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Establishing a Pipeline for the Scanning, Editing, and Full-Color Additive Manufacturing of Cadavers for Anatomy Training

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Abstract

Gross anatomy dissection is often seen as the ideal standard for anatomy education. However, gaining access to donated bodies can be challenging, expensive, and requires a range of resources not available at all institutions. While digital visualizations may address certain aspects of anatomy training when cadavers are not available, the use of complementary physical artifacts, such as 3D models, offers the potential to enhance educational outcomes in a way not achievable solely through virtual means. This paper establishes and demonstrates a pipeline for the creation of full-color physical facsimiles of cadaveric anatomy. This is achieved through a combination of photogrammetry, mesh and texture editing, and material jetting. The approach is then demonstrated using two case studies of varying geometric and color complexity, including an arm dissection and combined heart/lung model. Through this method of full-color reproduction, true-to-life specimens for anatomy training can be generated and deployed in education.

1. Introduction

Additive manufacturing (AM) is becoming an increasingly used tool in medical practice and education. By eliminating the need for an initial mold, the inherently individualized nature of the structures comprising the human body can be quickly and efficiently recreated using a range of AM systems [1]. Additionally, the geometric complexity enabled by AM ensures that the organic appearance of structures within the body can be replicated without extreme cost or waste. When combined with robust, already-existing scanning techniques within the medical field, AM is a natural support tool in the pursuit of human health and education. Computed tomography (CT) scans, for example, are widely applied to the creation of physical representations of internal muscular-skeletal structures via AM technology. By extracting bone, tissue, etc. based on the Hounsfield units in the CT scan, it is then possible to reconstruct these elements in 3D for later printing and visualization [2]. The result is that medical practitioners are more easily able to understand an individual patient's needs and prepare appropriately for medical interventions, such as surgery. However, given the relentless and rapid advance of both AM technology and medical practice, the simple recreation of single-material, patient-specific structures is no longer the pinnacle of medical structures replication that can be provided via AM. There is a need for AM researchers and medical practitioners to continue synergistically investigate the myriad possibilities for high-fidelity, lifelike, physical representations of the human body created via AM, in order to continue supporting patient outcomes.

One possible avenue for improving medical representation with AM is through advanced multi-material and multi-color systems. Advancements in material extrusion, binder jetting, and material jetting processes in particular have enabled the creation of full-color structures, as well as structures with a range of physical material properties [3,4]. By leveraging such advancements in technology and marrying them with advanced scanning techniques used in medical practice, it is becoming increasingly possible for designers to pursue the lifelike recreation of entire human bodies. However, such a task is non-trivial; it requires synergistic efforts from experts in both anatomy and design for additive manufacturing (DfAM) working in concert to create robust replications that are accurate to the complexities of the human body, rather than simplified textbook models with representative of detail and realism.

To this end, in this paper, the authors propose, discuss, and demonstrate a pipeline for the creation of full-color, high accuracy, cadaveric models via AM. Specifically, the authors show how photogrammetry, open-source mesh editing software, and material jetting can combine in a way that creates cadaveric models of a level of geometric and color fidelity not seen previously. In so doing, the authors provide a new avenue for the inclusion of AM to help address issues with medical practice and education, namely the challenges associated with procuring and preparing cadavers at scale for study by students across a range of institutions with varying resources.

2. Background

The novelty of the team's approach lies at the intersection of cadaveric model use in medical education (Section 2.1) and the opportunities and challenges associated with producing cadaveric models in AM (Section 2.2).

2.1. The Role of Cadaveric Models in Medical Education

A comprehensive understanding of human anatomy is essential to professional medical training. Broadly speaking, gross anatomy dissection is considered to be the ideal standard for anatomy education [5]. However, gaining access to donated bodies can be challenging, expensive, and require a range of resources which are not always available [6,7]. While medical schools typically have access to cadaveric specimen for learning anatomy, these are not always available to undergraduate institutions, allied-health programs, programs with constrained finances, or internationally. Accordingly, many programs will use a variety of lower-fidelity resources such as physical 3D models [8,9], computer or mixed-reality digital anatomy models [10,11], and 2D anatomy atlases [12,13]. While such resources help to expand the reach of anatomy education, they are often severely limited when compared with traditional dissection practices. For example, commercially available human anatomical models can vary in their detail; to reduce cost, many rely on low-fidelity plastic replicates with limited color and few relevant anatomical structures [14].

Computer-graphics based anatomical models are commercially available, and while some portray a more complete menu of anatomical structures along with applied textures to make these appear more 'realistic', the graphics are idealized; structures do not have nearly the organic appearance or layout as their actual cadaveric counter-points. Virtual models of cadaveric specimen can portray actual anatomy, faithfully reproduced via photogrammetry of dissected cadavers [15], however, the limitations of XR technologies are multifold. Some of the challenges are the maintenance of the hardware and software, the need for training of the students and faculty, the lack of haptic feedback, and the innate difficulty of using technology or viewing 3D structures using VR/AR. While students can utilize these and other cadaveric proxies to learn basic concepts including the names and general locations of structures, cadavers provide a realistic representation of human anatomy in terms of texture, color, feel, physical manipulation, and spatial relationships. The hands-on experience with a cadaver allows students to appreciate the intricacies and variations of the human body in a way that current models, digital technologies, and 2D anatomy atlases cannot replicate [16].

2.2. Opportunities and Challenges in Additively Manufactured Cadaveric Models

Due to the challenges associated with procuring cadaveric specimens, as well as the limitations that exist with current substitutes, there is a critical need to create realistic cadaveric facsimiles capable of broadly supporting anatomy education. AM is uniquely poised to address this need by leveraging its unique capabilities in mass customization and geometric complexity. As previously discussed, AM continues to find a place in medical training and practice, especially regarding visualization of the human body. Numerous studies have explored the use of CT and MRI data to reconstruct anatomical structures in a physical space [17–19]. Software, such as InVesalius and Materialise Mimics, has likewise expanded to support this capability in the medical field [20,21]. However, most existing models generated in this way typically focus on reconstructing a single material phase in the AM object. Most commonly, this phase is bone, which is easily identified in scans and is relatively well represented by common PLA-centric desktop printers whereas recreating soft-tissue phases is more challenging [22].

Unfortunately, with CT and MRI scans forming the main approach to reconstructing physical representations of the human body, produced structures do not often consist of the realistic colors and textures that may be seen during the dissection of a real cadaver. This is because, though they are capable of distinguishing between material phases, MRI and CT scan results are visualized on a greyscale spectrum and are unable to natively capture the color of internal anatomical structures [23,24]. As a result, some AM-produced anatomical models have attempted to incorporate multiple colors assigned to different material phases collected from medical scans [25–27]. However, such colors are arbitrarily chosen to emphasize certain anatomical structures [28] or overly simplified renditions of real-world colors and textures, similar to what might be found in traditional medical illustrations or computer-graphic renditions. While the field is starting to see stronger forays into the manufacturing of more life-like, full-color, multi-material anatomical models, even these high-quality models are based on interpretation of cadaveric geometries, rather than direct recreations of them [29]

The result of these challenges is that AM's capacity to recreate color-accurate, life-like anatomical structures has outstripped approaches to capture accurate geometry and color information from CT and MRI scans. An approach is needed that is capable of (1) capturing high-quality geometric information of a range of cadaveric specimens and (2) rendering facsimiles of these cadaveric specimens in the physical space with high-quality color information for both internal and external structures. As such, the remainder of this paper will focus on proposing, detailing, and demonstrating a pipeline for creating full-color, additively manufactured cadaveric models through a synergistic merging of traditional gross anatomy dissection, high-fidelity photogrammetry, robust mesh and texture editing, and detailed, high-resolution, full-color AM.

3. A Proposed Pipeline for Full-Color, Additively Manufactured Cadaveric Models

Given the opportunity to expand access to highly accurate, cadaveric models, this section will detail and discuss a potential pipeline to achieve the same. The novelty of this work centers on this pipeline and its ability to recreate cadaveric specimens rapidly, with high-fidelity, and in way that accounts for the individual nature of human specimens. The proposed pipeline is separated into three specific phases: geometry and color *capture* (Section 3.1), geometry and color *editing* (Section 3.2), and geometry and color *reproduction* (Section 3.3). The overall process is summarized in Figure 1.

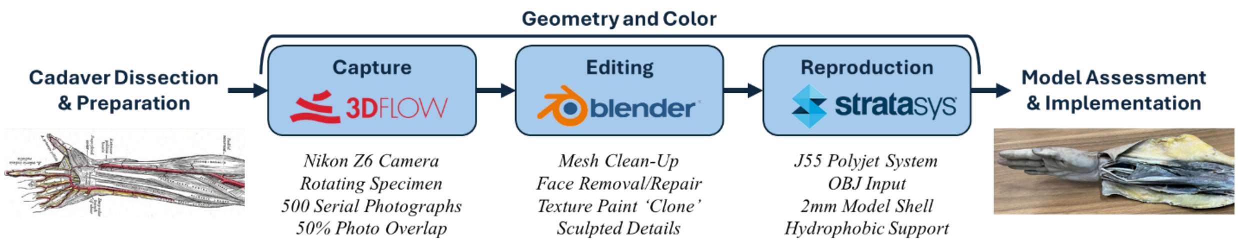

Figure 1. Overview of Proposed Pipeline for Cadaveric Models

3.1. Geometry and Color Capture

Photogrammetry is a common 3D scanning process of taking a series of photographs and stitching them together to create a 3D reconstruction. Given the need to capture robust color data in addition to geometric data from cadaveric specimens, photogrammetry serves as a superior alternative in the proposed pipeline compared with traditional CT or MRI approaches. Figure 2 shows a general schematic of the scanning arrangement used in the pipeline proposed for anatomical structures in this paper. However, where such a photogrammetry approach is limited is in its inability to easily distinguish between structures comprising different material properties, which is where the traditional cross-sectional medical scans have an advantage.

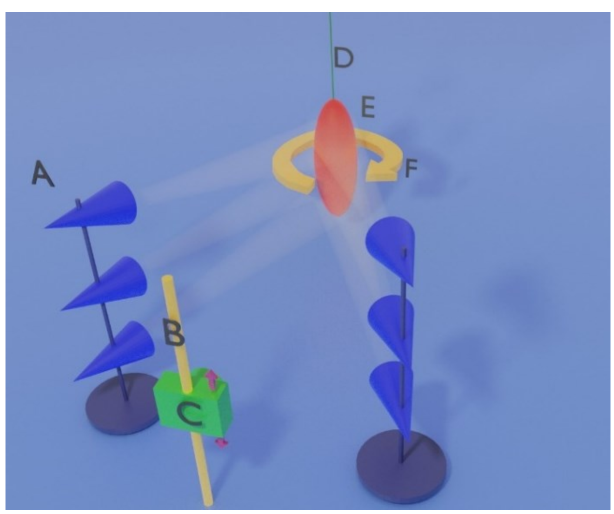

Figure 2. Schematic of Photogrammetry Set-Up for Specimen Scanning including (A) Lights, (B) Camera Slider, (C) Camera, (D) Suspension of Subject, (E) Subject, (F) Rotation of Subject

The anatomical structures captured using the proposed pipeline must be held in a static position using a combination of retractors and armatures, then the isolated structure is suspended from a motor that rotates the specimen at a rate of one revolution per minute. Approximately 500 serial photographs are taken using a Nikon mirrorless camera (Z6) equipped with a variable-zoom lens (AF-S NIKKOR 200–500 mm f/5.6E ED VR) set at 300 mm. To limit motion artifact caused by the rotation of the specimen, photographs are taken at 1/80 s. Aperture size is set at f/18 to maximize depth-of-field, and ISO is set at 800 to limit noise. To achieve these settings, six continuously-on 200-watt LED work lights are used to flood the specimen with light from six angles against a black backdrop. During each rotation, approximately 30–50 photos are taken. Photos are taken at a rate of approximately 1 photograph every 2 seconds using a shutter release cable to prevent camera shake, except for areas having greater detail (e.g., multiple isolated arteries and nerves) in which case photographs are taken at a rate of approximately one per second. After each rotation of the specimen, the camera is repositioned vertically on a slider so that all aspects of the specimen can be captured from a maximum number of views, with each view (photograph) having approximately 50% overlap with at least one additional photograph.

The photographs are then compiled using photogrammetry software (3DF Zephyr v6.0, 3Dflow, Italy) to convert the 2D photos into a 3D model, then the model is post-processed using Blender. The time it takes to create a model depends heavily on multiple factors. First, different areas of the body take more time for the baseline dissection. For example, the detailed structures of the face take more time to dissect than the relatively sparse forearm anatomy. Moreover, the number of layered dissections desired can impact time investment, with more layers taking more dissection sessions and therefore more time. Additionally, the number of photographs taken impact total time, with more photos taking more time. Computer specifications including available random-access memory (RAM) and the graphics processing units (GPUs) of a computer's graphics card also impact the process and rendering time to create the 3D model. Time also varies from person to person based on experience level and comfort with each step including body donor dissection and setting up the photogrammetry.

3.2. Geometry and Color Editing

After capturing the desired geometry and associated colors in OBJ format, it is necessary to import it into mesh editing software for further editing. In the case of this pipeline, all 3D models were post-processed using Blender, a free, open-source mesh editing, animation, and rendering software. Despite the high quality of the photogrammetry scanning process, there is still a significant amount of editing required to adequately prepare the model's geometry and color for eventual reproduction via AM.

As with many mesh repair approaches, the proposed pipeline begins editing via removal of easily identified noise within the scanned data. This includes triangles or shells that are isolated from the rest of the model geometry. One the initial scan has been cleaned, the geometry itself must be adjusted to best display the chosen cadaveric topology while also ensuring it is capable of being printed. For the former, all support structures from dissection and scanning must be manually deleted from the model. This includes all wires required for suspension of the cadaveric element as well as all tools (e.g., forceps) required to ensure that the scan can fully capture internal geometry. With supporting tools removed, the cadaveric topology must next be adjusted to ensure manufacturability while also ensuring that it remains accurate to the original scanned specimen.

Depending on the fidelity of the scan and the specimen arrangement, small elements such as small nerves or veins may not be fully rendered in the scanned mesh. Depending on the importance of these elements to the educational value of the model, they can either be thickened to ensure manufacturability or deleted to remove any potential concerns. In addition, the mesh may need to be edited to adjust topological details that were lost in the scanning process. For example, depending on the scanning process used, small gaps between surfaces may be inadvertently merged in the scanned mesh. If it is important for such surfaces to be separated in the manufactured product, then the relevant surfaces must be split and separated in the mesh itself.

The removal of supporting tools, splitting of merged geometries, and deletion of unmanufacturable features will almost always result in unwanted holes in the mesh. Such holes must be filled in order to maintain a water-tight OBJ file for later printing via AM. While these holes are easily filled in Blender, the result can be triangles of inconsistent size relative to the rest of the mesh. Later stages of the process require consistency in triangle sizing; as such surfaces used to fill holes may need to be further subdivided to ensure a clean, workable mesh. For the proposed pipeline, it is essential to avoid remeshing the entire mesh to achieve consistent editable triangles or change the level of detail/file size. The use of full color textures in the cadaveric scans is one of the transformative aspects of the proposed approach; however, if the scan is at any point completely remeshed, then it will cause the textures to become disconnected from the mesh itself. In simple geometries, this may not be a problem, as the texture can be easily reassigned to the mesh through a process of texture baking. However, the organic, complex nature of the cadaveric models makes this process completely intractable. As such, care should be taken to avoid adding, subtracting, remeshing any regions of the mesh unless absolutely necessary.

After filling holes that resulted from edits and deletions in the scanned mesh, it becomes necessary to remap the newly created mesh faces to the texture file associated with the scan. To accomplish this, each newly created face in the mesh must be mapped to the UV space in the texture file. To avoid the need for a new texture file, it is possible to map these newly created faces to a location in the texture image that is either (1) currently unused in the model or (2) similar in color/texture to what is desired in the new model face. The image in Figure 3 shows an example of mesh faces mapped to a texture image.

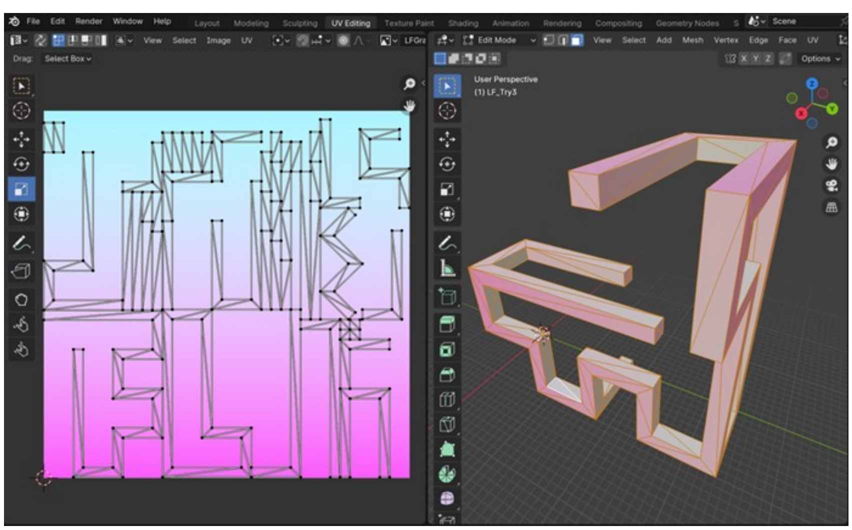

Figure 3. Blender Mesh Interface with Associated Texture Image for Example Full Color Part

With all newly created faces mapped to a location on the texture image, additional color detailing can be conducted in the model. This can be done to (1) enhance the realism of the model, (2) address deficiencies in the original scan, or (3) to create new, accurate color for newly added faces in the model. However, given the color and texture complexity in cadaveric scans, it is necessary to find a means of easily adjusting the color of any given face to create as natural an appearance in the final model as possible. Fortunately, within Blender's texture paint tools is a command dubbed "clone," which enables the user to copy colors from a specific image location in Blender and copy them to a new location in the same image. Using this tool, it is possible to transfer nearby colors/texture to faces which may lack accurate or pre-existing color. Though the use of such copying may not be fully reflective of the original cadaveric specimen, it nevertheless enables designers to rapidly generate life-like textures throughout the model by leveraging the textures that already exist in the scan. Obvious repetition in texture that arises from the use of cloning can be offset with other texture paint tools, such as "smear" or "blur."

With undesired geometries removed and colors adjusted, the final stage of editing within the cadaveric model is to further improve detailed realism prior to printing. The objective of this phase is to improve the lifelike feel of the model in a way that may have been lost during the photogrammetry process. As an example, though the texture image may contain the color information that shows the presence of wrinkles on scanned skin, the physical texture of these wrinkles may have been lost during scanning. By manually adjusting the mesh using Blender's sculpting tools, key details such as this can be reintroduced to the model before printing. Though the designer is most likely to rely on the use of the "smooth" tool, it is also possible that the "grab," "crease," and "flatten" tools, among others, may prove useful throughout the process of adding detail to the model. Of important note, this stage of reintroducing physical detail to the model may require the designer to embrace artistic skills that they may feel foreign to engineers. However, as with the use of the "clone" tool in texture painting, other points in the model may help serve as references which can guide the addition of detail. As an example, wrinkle geometry that was successfully scanned in one part of the model can help guide the creation of wrinkle details with manual tools in another, less defined part of the model.

Finally, with the mesh geometry repaired, undesired geometries removed, colors and textures applied, and sculpting details introduced, the cadaveric model is prepared for printing. As with the majority of CAD tools, Blender includes a simple export process for AM. However, given the need to include full-color information for the final printed models, STL exporting cannot be used. STL files are well-known for their lack of included information, which includes the inability to include any information regarding color associated with a model. Instead, the cadaveric model is saved as an OBJ file, which allows for the corresponding texture image to be retained and later reapplied to the geometry itself prior to printing.

3.3. Geometry and Color Reproduction

Given the complexity of both the capture and editing phases, the reproduction phase is relatively straightforward. In this case, a high-resolution multi-color AM system is needed to reproduce the models in the most realistic fashion. Historically, this limits designers to the use of either binder jetting or material jetting technology. In the case of the proposed pipeline, material jetting is preferred due to its increasing use in the generation of full color models across industries, along with its general office-friendliness compared with binder jetting (a consideration that is important in medical facilities). To this end, the proposed pipeline uses a J55 Polyjet system from Stratasys, which is a midsized system with a horizontal build area of 1,174 cm^2, a build height of 190 mm, and an accuracy of ±150-180 µm.

OBJ files exported from Blender in Section 3.2 are directly imported into the J55 system using the GrabCAD Print software. Once imported, files are oriented, scaled, and positioned on the build tray according to the designer's preferences. Standard considerations for AM build preparation (e.g., shortest dimension aligned with the Z-axis) should be accounted for at this stage. Figure 4 shows an example tray for a full-color specimen.

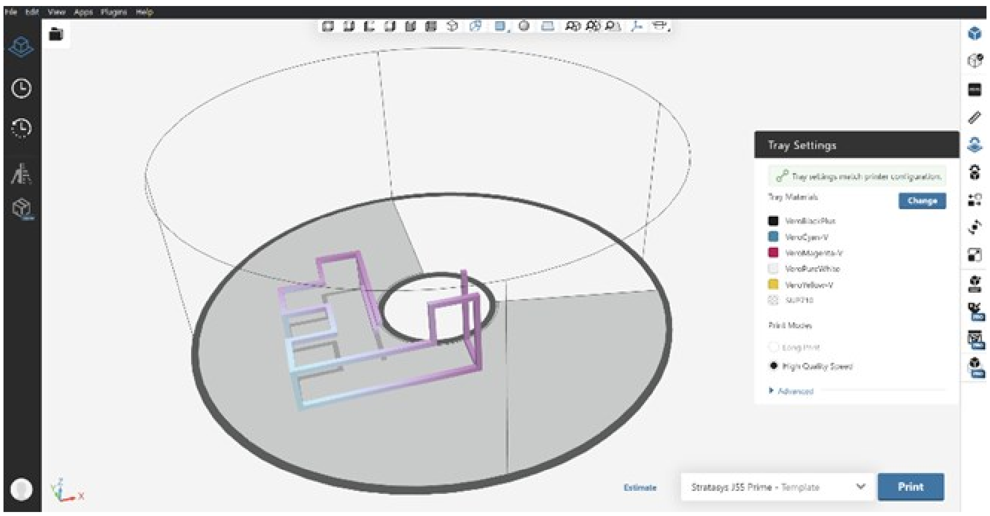

Figure 4. Example Full-Color Build Tray for J55 PolyJet System with Shortest Dimension Aligned with Z-Axis

The J55 Polyjet system is beneficial in several ways for the recreation of scanned cadaveric models. As mentioned, material jetting is one of the few process types capable of full color printing using one of several available palettes built into the printing software. Additionally, material jetting is capable of high-resolution prints, with a minimum feature size on par with the detail capable with vat photopolymerization systems. This detail will make it possible to accurately replicate the small surface textures and details added throughout the geometry and color editing phase of the pipeline. However, it is worth noting that the material properties of the photopolymeric materials used in material jetting are not typically sufficient for functional components under high cyclic loading. Fortunately, this concern is minimized considering the primarily aesthetic and tactile focus of the cadaveric models under study. Advantageously, material jetting can produce parts with highly variable, functionally graded material properties as well. Though this capability has not been leveraged in the current work, it will prove essential in future expansion of the research, where different material properties could be applied to different body tissue materials. This would enable components such as skin and bone to feel distinct from each other, while also looking photorealistic.

As with most AM process types, material jetting requires a secondary, sacrificial support material during printing which can be removed during post-processing. In the case of the proposed pipeline, printing relies on the J55's hydrophobic support material, which is deposited in all locations where the overhang angle is not perfectly vertical. This material is then washed away using a high-pressure water jet after printing. As such, care must be taken not to damage fine features in the model during the cleaning process. In the case of full color models, such as those under study here, this relatively inexpensive support material can also be used as an infill within a shell of the more-expensive model material that forms the shell of the structure. For the models in this work, a shell 2mm thick was used, with the rest of the infill being comprised of the support material.

4. Demonstrating the Pipeline with Two Case Studies

To demonstrate the proposed pipeline detailed in Section 3, two distinct case studies were investigated. These case studies aimed to show the relative challenges and possibilities in two different contexts, the first being a cadaveric arm and the second being a cadaveric heart and lungs.

4.1. Cadaveric Arm

The first case study is of a partially dissected cadaveric arm, with skin arranged in such a way as to show both the interior and exterior structure of the donor arm. This case study offers the chance to demonstrate the ability of the pipeline to generate accurate internal details of a structure, while also generating a highly accurate, yet smooth, external skin surface.

Geometry and Color Capture. For the first of the two case studies, the photogrammetry techniques detailed in Section 3.1 were used to build a virtual anterior forearm. The process for creating the virtual model began with a detailed stepwise dissection; the process included incision and reflection of the skin along the anterior forearm, followed by separation of the deep muscular fascia which binds the individual muscles of the forearm's superficial layer. The flexor carpi ulnaris muscle was separated and retracted medially (pulled to the "ulnar" or "pinky finger side" of the forearm) to reveal the ulnar artery and nerve; the pronator teres and flexor carpi radialis were similarly pulled medially to reveal contents of the cubital fossa, including the supinator muscle, brachial artery and its terminal branches along with the median nerve. In the distal forearm, closer to the hand, the muscles and their tendons were further separated to reveal the deeper anatomical structures including the flexor digitorum superficialis, flexor digitorum profundus, and flexor pollicis longus. In all, the forearm model requires approximately 2 hours for dissection. Upon completion of the dissection process, the forearm was suspended vertically within the photogrammetry setup shown in Figure 2. After it was suspended, the scanning process was executed according to the details presented previously in Section 3.1. In total, the forearm required approximately 4 hours for imaging and initial scan processing before moving to the editing stage.

Geometry and Color Editing. After scanning, the OBJ file imported into Blender required a range of significant operations to achieve a model suitable for printing. After an initial pass at removing wires, background noise, and other disconnected triangles, larger dissection tools needed to be removed to isolate just the arm geometry. For example, the original scanned model was held open using a set of forceps to allow users to view further within the dissected arm. However, these forceps were resting on the palm of the hand, resulting in a large gap in the mesh when they were deleted from the model. This gap had to be filled and subdivided to create a mesh surface appropriate for later smoothing. Likewise, when the arm was scanned initially, the fingers were merged sufficiently close that the scanner was not able to capture the small gaps between them.

As such, each finger needed to be separated from the ones next to it and have the sides of the finger be repaired and subdivided.

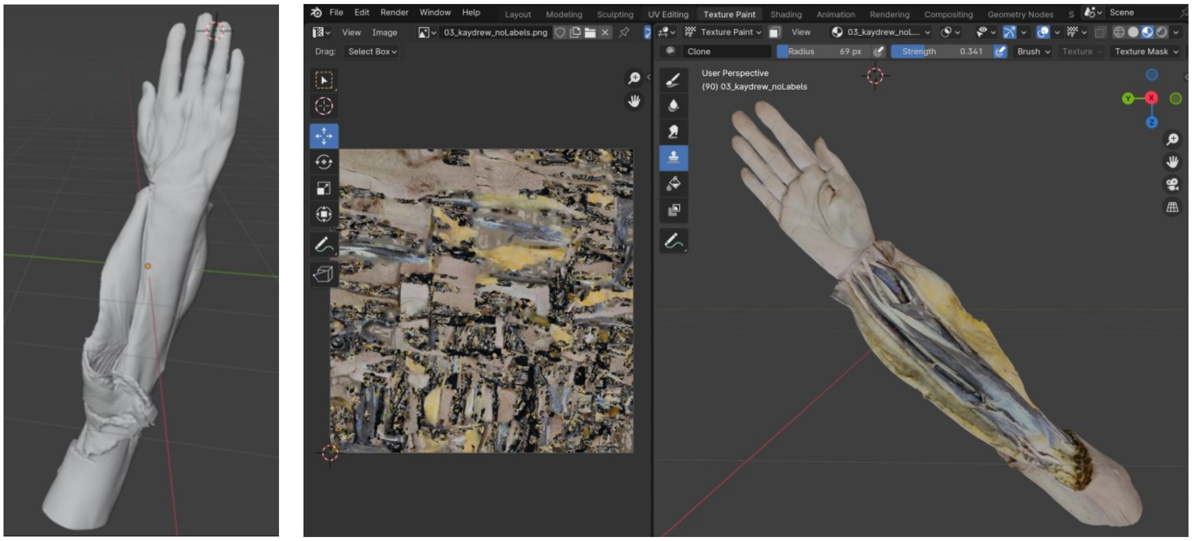

Figure 5. Cadaveric Arm Mesh with Colors in Blender

Due to the large number of gaps that needed to be filled in this particular model, the arm required an extensive amount of manual smoothing using the sculpting tool in Blender. Each of the gaps that had been filled needed to be carefully adjusted to match the surrounding geometries and maintain the initial intent of the scanned arm. To further emphasize separation between certain elements, such as the fingers, the creasing tool was also used to add a clear physical difference between features. Finally, when surfaces are filled in a color model such as the arm, the resulting triangular faces lack color information. To re-color these filled gaps, painting tools in Blender were used to clone colors and textures from nearby faces and apply them to the newly filled faces.

<u>*Geometry and Color Reproduction*</u>. The final manufactured arm model is shown in Figure 7, printed at a length of approximately 6 inches. When comparing this model against the mesh in Figure 5, the reproduction appears to be relatively accurate. Producing three replications of the model used 3.3 kilograms of material (1.2kg of model material and 2.1kg of support material) and required 30 hours of print time when oriented in the with the shortest dimension aligned with the Z-axis, as shown in Figure 6.

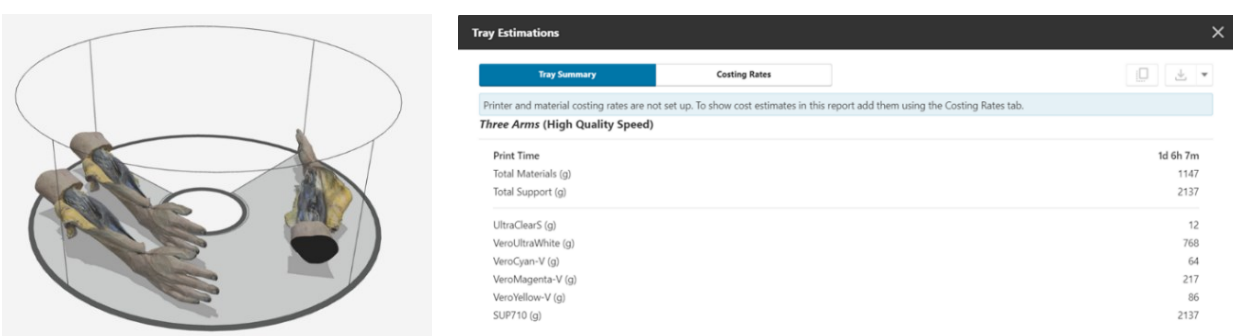

Figure 6. Prepared Full-Color Build Tray for Three Copies of Cadaveric Arm

Figure 7. Final Manufactured Cadaveric Arm via Stratasys J55 PolyJet

From a geometry perspective, almost no details within the arm model were near the minimum feature size of the J55 system (~0.5mm); the majority of geometries that were clearly smaller than the minimum feature size were eliminated in the editing stage. Because of this, no geometric details were unable to be resolved in the final model. The greatest difference between the manufactured model and the scanned model is in the colors of the final arm. Most notably, the skin throughout the arm has lost the pink hue present in the original model and instead looks blue in the final manufactured structure. Similarly, the blue in the internals of the arm is over-emphasized, with parts that should be colored white taking on a blue tint instead. This is likely due to the default color palettes used by the J55 when printing parts. Modifications to voxel-level color assignment at the slice-level may help to create as-manufactured parts that better reflect the as-scanned geometry. However, despite this shift in tone throughout the model, the texture details on the structure are still realized in a high level of fidelity. This is especially visible in the skin, where individual freckles and wrinkles around the elbow are rendered with accurate textures, even if the color tone is not precise. Further texture details, such as the fingernails of the arm are likewise recreated to a high degree of fidelity.

4.2. Cadaveric Heart and Lungs

The second case study focuses on an isolated heart/lung system. When contrasted with the arm case study, the heart/lung offers up a significantly more challenging topology, with a larger number of small features which may prove challenging to capture, edit, and reproduce.

Geometry and Color Capture. While the forearm case study from Section 4.1 demonstrates a stepwise dissection to reveal the anatomical structures beneath the skin of the arm, the heart/lung system was instead prepared so that it could be isolated during the process of dissection. In this way, the structure could be scanned from a full 360 degree perspective, and all color nuance and geometric detail could be captured from both the heart and lungs without the rest of the cadaveric anatomy obstructing the three-dimensional scan. As with the forearm, once dissection and isolation were completed, the specimen was suspended within the photogrammetry set-up from Figure 2.

Likewise, the scanning parameters discussed in Section 3.1 and applied in the forearm case study were held constant for the heart/lung structure.

Geometry and Color Editing. While the cadaveric arm specimen required a significant amount of post-processing on the geometry to remove tools and create more realistic topologies, such as between the fingers, the heart and lung model required significantly more effort on the colors in the model. This began with the need to improve the color contrast and brightness of the original scanned texture image; the original image caused many of the color details to be lost given its washed-out appearance. Furthermore, significant paint cloning needed to be performed throughout the model. With the large number of concave surfaces in the model, there were several regions that were covered in shadow in the final mesh, especially on the underside of the model and between the lungs. Textures from other surfaces needed to be copied to the shadowed surfaces to give a more realistic appearance once the model was printed. The detailed colors in the model can be seen in Figure 8.

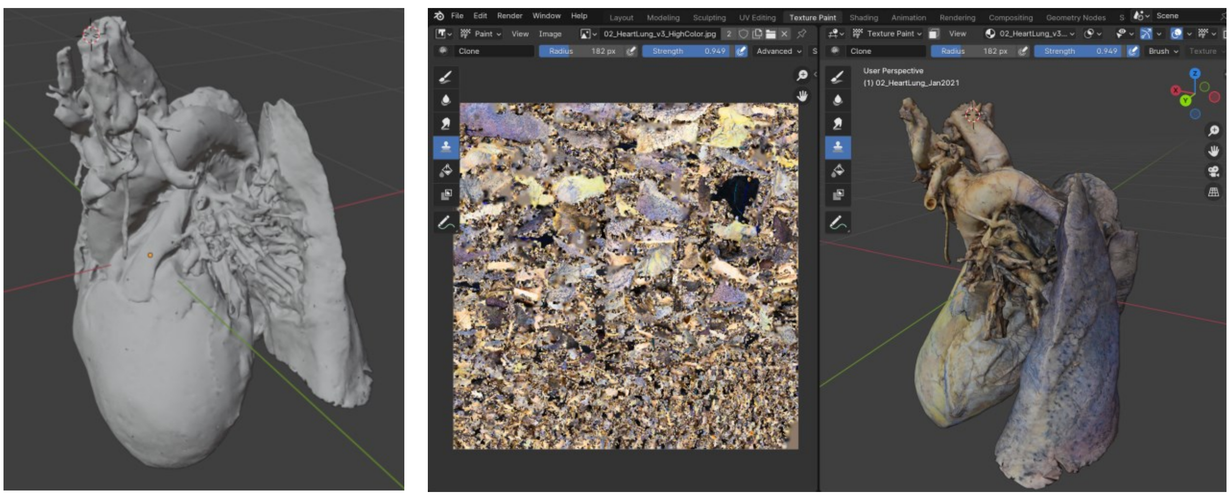

Figure 8. Cadaveric Heart/Lung Mesh with Colors in Blender

In addition to the extensive color modification in this model, there was still some geometric editing that was also required. In particular, there was a region of the model (seen in Figure 8) that consisted of a cluster of small features between the heart and one of the lungs. Despite the high quality of the photogrammetry approach, this region still contained a significant amount of noise that needed to be identified, selected, deleted, and repaired in the model. A general pass for manufacturability also needed to be conducted in this same region; even after the noise was eliminated, there were still several geometries in the space that were too small to be manufacturable given the minimum feature size of the J55 Polyjet system.

Geometry and Color Reproduction. The final manufactured heart/lung model is shown in Figure 10, printed at a height of approximately 4 inches. As with the arm model, this structure appears to be relatively accurate when compared against the mesh in Figure 8, though deviations in color are again noted. Producing three replications of the model used 3.3 kilograms of material (1.1kg of model material and 2.2kg of support material) and required 21 hours of print time when oriented in the with the shortest dimension aligned with the Z-axis, as shown in Figure 9.

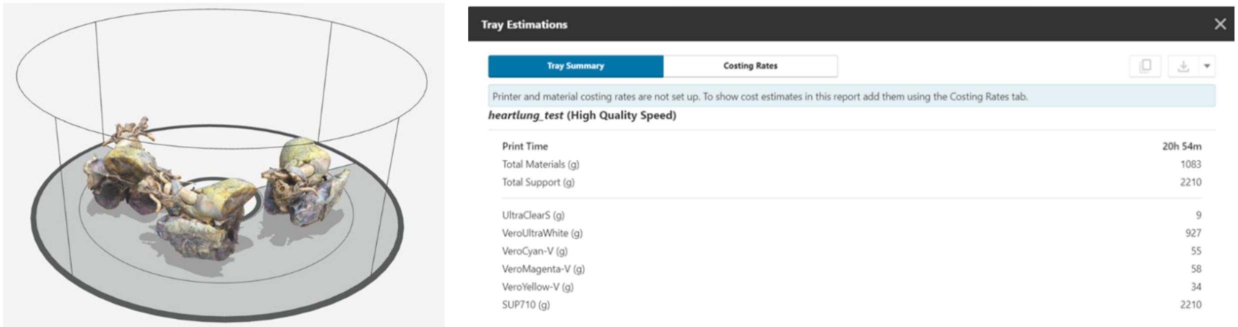

Figure 9. Prepared Full-Color Build Tray for Three Copies of Cadaveric Heart/Lung

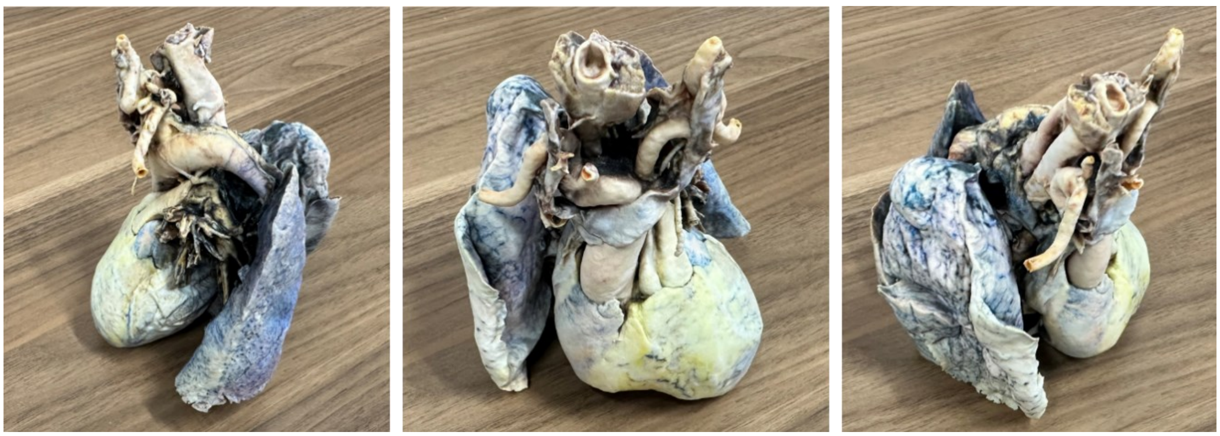

Figure 10. Final Manufactured Cadaveric Heart/Lung via Stratasys J55 PolyJet

While the edited arm mesh had few structures near the feature limit of the J55 PolyJet system, the heart/lung model by contrast has numerous anatomical elements near the minimum feature threshold. These elements, most clearly seen in the leftmost image in the Figure 10 triptych, join to form a crucial percentage of the overall heart/lung anatomical model. Because of this, they could not simply be removed during editing, for fear of reducing the overall educational value of the model. While this group of small features was successfully manufactured, their overall fragility could lead to easy breakage during handling. As with the arm model, the general textures throughout the model were highly realized; this can be clearly seen in the textures throughout the lungs in the model. However, also as with the arm model, the colors do not appear to be accurately recreated from the edited mesh. Where the arm model suffered from an overabundance of a blue tone throughout the model, the heart/lung model appears to have the opposite issue; much of the structure appears to be overly brightened, with colors appearing to be more yellow than initially designed in the mesh. Between the color inaccuracies in this model and the arm model, there is clearly a need for future experimentation to ensure that the as-manufactured colors more precisely match the as-designed colors.

5. Conclusions and Future Work

In this work, the authors have proposed and demonstrated a scanning, editing, and manufacturing pipeline for the creation of full-color, high-fidelity cadaveric models. This pipeline was then applied to two distinct case studies: one of a cadaveric arm and one of a cadaveric heart/lung model. The results of these case studies show the potential in realizing such models via AM, but also illustrate the challenges that accompany such a process. As an example, while the geometry and color capture process can be somewhat automated, the geometry and color editing process currently requires a significant amount of interdisciplinary expertise along with a high number of hands-on hours. Additionally, color accuracy in the final manufactured models is still lacking when compared with the collected scans, though geometric feature recreation is generally of high quality.

Future work is twofold. First, future efforts must focus on improving the realism of the manufactured cadaveric models. Color palettes must be adjusted to ensure that the as-manufactured colors accurately reflect the as-designed colors from Blender. This can be done through making voxel-level changes to the colors in prepared slice files before sending them to be deposited by the J55 system in the final part. Additionally, models should be augmented to include multiple material phases that are more representative of the tactile feel of the cadaveric materials (e.g., bone, muscle, skin). Ensuring realism also requires a robust measurement of the final manufactured model's geometric accuracy when compared against the original model; there is the possibility of error stack-up when moving from the original cadaver to the scan and finally to the printed artifact. Beyond improving the quality of the model, future work will also focus on understanding the use of these models in educational practice. While the authors are optimistic about the potential use of these AM models, there is a need for robust human-subjects experimentation to identify statistically significant impacts that the use of such AM models have on student learning when compared against real donated cadavers.

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