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3D PRINTING FOR CASTING PROPORTIONAL REPLICAS IN THE CONSERVATION OF ARTICULATED SKELETONS

CHRISTINE HAYNES, JULIA SYBALSKY, AND FRAN RITCHIE

The anatomical accuracy of natural science specimens is important for their use in education and display. This case study explores the recreation of missing elements of an articulated brant goose skeleton (*Branta bernicla*) using 3D digital techniques along with traditional mold-making. This research details the options available for 3D scanning, file manipulation, printing processes, and materials with emphasis on cost, practicability, and long-term stability. For this case study, the final cost was less than $60 for the scanning and printing of five small bones. Combining digital technology with traditional mold-making techniques allowed for the more accurate calculation of shape and proportion of the bone replicas and the quick and economical creation of highly detailed molds.

KEYWORDS: 3D Scanning, 3D printing, Rapid prototyping, Plastics, Casting, Replica, Articulated skeleton, Natural history

1. DIGITAL PROCESSES IN ART AND CONSERVATION

3D scanning and printing have been eagerly anticipated as the answer to replication and loss compensation needs in conservation. Scanning and replication are commonly being used as a form of cultural heritage documentation and as a tool for distributing information beyond institutions and across borders (Wachowiak and Karas 2009; Roosevelt et al. 2015). Artists and architects are increasingly using 3D printing in their work, often creating born-digital files using different modeling software. However, conservators have hesitated to incorporate 3D printed materials in their treatments due to the unknown aging characteristics of the various plastic polymers involved. During the treatment of an incomplete articulated goose skeleton at the American Museum of Natural History, the authors combined 3D scanning and printing with traditional mold-making techniques to create relatively stable and anatomically accurate replica bones.

2. OBJECT INFORMATION

The articulated goose skeleton is part of the education collection in the ornithology department at the American Museum of Natural History (fig. 1). It is one of the department's historic mounted specimens, dating possibly from the early 1900s. The historic tag reads "*Branta branta* Europe," a taxonomical name currently not in use. *Branta* is the genus for black geese, which includes six to eight extant species (Jobling 2010). The specimen has anisodactyl feet (three toes in front, digits II, III, and IV, and one in the back, digit I) with palmate webbing (only the anterior digits II through IV are joined) consistent with *Branta* goose anatomy (Gill 2001). The small size suggests that this skeleton may be *Branta bernicla*, called the *brant* or the *brent goose*.

The object lacks the proper collection data to be studied as a type specimen, a specific organism or specimen formally attached to a scientific name that anchors the defining features of that particular species or type. However, it can be used by researchers as an historic object to evaluate early-20th-century preparation and mounting methods and to make qualitative anatomical comparisons to other specimens. The object had been on loan to the Conservation Center at the Institute of Fine Arts, New York University (NYU), as a teaching tool for a course on natural science specimens taught by co-authors Julia Sybalsky and Fran Ritchie. The skeleton was on open display in a conference room and was slated for cleaning, having accumulated a thick layer of dust.

Fig. 1. Before treatment images. Goose Skeleton, *Branta bernicla*, bone, iron alloy, copper alloy, aluminum, wood, and paint, 38 × 29.2 × 17.3 cm. Department of Ornithology, American Museum of Natural History, 581

However, in addition to dust accumulation, the skeleton was missing several bones, including the first and second digits from the wing and digits II and III from the foot. Detached elements were also found near the object, including several tail vertebrae and a claw from digit V. Although this is not a type specimen, accurate representation of the species is still a primary aspect of natural history objects. The conservation team consulted with Collections Manager of Ornithology Paul Sweet to honor the authenticity of the object and its representation of a species. After examination, he determined the detached tail vertebrae had been too large and not proportional to the rest of the specimen, and hypothesized that these bones may have been a later addition. Therefore, we were missing the correct tail element in addition to the missing digits. In addition to cleaning, it was decided to pursue the reintegration of the detached elements along with the accurate replacement of missing bones. The overall goal of treatment was to produce a specimen more complete and identifiable than it was in its current state (fig. 2).

In current practice, reproductions of missing skeletal elements are cast from molds taken from analogous bones of other specimens of the same species. We began by measuring our specimen and looking for analogous bones in other collection objects. As an early-20th-century specimen, this could be due to changes in the species' average size over the past 100 years. Alternatively, the specimen may have been originally hunted for its large size, as this was a common practice in early-20th-century trophy hunting.

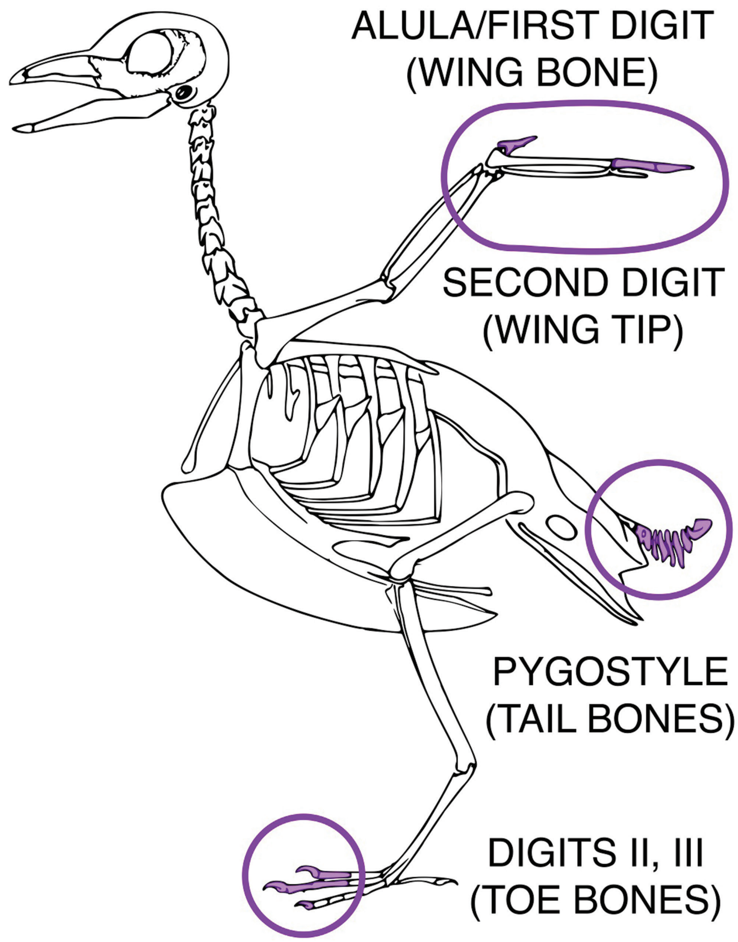

Fig. 2. Annotated diagram of avian anatomy showing the detached and missing elements of the object

The specimen lacks any provenance, so the primary reason for its collection and preservation, be it scientific or aesthetic, is unknown.

3. TREATMENT PROTOCOL

Since there were no proportional geese from which we could take molds, we identified three other options: (1) leaving the skeleton as is, with missing parts, which could be distracting and misleading; (2) hand-carving or hand-building replicas, which would be very time consuming; or (3) exploring digital reproduction methods to modify the proportions of other brant specimens' bones to fit our specimen—the option that was eventually selected. The initial plan for loss compensation was to choose analogous bones from a smaller specimen, 3D scan them, increase the size with modeling software (making an assumption that the proportions would remain accurate, or at least more accurate than free-hand sculpting would otherwise be), and 3D print the replicas (fig. 3). We utilized NYU's digital media facility, the LaGuardia Studio, where specialist Taylor Absher was consulted throughout the project. There are an increasing number of companies offering 3D scanning and printing services, making it an available option to both institutions and private conservators. Sculpteo.com (Sculpteo n.d.) can be a useful resource for finding local digital services.

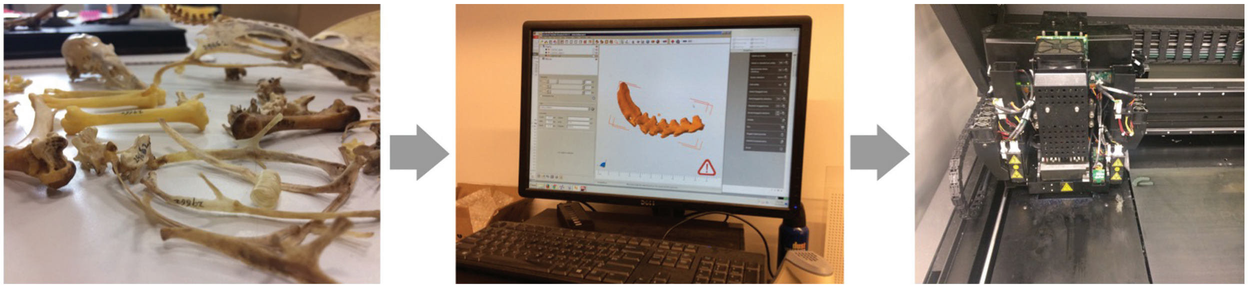

Fig. 3. Original proposed workflow. 3D scan analogous bones (left), modify size and orientation (middle), 3D print replicas (right)

3.1 Selecting a 3D Scanner

The term *3D scanner* describes any device that measures the physical world to create dense point clouds and polygon meshes. This includes standing scanners, handheld scanners, and photographic methods such as photogrammetry and emerging software that uses a phone or tablet (Digital Scan 3D 2018). Although these photographic methods are easily accessible, they are still fairly low resolution for an inch and a half long bird bone. High-performance scanners that were previously only used in space stations and the medical industry are now available at both university-run and public digital media studios. To choose an appropriate scanner and scanning method, the team needed to balance the quality and detail of the scan with its cost and availability.

There are two main types of short-range scanners that work very similarly: structured white light scanning (fig. 4) and laser triangulation (fig. 5). Structured light scanning measures the deformation of a light

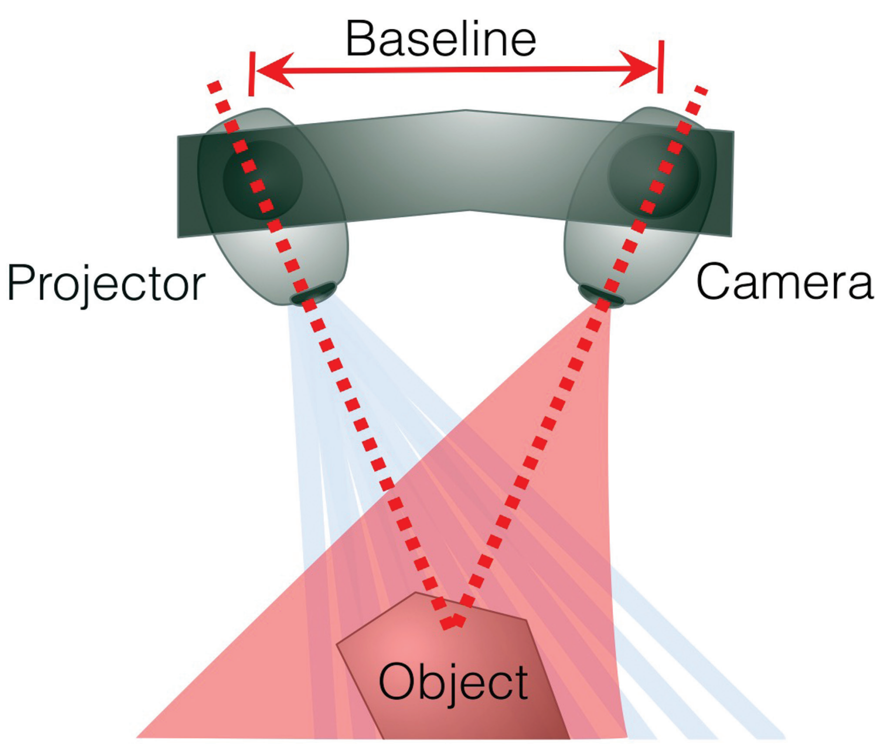

Fig. 4. Structural white light 3D scanning

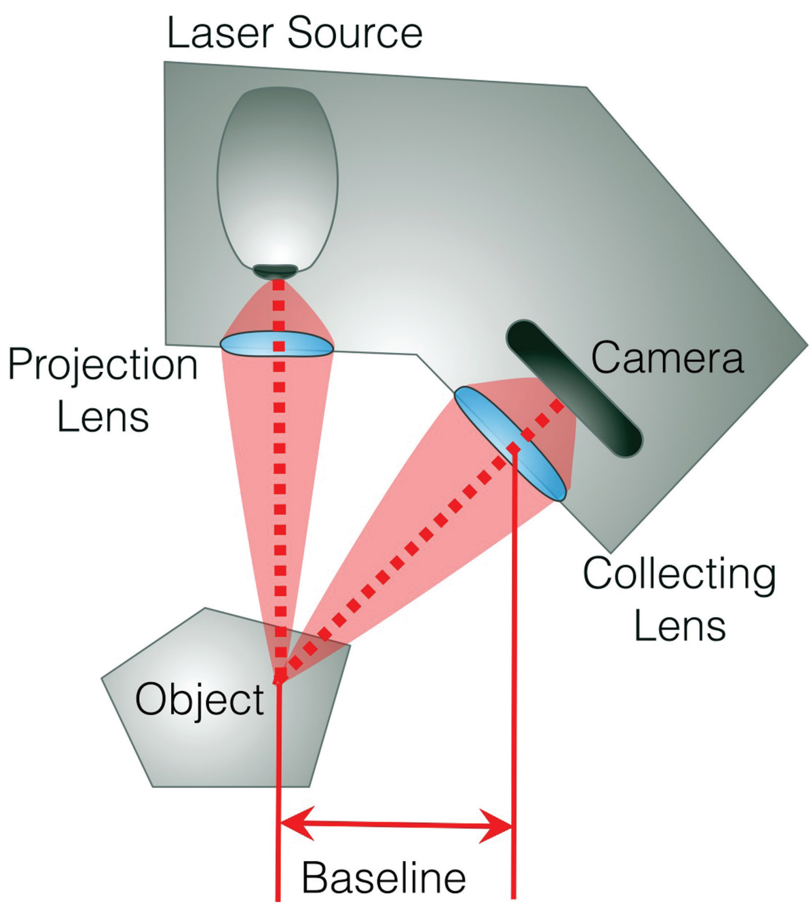

Fig. 5. Laser triangulation 3D scanning

pattern across a surface, and laser triangulation measures the deformation of a laser beam across an object (NeoMetrix Technologies Inc. 2015). From these data points, the accompanying software can then model the form as a point cloud or polygon mesh. The main difference between the two methods is that structured light scanning can give higher resolution and accuracy, whereas laser triangulation can be more versatile with less specialized preparation required before scanning (table 1).

Ambient white light can interfere with how the structured white light scanning acquires data, so it may require a more controlled environment, whereas laser triangulation can be used in most lighting

Table 1. Short-Range 3D Scanning

Scan Type	Ideal Application	Resolution	Preparation	Light
Structured Light	Small objects, textured surfaces; ability to scan in controlled environment	Higher resolution and accuracy	Sample may require surface prep	May require specialty lighting
Laser Triangulation	Translucent or transparent surfaces; quick, on-site scanning	Moderate resolution, more noise	Little to no preparation needed	Less sensitive to ambient light

conditions. However, the resolution for laser triangulation is generally lower for most objects. Structured light scanning is more sensitive to the surface finish resulting in higher resolution. The drawback is that the higher sensitivity can cause difficulty with scanning translucent and reflective objects. This can be mitigated with sample preparation and coatings, or by using post-processing software. Out of the five bones, there were only two localized areas of translucency, so we prioritized the overall higher resolution and chose the structured light scanner. Generally, structured light scanning is ideal for small textured objects and laser triangulation for translucent surfaces or on-site scanning (Artec 3D n.d.).

La Guardia Studio's structured light scanners are the Space Spider and the Eva by Artec 3D. They are portable and can be handheld or attached to a robotic arm. Artec recommends the Space Spider for scanning high-resolution form and color at a close range. The company cites the scanning speed as 7.5 fps with high 3D point accuracy of 0.05- and 0.1-mm resolution. Due to its high accuracy, it requires no added targets, reducing unnecessary contact with the object being scanned. The scanner comes with its own Artec software but also generates several file formats that that can be manipulated in a variety of programs, including OBJ, PLY, WRL, STL, AOP, ASCII, Disney PTX, E57, XYZRGB, CSV, DXF, and XML.

Absher assisted in setting the bones onto a post and used a robotic arm on the Artec Spider to move around the entire object. Although we could scan both form and color, we only scanned the form because the color of the analogous bones differed from that of our specimen. Scanning of the five objects came to a total of about $50, approximately $10 per cubic inch.

3.2 File Modification: Software and File Types

There are several different free, open source, and paid subscription file modification software tools available (table 2). Modification tools can be sorted into three main types: CAD tools based on geometric shapes; sculpting tools that are similar to digital clay that you can push, pull, and pinch; and free-form tools. There is also print preparation software that slices the data into printable layers and can troubleshoot damaged meshes (3D Printing for Beginners n.d.).

If the 3D model will be used as a form of documentation and preservation, there are additional issues with the saving of file formats, versioning, and obsolescence. Since the museum did not plan on saving these scans as documentation, this was not included in the scope of the project. 3D scans can create a lot of complex data, so it is important to consider the cost of storage space and the usability of the file if it is important to retain it.

Two of the most common file formats for representing 3D objects are STL (stereolithography [SLA], or standard tessellation language) and OBJ (object) (table 3). STL is one of the original 3D printing formats and can be used universally with different software and 3D printers. However, STL lacks the ability to

Table 2. File Modification Software

	CAD	Sculpting	Free-Form	Print Prep
Free	Sketchup; Freecad	SculptGL; Sculptris	Blender	Slic3r; Autodesk Meshmixer
Paid	3D Solidworks; Rhinoceros	Geomagic Sculpt	Cinema 4D; MAYA	Simplify 3D; Netfabb

Table 3. Features of Two Most Common 3D File Types

File Type	Compatibility	File Size	Color and Texture Data
.STL	Open format; universal: compatible with third-party software and nearly all 3D printers; free .STL viewer software available, can be easily converted and edited	Relatively smaller file size resulting in quick processing	Does not include metadata, color information, material information (can use nonstandard versions of format that add color information)
.OBJ	2nd most widely used format; compatible with may third-party software	Generally very large file	Can specify multiple colors, textures, and materials

save additional information such as color or material unless a modified STL format is used. OBJ seems to be the most commonly used format for incorporating color information. Both file formats can be used with many open source viewing and editing software. However, it is important to understand how the file is displayed after it is opened in different applications and how it is subsequently saved. Certain proprietary software may change how the file is saved, most commonly adding compression. A compressed file may render differently when opened in different software, so it is advisable to stay consistent and note in treatment documentation what software and version you have used (All3DP n.d.).

Since we did not scan color, we saved the scans as STL files to have a smaller file size with easier workability. The LaGuardia Studio uses Netfabb Pro software, which has been designed for 3D printing. It is robust subscription-based software that uses all three types of modifying tools, can troubleshoot manufacturing issues, and can aid in the design of mounts. If scanning and printing through a service, the service will likely have a preferred software that their team uses.

In Netfabb Pro and most software, the model can easily be proportionately rescaled by increasing one of the coordinates. For the digits on the proper left side of the body, we increased the length to match the proportions of the digits on the proper right limb. For the tail size, we needed to determine the ratio between the articulated skeleton and the analogous skeleton. We compared measurements within the articulated skeleton, between specimens, and during a final consultation with the ornithologist, Paul Sweet. After modifying the files, we were ready to choose what processes and materials would be used to manufacture the replicas.

3.3 3D Manufacturing Processes and Materials

The two ways to create a physical object from a digital file are additive printing or subtractive milling. A range of stable materials can be used in subtractive methods such as computer numerical control milling or machining, including metals, stone, plastics, waxes, and wood. The milling heads can move in different geometries to systematically remove material to create the final form. The process is highly accurate and can create objects with high resolution, but due to the geometry of the milling heads, it is better suited to larger-scale objects. It is generally a much more expensive process and is often used in industry to make robust and exact prototypes (3D Experience Marketplace | Make n.d.). For the small bird bones we were attempting to replicate, this process would not be very practical since the large

Table 4. Comparison of Common 3D Printing Processes

Type	Method	Ideal Applications	Resolution	Materials	Post-Processing	Cost
Fused deposition modeling (FDM)	Deposits two lines of UV-curable resins (one resin for the objects and one for the support)	Consumer-grade prints; simple and quick	Low: 0.5–0.127-mm layer	Acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), nylon (PA), polycarbonate (PC)	Option to polish/alter surface; remove support by hand	$
Stereo-lithography (SLA)	Vat of liquid resin, cured with UV light	Large models; hollow structures	Moderately high: 0.05–0.01-mm layer	Most rigid, opaque photosensitive resins (not compatible with color dyes)	Hand-sanding to remove support	$$
PolyJet	Up to six print heads deposit dots of liquid resin, cured with UV light	Fine details; small objects; multimaterial; multicolor	High: 0.016-mm layer	Most rigid/flexible, opaque/transparent photosensitive resins	Water-blasting to remove support	$$
Selective laser sintering (SLS)	Powdered resin sintered with carbon dioxide laser	High strength; chemica resistance (nylon)	Moderately high: 0.05–0.01-mm layer	Nylon (PA), polystyrene (PS), thermoplastic polyurethane (PUR), metal	Option to polish, etc.; no support to remove	$$$

milling heads would likely not have enough space to move in the precise geometry required for the small object.

Four of the most common additive 3D printing methods are fused deposition modeling (FDM), SLA, PolyJet printing, and selective laser sintering (SLS) (table 4). These methods were all available at NYU's LaGuardia Studio and are generally the most common types of rapid prototyping units in commercial digital studios. FDM is a common consumer printer that deposits photo-curable resin in lines, visible as characteristic ridges (fig. 6). This method is ideal for quick prints and prototypes. PolyJet uses multiple print heads to deposit dots of liquid resin cured with UV light (fig. 7). The dot-matrix can create fine details and render small objects. SLA focuses UV light into a vat of liquid resin, curing patterns layer by layer, allowing for large, hollow prints (fig. 8). SLS uses a high-power laser to bind powdered resin or powdered metal. Laser sintering can be ideal when chemical resistance is necessary (fig. 9).

Industrial studies have shown poor aging properties among 3D printed materials, including high susceptibility for mechanical creep (Costa, Linzmaier, and Pasquali 2013). For most printing techniques, the polymer options are limited by viscosity and melting temperatures, as they must be able to flow into

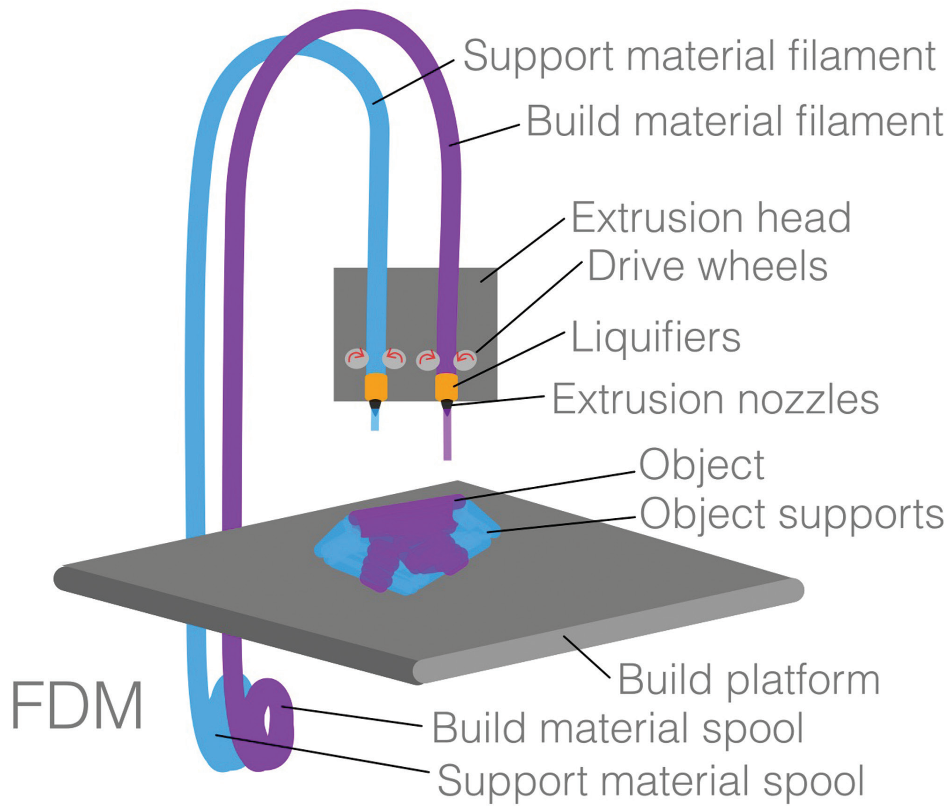

Fig. 6. Fused deposition modeling

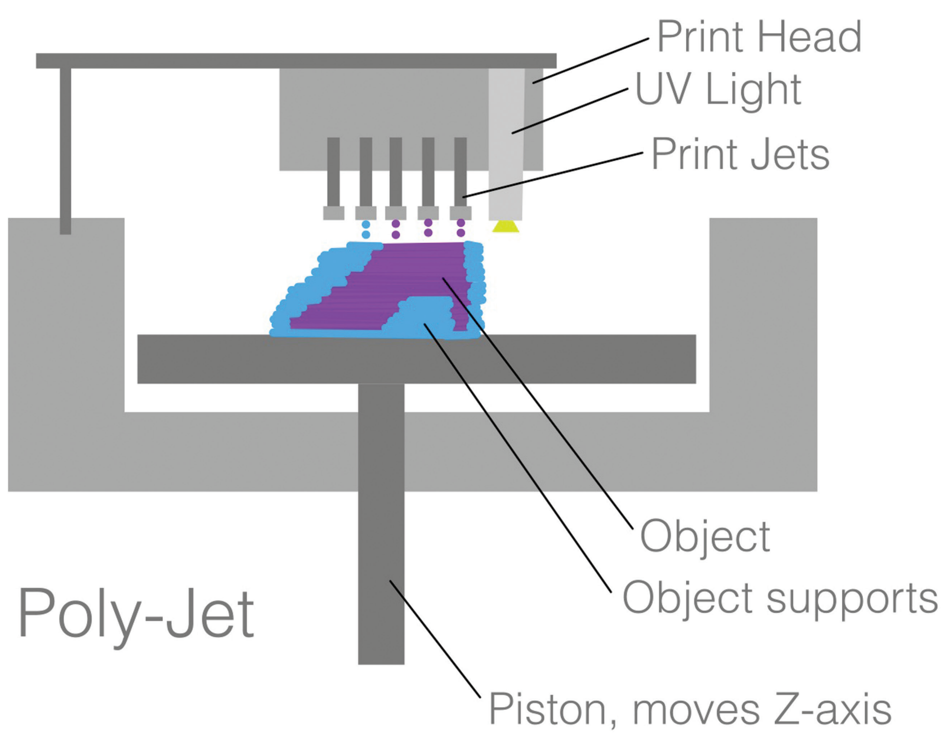

Fig. 7. PolyJet printing

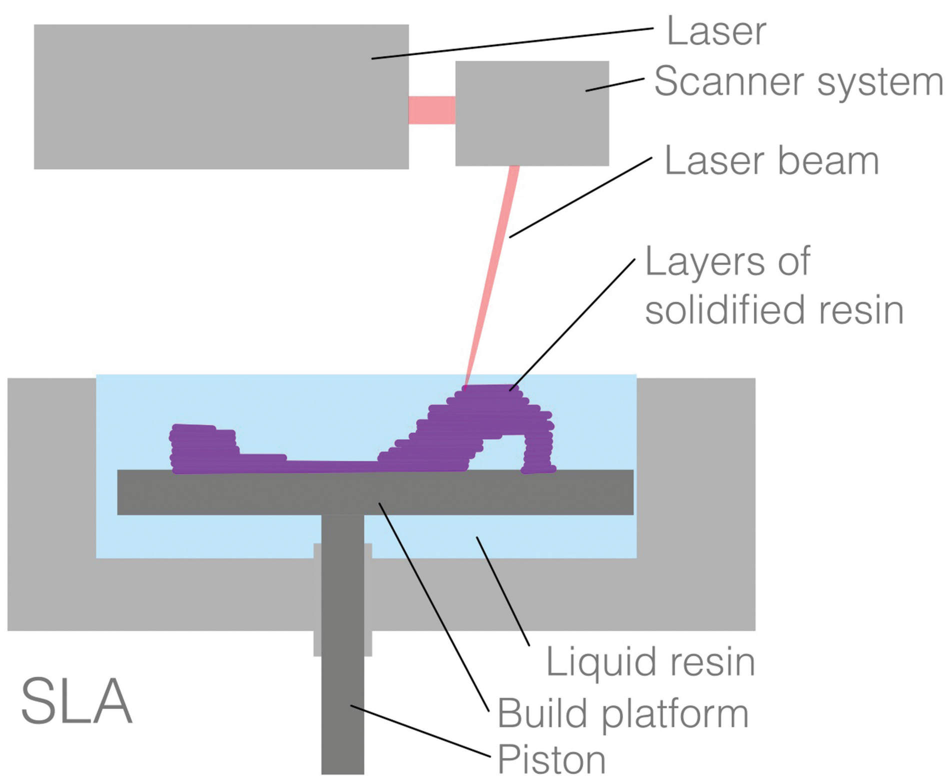

Fig. 8. Stereolithography

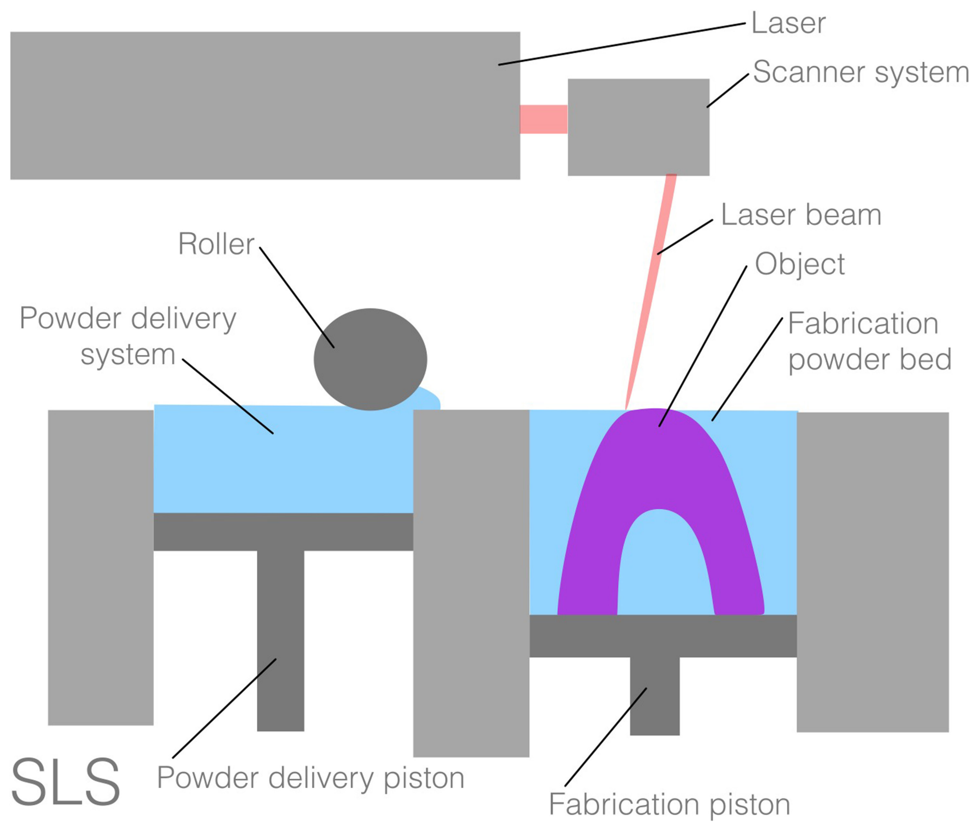

Fig. 9. Selective laser sintering

Table 5. Common 3D Printing Polymers

Polymer	Degradation Pathways	Process Compatibility	Cost
ABS (acrylonitrile butadiene styrene)	Photo-oxidation, thermal degradation; susceptible to UV light, oxidation, and high temperature	Fused deposition modeling (FDM); PolyJet	$
PLA (polylactic acid)	Biodegradable, hydrolysis degradation; susceptible to relative humidity	Selective laser sintering (SLS), FDM; PolyJet	$
Nylon/PA (polyamide)	Hydrolysis and thermal degradation; susceptible to high temperature and relative humidity	SLS; FDM	$$
PC (polycarbonate)	Fair UV resistance; good temperature resistance	FDM	$$$

the printer head. The most commonly used 3D printing polymers include thermoplastics such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and nylon (polyamide, PA) (table 5). SLA does not require the polymer to flow through a print head, allowing the use of thermosetting acrylates and epoxies that cure with UV light. Similarly, the lasers used in SLS have different requirements regarding how the material can be sintered. Although the polymer type can give one an idea of a resin's basic properties, commercial plastics often have proprietary formulas that do not disclose the additives and fillers that affect long-term aging. These additives may aid the resin in the final object's initial durability, but they are less predictable in how they will perform over time and affect degradation mechanisms since they are not studied in this way. Additionally, resin properties are further obscured by some of the names, like Duraform or Tangoplus, that do not disclose the main polymer (Stratasys Direct Manufacturing 2019).

The inherent degradation issues with 3D-printed materials are not just due to the types of polymers and additives used, but how the resins must be processed to flow through the print head and be cured on the manufacturing platform. The stability of these materials is especially dependent on how the resins are cured (Van Oosten 2015). The most common methods cure resin with UV light, resulting in a final object that has a greater susceptibility to photodegradation than other curing techniques.

Laser sintering is a promising technique since it does not use UV light. Laser-sintered nylon has passed initial Oddy testing, possibly making it a viable method and material for future conservation uses (Breitung 2018). However, suppliers use different polyamide types with varied manufacturing processes that impact the long-term stability. Multiple publications have noted rapid yellowing from SLS nylon samples (Madsack 2011; Van de Braak et al. 2017). The common practice of re-melting excess nylon to use in later prints results in objects more susceptible to yellowing and embrittlement. Conservation use of SLS nylon would require specific knowledge of the polymer, additives, and manufacturing processes to understand its longevity.

Although SLS can produce fairly high resolution, it was not high enough for the subtle texture of the bird bones. Any discrepancies or printer registration marks could be made up for in post-processing methods such as hand-sanding. However, since this project was initiated with the hope of finding a method that could be more precise than hand-building, we decided to look into other printing methods. Accuracy was deemed most important since the prints had to represent a very specific bone from a specific species.

The PolyJet printer has the highest resolution of any of the additive printing methods available at the time of treatment. PolyJets print in dots of liquid resin, in multiple colors with rigid or flexible polymers, allowing highly accurate and versatile prints. However, no matter which polymer is used, these prints do not all have the longevity usually required in conservation. The flexible polymers have all of the condition issues associated with elastomers (plasticizer migration, weeping, and embrittlement), and the rigid polymers have inherent weak points where each dot is sintered in the matrix, resulting in an overall brittle object. The condition issues of each polymer type are intensified by the vulnerability to photodegradation resulting from the UV cure. Similarly, the dyes used for colored polymers universally fade with UV light exposure. In certain cases, light exposure may be able to be mitigated, and these degradation issues may not be as prevalent of a problem.

3.4 Traditional Mold-Making and Casting

Although the PolyJet printer was desirable for its high resolution, the resulting dot-matrix structure of the finished object would be brittle regardless of the polymer type selected. Additionally, as the specimen would return to open display in the conference room, any plastic would be exposed to high light levels. The team could have chosen to incorporate the plastic prints themselves in the specimen, with a plan to eventually replace them as needed; however, we wanted to create long-term replacements that would not need maintenance. Therefore, we decided to make molds of the 3D prints and cast them in a more suitable material using traditional mold-making techniques.

First, we printed the models with a PolyJet printer using ABS, the cheapest available material, which totaled $4.59 for all five prints. We then created two-part silicone molds of the ABS prints using OOMOO 25 Tin Cure Silicone Rubber. WoodEpox, a commercial epoxy that is lightweight and pH stable, was chosen as the casting material. We toned the replacements with Golden Fluid Acrylics to look cohesive from far away but to be obvious as painted replicas when examined closely (fig. 10). Therefore, any researchers can understand the form and proportion of the bones they are replacing while knowing that they are not the originals to be measured or sampled from. We then adhered the replacement parts to the specimen with 50% Paraloid B-72 in acetone, bulked with glass microspheres so they could be easily removable in the future, if desired.

4. CONCLUSION

This process allowed our team to create accurately sized replicas of missing and unavailable components from a specimen quickly and cost-effectively (fig. 11). The scanning and printing took about two weeks, mostly due to scheduling with the LaGuardia Studio rather than actual production time, which was minimal. The final cost was less than $60 for the scanning and printing of five parts. When reproducing small components, the high-resolution scanning is the most costly part of the process. Printing costs will depend on the machine and polymer chosen, as well as size.

Although current plastics available for 3D printing are generally unsuitable as fill materials for objects, digital capture and reproduction methods can be employed as intermediary tools in aiding traditional loss compensation. In considering the use of 3D printed materials in conservation, it is important to consider

Fig. 10. After treatment images of the brant goose specimen along with analogous bones from a brant specimen, 3D-printed ABS replicas with size modifications, and toned epoxy casts

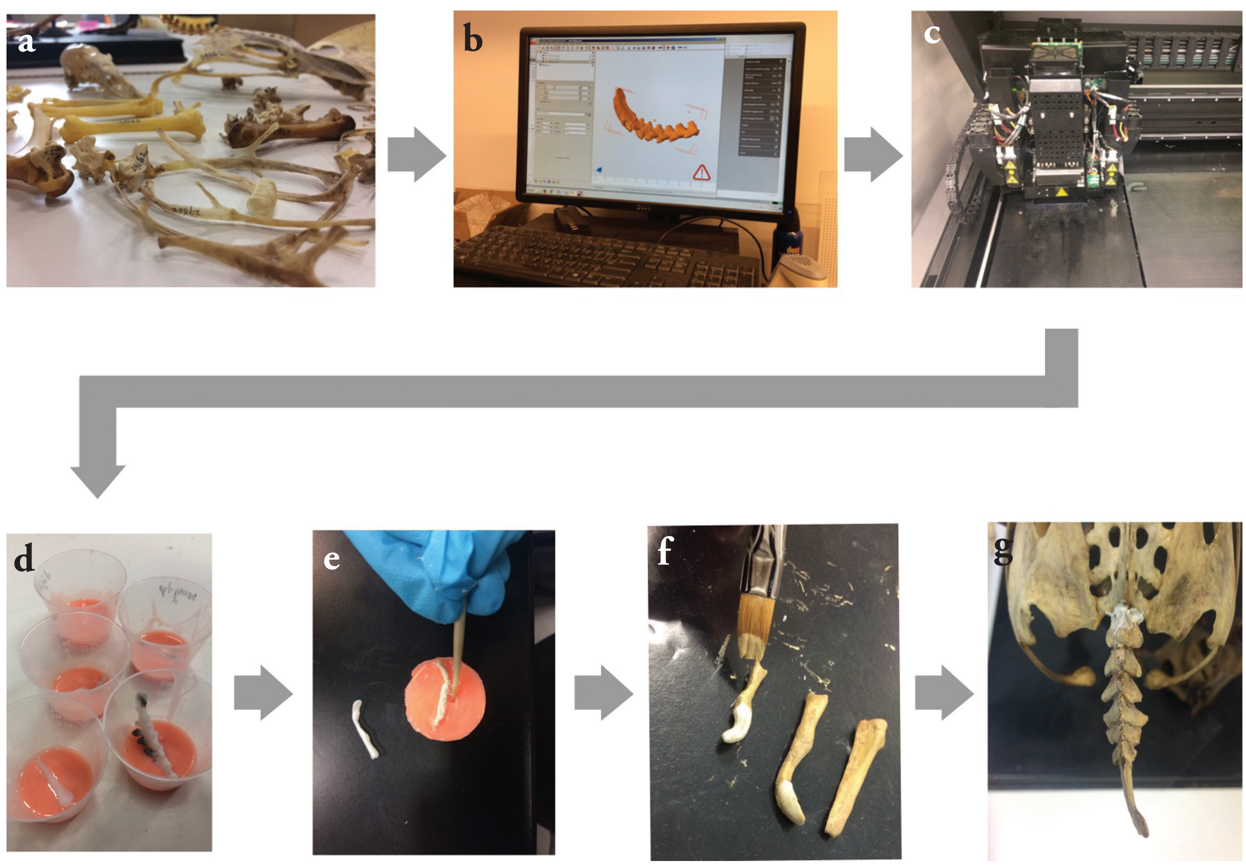

Fig. 11. Full workflow: (a) 3D scan analogous bones; (b) Modify size and orientation; (c) 3D print replicas in ABS; (d) Create silicone molds; (e) Cast in stable epoxy (WoodEpox); (f) Tone with Golden Fluid Acrylics; (g) Adhere with Paraloid B-72 bulked with microspheres

not only the inherent material instability of specific polymers employed but also their manufacturing processes and the environments in which they are kept.

This project is only one facet of research into accessible uses for 3D scanning and printing. In addition to applications for scanning and printing, future research may include issues surrounding digital file formats such as obsolescence, storage, and legal ownership.

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SOURCES OF MATERIALS

ABS, Stratasys PolyJet
Stratasys Direct Manufacturing
7665 Commerce Way
Eden Prairie, MN 55344
952-937-3000
https://www.stratasysdirect.com

Artec Space Spider
Artec 3D 2880 Lakeside Dr., #135
Santa Clara, CA 95054
669-292-5611
https://www.artec3d.com

Netfabb Pro Software
AutoDesk Inc.
111 McInnis Pkwy.
San Rafael, CA 94903
https://www.autodesk.com

OOMOO 25 Tin Cure Silicone Rubber
Smooth-On Inc.
5600 Lower Macungie Rd.
Macungie, PA 18062
610-252-5800
https://www.smooth-on.com

WoodEpox
Abatron
5501 – 95th Avenue
Kenosha, WI 53144
262-653-2000
https://www.abatron.com

Paraloid B-72, Microspheres
Museum Services Corporation
385 Bridgepoint Dr.
South St. Paul, MN 55075
651-450-8954
https://www.museumservicescorporation.com

Golden Fluid Acrylic Paint
Blick Art Materials
21 E. 13th St.
New York, NY 10003
212-924-4136
https://www.dickblick.com

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