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Novel Applications of Rapid Prototyping in Gamma-ray and X-ray Imaging

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Abstract

Advances in 3D rapid-prototyping printers, 3D modeling software, and casting techniques allow for the fabrication of cost-effective, custom components in gamma-ray and x-ray imaging systems. Applications extend to new fabrication methods for custom collimators, pinholes, calibration and resolution phantoms, mounting and shielding components, and imaging apertures. Details of the fabrication process for these components are presented, specifically the 3D printing process, cold casting with a tungsten epoxy, and lost-wax casting in platinum.

I. INTRODUCTION

Imaging apertures designed for gamma-ray or single-photon emission computed tomography (SPECT), typically consist of pinhole inserts made of a high-density materials such as platinum, gold, or tungsten. To provide shielding and to reduce scattered or background events, a supporting aperture structure is also made from a high-density material such as lead or tungsten. With complex camera geometries, imaging aperture design and fabrication becomes expensive and difficult using traditional machining techniques.

At the Center for Gamma-Ray Imaging (CGRI), recent designs of stationary and adaptive SPECT imaging systems [1], [2] have prompted the need for cost-effective fabrication of imaging apertures which are designed specific to an imaging task and independent of geometric complexity. The need for complex imaging apertures has spurred the development of a novel fabrication method which involves the use of 3D rapid-prototyping printers, cold casting in high-density tungsten composites, and lost-wax casting in high-density materials such as platinum.

3D rapid-prototyping printing is becoming an integral tool in system design, fabrication, and calibration. In this paper we present fabrication methods and results in the context of a pinhole imaging aperture developed for a stationary SPECT system called FastSPECT III [1]. Additionally, we present utilities of 3D printing in SPECT and x-ray CT imaging. These include fabrication of resolution phantoms, calibration phantoms, and custom animal holders, for example.

II. 3D RAPID PROTOTYPING PRINTING

At CGRI, we have made heavy use of recent advances in rapid-prototyping printers, specifically, Eden350™ [3] and Connex350™ printers made by Objet Geometries, Ltd., [3]. The Eden350™ printer is operated by the Laboratory for Engineering Non-Traditional Sensors (LENS) and the Connex350™ is operated by CGRI, University of Arizona.

A 3D model of a part to be printed is created in a 3D modeling program, e.g., Solidworks® [?]. The part is saved as a stereolithography file (STL), and data are sent to the printer as individual slices. For each slice, the printer deposits a layer of photosensitive resin 16 microns thick and laterally deposits resin at a resolution of 42 microns. Two types of resins are deposited: a support material, and a model build material. The support material is a gel-like UV resin, which is specifically designed to support complicated geometries during printing and is easily removed by hand and water jetting. On the Connex350™ printer, parts and assemblies can be made of multiple materials having variable color, hardness, and flexibility. Additionally, the printer has a large-printing-volume of $30 \times 30 \times 20 \text{ cm}^3$. An image of the Connex350™ printer is shown in Figure 1.

III. SPECT IMAGING APERTURE FABRICATION

The high-resolution and large-printing-volume capabilities of 3D printers have led to the development of a novel fabrication method which allows us to cost-effectively produce custom aperture/pinhole configurations which would otherwise be prohibitively expensive or impossible to fabricate using standard machining techniques. An important distinction should be noted regarding the cost functions for standard machining fabrication versus rapid-prototyping fabrication. Standard machining cost is largely dependent on the number and complexity of operations required to machine a part whereas rapid prototyping cost is almost entirely dependent on part size rather than complexity, e.g., printing a part with square holes or printing curved channels embedded within a solid block is easily accomplished with rapid prototyping.

As previously mentioned, an imaging aperture for SPECT systems typically consists of pinhole inserts and a supporting structure; both are made from high-density materials to shield detectors and suppress background events. A Solidworks® [?] design of a SPECT imaging aperture is shown in Figure 2.

A. Supporting Aperture Fabrication

For fabrication of the supporting aperture structure, we worked with Tungsten Heavy Powder, Inc. [4] to create parts made of a tungsten composite material. This process involves designing a mold, in software, of the desired part. For the FastSPECT III aperture, the Solidworks® model (Figure 2) was split in to five sections (three unique pieces) and mold assemblies for each were designed and printed. Next, the aperture sections are cold-cast using a tungsten powder/epoxy mixture. This process involves mixing a high-density tungsten powder with an epoxy and then pouring the mixture into the mold assembly. While curing, the tungsten powder displaces the epoxy and settles to the bottom of the mold. After curing, the tungsten-composite part is removed from the mold and has a density near that of lead, $\sim 11 \text{ g/cm}^3$. An additional advantage of this process is that multiple parts can be fabricated from a single mold. Printed mold assemblies and cast pieces are shown in Figure 3. The casting/pouring process is shown in Figure 4.

An additional feature of Objet printers is the ability to print flexible, silicone-like parts. We have found this material useful for casting parts where part removal after casting requires the mold to be sacrificed; such as parts with voids or embedded holes, for example. The central aperture of FastSPECT III, seen in Figure 5, has angled/tapered holes which support pinhole inserts. This central aperture has a decagonal shape, a central ring of ten holes for pinhole inserts, and two outer rings each with five angled tapered holes for angled pinhole inserts. The design is such that all pinholes will share a common field of view. Fabrication of this part would be difficult and expensive using traditional machining techniques. To fabricate this section of the aperture, we print the sacrificial, silicone-like mold and pour the tungsten/epoxy mixture. After curing, the the flexible mold is forceable removed in

conjunction with a solvent, for example. A flexible mold and an associated cast of the central aperture are shown in Figure 6.

Another example of cold casting in high-density tungsten composite material is the fabrication of a custom X-ray shutter designed for the CGRI FaCT system, a high-resolution small-animal CT system [2]. The mold and cast shutter are shown in Figure 7. The shutter is currently being used in the CT system and provides excellent beam stopping.

B. Pinhole Fabrication Using Lost-Wax Casting

For pinhole hole fabrication, we print the 3D model of the pinhole insert and cast using lost-wax or investment casting methods. In lost-wax casting, a wax model of an object is encased within a ceramic mold. The wax, or in our case, the 3D printer photopolymer, is burned away and replaced with metal. Pinhole inserts for FastSPECT III were cast in an alloy of 90% platinum, 10% iridium by Techform Advanced Casting [5]. Pinholes made from this platinum alloy are superior to gold inserts as platinum has a higher density than gold. Also, hardening gold typically results in an alloy which is effectively less-dense and thus, has a lower attenuation coefficient; hardening platinum with iridium, however, results in an alloy having an increased average density.

Section views of the pinholes used in FastSPECT III are shown in Figure 8. Note the complexity that would be required to fabricate the angled pinhole using conventional machining techniques. To ensure that a pinhole is cast to the correct diameter, a quartz rod is inserted into the hole of the printed part prior to encasing in investment ceramic. After casting, the quartz rod is dissolved using hydrofluoric acid. To date, we have successfully cast pinholes as small as 200 microns using this technique; see Figure 9. An additional benefit of this technique is that no machining is required and there is no material lost. Images of the pinholes and complete aperture assembly are shown in Figure 10.

In addition to the fabrication of pinhole apertures, we have utilized rapid prototyping and platinum lost-wax casting methods to fabricate coded apertures. In Solidworks®, we designed a 62×62 self-supporting, no-two-holes-touching uniformly redundant array (NTHA-URA) coded aperture [6], [7]. The 3D model of this aperture was printed and cast in platinum. The final coded aperture is 1-mm thick and has 480, 0.5-mm diameter pinholes. The Solidworks® rendering of this part and the final cast piece are shown in Figure 11. This fabrication method resulted in no platinum material loss, no machining time/labor, and a rapid turnaround time from aperture design to piece-in-hand.

IV. ADDITIONAL CASTING APPLICATIONS

In addition to new aperture fabrication methods, 3D rapid prototyping printers can be used to print custom small-animal imaging beds with built-in anesthesia and respiration channels, Jaszczak-style SPECT and CT phantoms, and geometric calibration phantoms for X-ray CT, for example. Images of these parts are shown in Figure 12.

V. CONCLUSION

We have found that, by using 3D rapid prototyping in conjunction with lost-wax and cold-casting techniques, we can fabricate complex aperture designs, cast pinholes for high-resolution SPECT imaging, and produce high-density shielding components for gamma-ray and x-ray applications. Notably, the cost of this process scales with part size rather than part complexity, in contrast to traditional machining where cost typically scales with complexity and the number of operations required for fabrication. Additional benefits from this process include minimal or no machining requirements after casting, and little or no material loss.

We have also found that, by using 3D rapid prototyping, we can fabricate a host of supplemental components for application in SPECT and x-ray imaging. These include custom mouse beds with embedded channels for anesthesia and respiration delivery, spatial resolution imaging phantoms, and geometric calibration phantoms.

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Fig. 1. Objet Geometries Ltd. [3] Connex350™ printer. The tray contains printed parts for a mold assembly. The printer has a $35 \times 35 \times 20 \text{ cm}^3$ build volume and prints slices 16 microns thick with a lateral resolution of 42 microns. Additionally, the printer is capable of printing in multiple materials to create parts having variable color, hardness, and flexibility.

Fig. 2.
Solidworks® rendering of the FastSPECT III [1] imaging aperture.

Fig. 3.
Mold assemblies printed on an Objet Connex350™ printer and the associated tungsten-composite cast pieces.

Fig. 4. Tungsten Heavy Powder, Inc. [4] cold-casting process for creating high-density tungsten composite parts: a high-density tungsten powder is mixed with an epoxy and poured into a mold. The tungsten powder displaces the epoxy and settles to the bottom of the mold. After curing, the part is removed from the mold assembly and has a density near that of lead ($\sim 11 \text{ g/cm}^3$).

Fig. 5.
Solidworks® rendering of the central portion of the FastSPECT III imaging aperture.

Fig. 6.
Flexible, silicone-like mold used to cast the central portion of the FastSPECT III imaging aperture.

(a)

(b)

Fig. 7.
(a) Rapid prototyped mold for a custom X-ray shutter designed for the FaCT CT system [2]
and (b) the tungsten composite casting.

Fig. 8. Solidworks® rendering of pinholes used in FastSPECT III. Pinhole diameter is 200 microns.

Ø 200 microns

Fig. 9.

Printed pinholes and associated lost-wax casts in a 90% platinum, 10% iridium alloy. To date, we have successfully cast pinholes as small as 200 microns.

Fig. 10.
Complete FastSPECT III aperture assembly with platinum pinhole inserts and tungsten-composite supporting structure.

(a)

(b)

Fig. 11.

(a) Solidworks® rendering of a 62×62 NTHT-URA coded aperture having 480 pinholes and (b) coded aperture cast in 1-mm thick platinum with 0.5-mm diameter pinholes.

(a)

(b)

(c)

Fig. 12.

Additional applications: (a) SPECT / CT imaging mouse holder with built-in anesthesia and respiration channels, (b) Jaszczak-style SPECT and CT phantoms, and (c) phantom for X-ray CT geometric calibration.