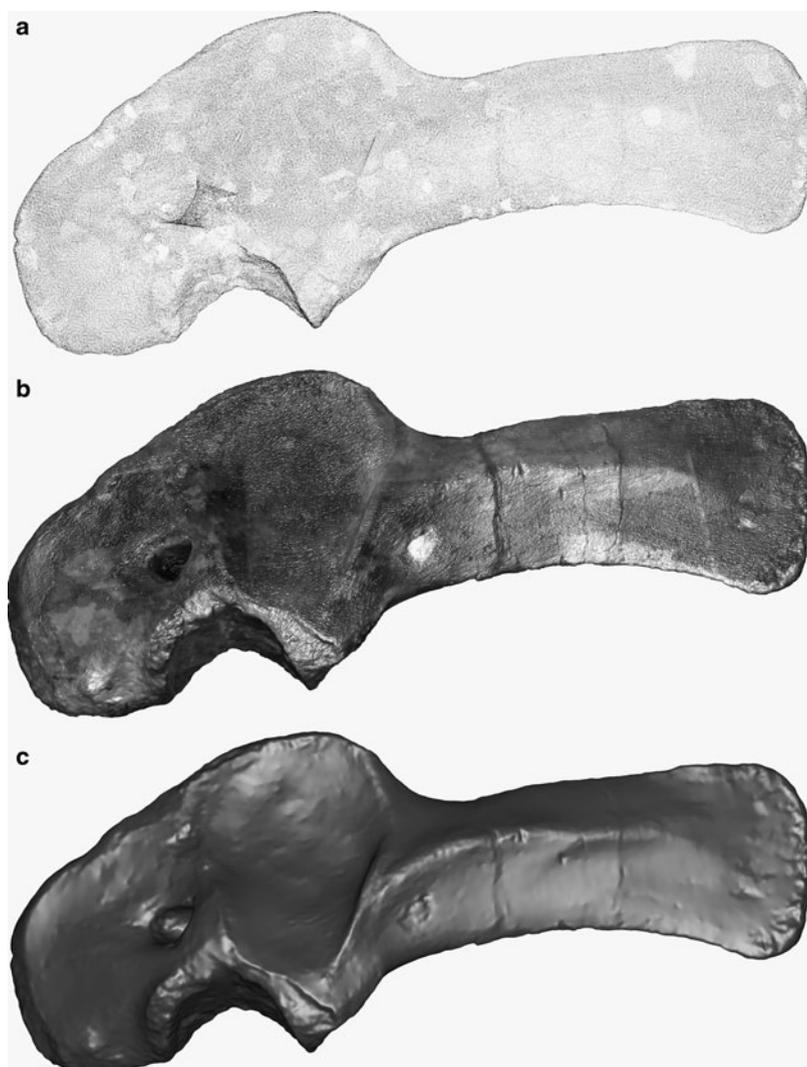
Fig. 2.7 Left scapula of *Kentrosaurus aethiopicus* (MB.R.4802) (**a**) Point cloud from high resolution laser scanning (shown in greatly reduced density) (**b**) High resolution polygon mesh with color textures (**c**) As (**b**), without color textures

much larger than the mesh triangle size, two parallel surfaces will be created. If the distance is sufficiently close to the distance between points on each scan, triangles will be created between points in both clouds. The resulting surface then looks as if it had been subjected to a shotgun blast, and requires extensive cleanup. This editing usually involves removing surface artifacts from inaccurate meshing and filling holes remaining in places where no points were scanned or the point cloud

density was low, as described below. Usually, the programs supplied with the scanners can perform the required tasks, but they often lack sufficient manual controls.

Sometimes, errors in surface creation are caused by highly uneven sampling densities. This problem can be circumvented by splitting the point cloud into parts, meshing each part separately, and then combining the surfaces. The resulting surface will need some editing, though. Similarly, complex shapes may be easier to create if split into discrete units.

A problem often encountered when attempting to mesh point clouds is the insufficient accuracy of some programs that leads to 3D shapes significantly different from the original specimen. It is therefore not sufficient to simple mesh the point cloud at the highest possible resolution. Afterwards, the surface must be compared in detail to the point cloud, to check if the mesh polygons in fact follow the extreme points, e.g., along crests and on sharp spikes, or if they "cut the corner", an error likely to happen. Studies analyzing morphometric differences (e.g., the relief of teeth) depend on accurate portrayal of such extreme point (e.g., Ulhaas et al. 2004; Hansen 2006), and their quality may suffer significantly when inaccurate meshes are used. When such errors are detected it is often sufficient to use a different software program for meshing to achieve sufficiently accurate surfaces. Sometimes, however, manual editing is required to reproduce thin, sharp structures of the original fossil.

Surfaces from CT Data

Surface extraction from CT slices is based on determining density differences (i.e., grayscale value differences), and connecting those of one slice to those of the next slice that lie closest (for a more detailed description see Sutton [2008] and references therein). This process is usually not problematic. However, setting the correct thresholds can be a daunting task. In many fossils the density difference between sediment infill and fossil material is minuscule, and sometimes both densities vary more across the specimen than the maximum difference in one spot. This means that combined fossil/sediment blocks would be extracted, with parts of the fossil missing. The sole possible solution is extracting partial surfaces and combining them later. It is often worthwhile to try two thresholds, not one, so that a medium density section can be discarded.

One issue that should be addresses early on in order to save editing time later on are unwanted internal structures. Often, the mineral content of a cavity is sufficiently different from that of external sediment that it can be split from the fossil. Here, using two thresholds is also advisable. Additionally, many CT handling programs offer options to create artificial breaks, or ignoring internal, disconnected surfaces. Problematic remain density isocurves that connect the interior and exterior of a fossil, e.g., breaks in a longbone that extend to the marrow cavity. In such a case extraction of the external surface from CT data will usually lead to extraction

of the internal surface, the marrow cavity wall, and the connecting duct as well (Fig. 2.4). Here, it helps if an extremely high threshold can be used, that basically separates any solid from air, so that crack infills are treated like the bone. On the other hand, the ability to digitally remove, along with the sediment, plaster infills and other repair materials can be a helpful tool for curators and preparators, too.

Resizing

Except for mechanical digitizing, all methods described here usually produce file sizes that cannot be easily handled simultaneously in large numbers by typical office and laboratory computers. A single ammonite of 10 cm diameter can result in a file of nearly 50 MB for low-resolution laser scanning, and up to 125 MB for CT or high resolution laser scanning. Even mechanical digitizing, using point clouds (the ridges on an ammonite are hard to reproduce using around-wrapping splines, so curve based digitizing is out) results in a 25 MB file. However, most research tasks can be carried out at much smaller resolution, allowing the use of much smaller files. It is, however, usually a bad idea to scan at a reduced resolution. Firstly, while it is somewhat faster, much of the scanning time is taken up by preparing and placing the specimen, adjusting the scanner position, saving files, etc. Additionally, specimens may need to be wrapped and transported – all tasks that need to be done regardless of the scanning resolution. Therefore, reducing the resolution to 50% will not result in cutting scanning time in half, but rather in a modest 10–20% time saving only. Additionally, one can never be sure what resolution and scan accuracy later research tasks may require. Who could have predicted, only 10 years ago, that 600 dpi 3D printing would become a standard application by 2010? Therefore, scanning at the maximum practical resolution (not necessarily the maximum technically possible, due to time and computing power limits) is always the best option.

If scanning at the maximum resolution is usually best, but research can usually only be carried out effectively using much smaller files, what can be done? The easiest way is to produce copies of the large files from scanning and reduce them in size until a compromise between resolution and file size is achieved that is appropriate for the task at hand. If the range of motion of a vertebrate limb is assessed (e.g., Mallison 2010b, c, in press), the fine details of surface structure of the bones are not helpful, and the digital files thus need not resolve them. For comparisons of proportional differences between different taxa, e.g. limb bone scaling within "Prosauropoda", even less detail is required, and potentially 10% file size of the original scan may be sufficient. However, such down-sized files must fulfill one important criterion: they must be accurate enough not to produce false study results. Downsizing a file is seemingly simple if it is a polymesh. Just select the proper option from the toolbar or menu, enter the target size or percentage by which to reduce, and press enter. However, this process is not always simple and reliable. Many programs offer options to preserved edges, i.e., the extremes of the 3D shapes remain supposedly untouched when the file is resized. Despite this, what happens to

a shape is a process I termed "digital erosion" when encountering it on the example of *Kentrosaurus* bone files. Edges become rounded, smoothed, and appear worn down, resulting in sometimes massive alterations of the finer structures. In the case of *Kentrosaurus* these changes were unacceptable, because the files were used for a motion range analysis (Mallison 2010c), and the largest damage was evident on the zygapophyses of the vertebrae. "Digital erosion" thus altered the outcome of my analysis significantly. Care must thus be taken not to reduce files too much, and the original file and the reduced version must be compared thoroughly to ensure that the smaller file portrays the originally scanned surface accurately enough for the task at hand.

If nothing else helps, manual editing of the mesh may allow a significant size reduction, albeit for a large investment of time. The mesh must be split, with those areas that may not suffer changes at all forming separate meshes that will not be edited, while the remaining parts can be reduced in polygon number. Then, the partial meshes must be re-welded, and the contacting edges between altered and unaltered surface parts smoothed. Often, the cost in time and money of this procedure is greater than that of buying a new, more powerful computer that can handle larger file sizes. Alternatively, it may be possible to avoid resizing altogether and work with partial assemblies, as I did in the case of *Kentrosaurus*, where I studied the neck, trunk, tail and limbs in separate files.

Point cloud files can be resized by reducing the point number. In some cases it may be possible to do so without losing edge definition, but usually a surface created from a reduced point cloud shows "digital erosion" as well. NURBS curve digitizing allows simplifying the surface during its creation from the curves. If this is done in moderation the resulting error is often negligible. However, extreme caution is advisable. Even if only minor changes are made to the surface creation rules, the algorithms are prone to cause massive changes in surface curvature and thus object volume that are hardly visible to cursory inspection on the screen.

A possible way out of the dilemma of file size and file quality being inversely proportional are hybrid techniques. Mechanical (and e.g., sonic) digitizing already allows adjusting the sampling density to conform to the require resolution, reducing file size compared to a scan at full resolution. Furthermore, it may be possible to produce both high and low resolution files of an object, then cut both into parts and combine those high resolution parts that are needed with low resolution parts of areas that are not of interest. However, how such a process can be done, and whether the resulting reduction in file size is worth the effort, depends on the specific object and intended use, so that a detailed discussion here is moot.

Repairing, Splitting and Combining

An important step of laser, CT and point cloud based mechanical digitizing is the repairing and cleaning of the original scan data and the initially created surfaces.

Some programs offer simple routines that perform the tasks well on standard files. Complicated problems, such as "back-to-back" surfaces, required detailed controls and can consume large amounts of time. "Back-to-back" surfaces often occur when a thin, plate-like structure is laser scanned. Usually, the two main sides are not covered by one scan, and small errors in calibration can lead to the two surfaces intersecting, and thus coming outside-to-outside (back-to-back) with each other. This also creates a long gap along the edge of the structure. This gap cannot be closed automatically, and manual closing leads to internal surfaces extending to the outside of the file, rendering it useless for many purposes, e.g., volume determination. In such a case, the two surfaces must be deformed so that their insides become sub-parallel and face each other, and then the gap along the edge can be closed. Usually, it is easier to adjust the raw data and generate a new surface.

A repairing option that must be used cautiously is smoothing or polishing the surface. This usually is intended to remove the little pyramid shapes protruding from the surface, both outwards and inwards, caused by points lying just outside or inside the surface. Automatic options remove these reliably, but can lead to problems when such pyramids are located close to edges. Similarly, filling holes is simple, unless the holes are in places with abrupt topography changes. Here, it may be necessary to manually remove pyramids, and close the resulting and other holes by creating bridges across them. The remaining smaller holes can then be filled automatically.

Thin, plate-like structures often show a stronger version of the above mentioned pyramid errors, when two errors on the two sides connect, so that a tunnel is formed. If the surface thickness is close to the sampling distance on each surface, this error can occur so often that the surface has numerous small holes (Fig. 2.8). Such errors cannot be corrected automatically, and it may be faster to extract a new surface using slightly different parameters from the original data, or even re-scan the specimen.

Splitting and combining surfaces is usually easy as far as the technical aspects are concerned. More difficult is the question of how to scan, scale and align the parts properly, and how to document this sufficiently to make it immediately clear to any reader of a publication that the surface is not an exact representation of a fossil specimen. Usually, the absolute minimum data required for combining specimens are three clearly defined and easy to detect landmarks present on both parts that will be merged. The spatial relation between these landmarks must be unaltered, so that deformed specimens cannot be used. For the actual combining operation it is advisable to use several views at the same time, ideally six axial Cartesian views (top, bottom, left, right, front, back) plus one freely rotatable perspective view. Sadly, computer monitors of sufficient size cost more than a small car, so normally one must be content with switching between one view (for editing) and four views (one rotatable, three axial, which must be flipped between their two directions) for checking the results. The same is true for creating digital arrangements in which the surfaces stay separate, such as digital skeletal mounts.
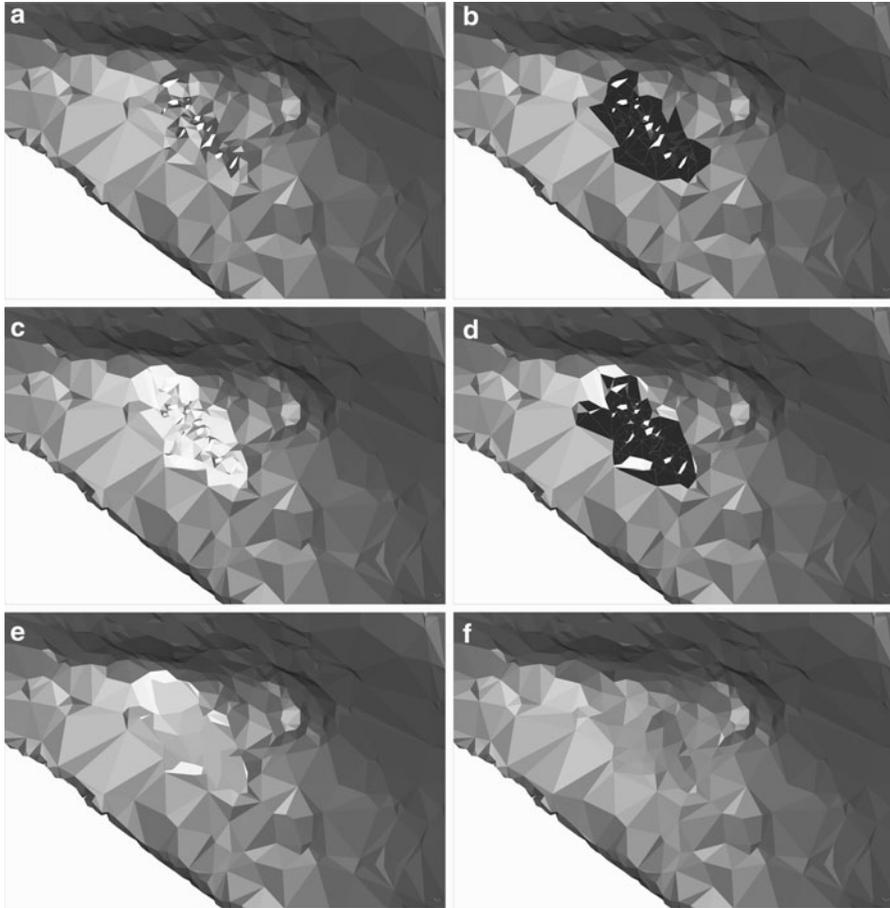
Fig. 2.8 Example for meshing error repair. CT scan based polymesh file of a *Tyrannosaurus* maxilla. The file was extracted from the slices at a very low resolution, so that the meshing distance is barely larger than the distance between the outside and inside of the bone in some places. (**a**) This has led to a number of small holes in close proximity. (**b**) To repair the triangles contacting the holes must be selected and (**c**) deleted, and (**e**), the process repeated for the other side. (**f**) Repaired surface. Note that this resembles the actual fossil more than the initially extracted surface, despite additional editing

Accuracy

How accurate a digital file represents the physical object determines what purposes it can be used for. Usually, accuracy is directly linked to scanning resolution, but later data handling can influence it negatively. For example, a high resolution laser scan point cloud may be meshed with badly selected settings, so that the size of the individual polygons is too large to create an accurate representation of the finer surface details.

File accuracy may also be influenced by elements external to the fossil that cause artifacts, e.g., by armatures or metal braces. Laser scanners have problems with reflecting or transparent materials, while metal parts (or a high content of metallic minerals) cause trouble for CT scanners. Mechanical digitizing also can face problems when fossils cannot be taken off armatures. For all methods, fixing the problems is usually easy, but requires additional time.

A significant problem for all digitizing techniques that are not touch and motion free (e.g., CT scanning, but especially mechanical digitizing) is motion by the fossil during data collection. This can lead to artifacts easily recognized, but small motions may go undetected, and induce significant errors. This is the main reason why any digital file should be checked again the original before use, e.g., by measurements of several length parameters.

The highest scan resolutions can be achieved with HR CT scanning and laser scanners. Up to approximately 10,000 points per centimeter [or ~ 24,000 dpi (dots per inch)] are possible for laser scanning, and less than 5 µ resolution for HRCT.

One especially dangerous source of error that can drastically reduce accuracy is human error during file editing. If the units of a file as set wrong (e.g., "mm" instead of "m") the mistake will be noticed and corrected. However, if a file is supposed, e.g., to be reduced to 90% of polygon number, but is rescaled for geometric size instead, the resulting error (equivalent to a erroneously scaled scale bar in a figure) may escape attention, and the results of studies based on this file may be taken at face value. Care must thus be taken that all file versions are kept, that the initial file version, the final version used for studies and the original fossil are compared, and that notes are kept of what was done to what file. Ideally, this information is included in the file name, e.g., Dactylioceras_IFGT332_50perc.stl indicating that the file of an ammonite scan was reduced to 50% polygon number.

Summary

Overall, digital models of fossils can be a helpful tool for preservation, research and education. Digital files make possible some research projects impossible on real fossils, because they allow non-destructive investigations of internal structures or (re-)deformations, greatly reduce the work load for others such as range of motion analyses for vertebrates, ease the tasks of planning museum exhibits, especially when large multi-part mounts are desired, and in some cases may be the only option for preserving fragile specimens for theoretically unlimited time.

However, digitizing is not a magical solution to all problems, and due to the potentially high cost and work effort proper planning is required to use it effectively. Many techniques are still in their infancy, and a certain degree of trial and error testing should always be allowed, because even minor changes to a technique may provide large benefits.

Researchers and curators alike should therefore publish not just the results of their research using digital files, but also the details of their digitizing technique and

their experience with handling and using the files. Only if the know how is properly exchanged can full use be made of the enormous potential digitizing offers for paleontology. Files should be made available for researchers worldwide, and file transfer should be provided without hassle, e.g. through FTP servers. This requires funding, and it is up to the professional paleontological community to convince funding agencies to provide the required support.

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