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(54) **Title:** THREE-DIMENSIONAL PRINTING FROM IMAGES

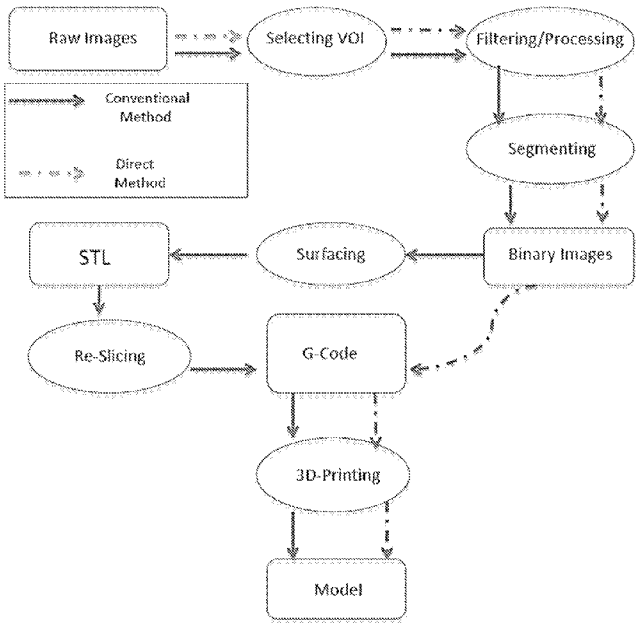

FIG. 1

(57) **Abstract:** Methods, systems, and computer readable media for for 3D printing from images, e.g., medical images or images obtained using any appropriate volumetric imaging technology. In some examples, a method includes receiving, from a medical imaging device, a multi-dimensional image of a structure. The method includes, for each two dimensional (2D) slice of the multi-dimensional image, converting, row-by-row for each row of the 2D slice, voxels of the 2D slice into 3D printing instructions for the 2D slice. The method includes 3D printing, by controlling a 3D printing extruder, a physical model based on the structure by 3D printing, slice by slice, each 2D slice using the 3D printing instructions.

[Continued on next page]

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THREE-DIMENSIONAL PRINTING FROM IMAGES

PRIORITY CLAIM

This application claims the benefit of U.S. Provisional Patent Application Serial No. 62/595,528, filed December 6, 2017, the disclosure of which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

This specification relates generally to three-dimensional (3D) printing from images, e.g., magnetic resonance (MR) images and computed tomographic (CT) images of anatomical structures.

BACKGROUND

Various imaging technologies allow generation of volumetric computer models that can be 3D printed. However, due to historic reasons, generation of the instruction set understood by 3D printers (e.g., G-Code) requires substantial user interaction and image manipulations. This process can take a significant amount of time depending on the type of images and application. Furthermore, during the conventional image-based G-Code generation process, some anatomical information could be lost due to surface rendition followed by re-slicing.

Accordingly, there exists a need for improved methods for 3D printing from medical images.

SUMMARY

This specification describes methods, systems, and computer readable media for 3D printing from images, e.g., medical images or images obtained using any appropriate volumetric imaging technology. In some examples, a method includes receiving multi-dimensional image(s) of an anatomical structure; for each two dimensional (2D) slice of the original or resampled/processed image(s), converting, row-by-row for each row of the 2D slice, voxels of the 2D slice into 3D printing instructions for the 2D slice;

and 3D printing a physical model based on the anatomical structure by 3D printing, slice by slice, each 2D slice using the 3D printing instructions.

The subject matter described herein may be implemented in hardware, software, firmware, or any combination thereof. As such, the terms "function" or "node" as used herein refer to hardware, which may also include software and/or firmware components, for implementing the feature(s) being described. In some exemplary implementations, the subject matter described herein may be implemented using a computer readable medium having stored thereon computer executable instructions that when executed by the processor of a computer control the computer to perform steps. Exemplary computer readable media suitable for implementing the subject matter described herein include non-transitory computer readable media, such as disk memory devices, chip memory devices, programmable logic devices, and application specific integrated circuits. In addition, a computer readable medium that implements the subject matter described herein may be located on a single device or computing platform or may be distributed across multiple devices or computing platforms.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a flow chart illustrating methods for 3D printing from medical images;

Figure 2A shows an image of a 5-layer print as an STL;

Figure 2B shows an example of a printed model;

Figure 2C shows a scanning electron microscope image of a section of the print;

Figure 3 shows a graph of processing time measured by time taken;

Figure 4 illustrates a model of G-Code generated for clinical resolution CT scan interpolated to an isotropic resolution of 1mm;

Figure 5 is a block diagram of an example system for 3D printing from medical images; and

Figure 6 is a flow chart of an example method for 3D printing from medical images.

DETAILED DESCRIPTION

This specification describes methods, systems, and computer readable media for 3D printing from images. The methods, systems, and computer readable media are described below with reference to a study performed on the methodology.

Bioprinting of tissue has its applications throughout medicine. Recent advances in medical imaging allows the generation of 3-dimensional models that can then be 3D printed. However, the conventional method of converting medical images to 3D printable G-Code instructions has several limitations, namely significant processing time for large, high resolution images, and the loss of microstructural surface information from surface resolution and subsequent reslicing. We have overcome these issues by creating a computer program that skips the intermediate triangularization and reslicing steps and directly converts binary images into G-Code.

In one study, we tested the two methods of G-Code generation on the application of synthetic graft model generation. We imaged human cadaveric proximal femurs at an isotropic resolution of 0.03mm using a high resolution peripheral quantitative computed tomography (HR-pQCT) scanner. These images, of the Digital Imaging and Communications in Medicine (DICOM) format, were then processed through two methods. In each method, slices and regions of print were selected, filtered to generate a smoothed image, and thresholded. In the conventional method, these processed images are converted to the STereoLithography (STL) format and then resliced to generate G-Code. In the new, direct method, these processed images are run through our computer program and directly converted to G-Code. File size, processing time, and print time were measured for each.

We found that this new method produced a significant reduction in G-Code file size as well as processing time (more than 90% reduction). This allows for more rapid 3D printing from multi-dimensional images.

Purpose

Medical imaging allows generation of volumetric computer models that can be 3D printed. However, due to historic reasons, generation of the instruction set understood by 3D printers (i.e., G-Code) requires substantial

user interaction and image manipulations. This process can take a significant amount of time depending on the type of images and application. Furthermore, during the conventional image-based G-Code generation process, some anatomical information could be lost due to surface rendition followed by re-slicing. We developed a method for rapid 3D printing from medical images such as MRI and CT by directly converting 3D image information into G-Code.

As an initial application, here we present data on how patient-specific models can be rapidly 3D printed. Tissue engineering has recently emerged as a promising substitute for autologous and allopathic grafts. The process involves cell proliferation on a biocompatible and biodegradable model followed by reimplantation. Cell sources include autologous or allogeneic cells and mesenchymal stem cells. The major challenge is creating a graft with sufficient mechanical stability that possesses good osteoconductive, osteoinductive, and osteogenic properties.

We present polycaprolactone (PCL) as a promising material for synthetic grafts. PCL degrades in physiological conditions, through hydrolysis of its ester linkages, slower than other biopolymers such as PGA and PLA, making it ideal for construction of long-term degradable implants. Its low melting point (60°C) allows for easy manufacturing and manipulation into various implants, making PCL a very compatible material for extrusion-based 3D printing [1].

After a patient is scanned, the images have to be processed into 3D printable instructions. We investigated different processes for producing these G-Code instructions for 3D printed modeling through high resolution imaging and extrusion based printing.

Method

To investigate 3D printing from high-resolution imaging, thirteen human cadaveric proximal femurs were selected for this study. The specimens contained seven female and six male, with ages ranging from 36-99. The femurs were imaged at a 0.03 mm isotropic voxel size using a high resolution peripheral quantitative computed tomography (HR-pQCT) scanner and stored as Digital Imaging and Communications in Medicine (DICOM)

image files. The resultant DICOM files need to be converted to a format compatible with the 3D printer. Two methods were successful in converting the original DICOM images into 3D printable G-Code instructions. Furthermore, to investigate 3D printing from clinical resolution imaging, we 3D printed human skulls from clinical CT scans.

Conventional Method

First, original DICOM files were converted into the STereoLithography (STL) file format. Next, the CT images were used to select the desired slices and region. The image undergoes 3D Gaussian filtering (sigma = 2.50) to generate a smoothed image. Lastly, the images are thresholded to make them binary, and converted to an STL file. The STL file is subsequently transformed into a G-Code file, which allows us to customize our G-Code, making any changes to layer thickness, print path, print angle, etc. For the purposes of this study, layer thickness was set to 0.1 mm. A simple script was created to condense all the steps for DICOM to STL file conversion into a single step to significantly reduce the time required for image processing and output generation.

Direct Method

Our novel method involves a computer program that converts DICOM to G-Code without going through STL. The DICOM images, though, still need to be processed and converted to binary, for which a batch script was also written. This program takes parameters including the printer's resolution, speed of the extruder, etc. The code also allows for choosing the method of printing, from linear, to any inputted angle rotation between each layer. The output is a G-Code file that is then loaded and printed from the 3D bioprinter. In this study, all prints were performed at a 90 degree angle.

Several tests were performed to analyze the advantages and disadvantages of each method. These consisted of tests for time taken to generate the G-Code, print time, and finally print quality. Time to generate G-Code was tested for several samples up to 1000 images, while print time was recorded for prints of ten layers, five layers, and two layers due to time limitations.

Figure 1 is a flow chart indicating the paths of both the conventional and direct methods.

3D-Printing

We utilized a desktop 3D bioprinter to construct all of our models. A single extruder was loaded with PCL and heated to 100℃ to allow for sufficient melting, and set to a pressure of 100 PSI with an air compressor. In both methods, a 27 gauge nozzle was used with an opening size of 0.2 mm, limiting the resolution to 200 microns. The layer height was set at 0.1 mm. We used circular acrylic glass slides covered with double-sided tape to allow for proper adhesion of the PCL.

Results

Figures 2A-C illustrate some results from the study. Figure 2A shows an image of a 5-layer print as an STL. Figure 2B shows the actual printed model using the conventional method. Figure 2C shows a scanning electron microscope image of a section of the print.

Table 1 shows that there was a significant reduction in pre-print preparation time, while file size was reduced by an average of 69.96% in the direct method.

	# of layers	Conventional Method	Direct Method
G-Code File Size	2	491 kb	137.2 kb
	5	1,120 kb	347.7 kb
	10	2,159 kb	672.0 kb
Pre-Print Preparation Time	2	4m39s	0.71s
	5	7m12s	1.00s
	10	14m10s	1.26s

Table 1

Figure 3 shows a graph of processing time measured by time taken to run the batch script for each method. The graph shows a linear relationship between number of slices and time for both methods. The processing time for the direct method was an average of 92.23% less than that of the conventional method.

Figure 4 illustrates a model of G-Code generated for clinical resolution CT scan interpolated to an isotropic resolution of 1mm. Produced by the direct method. Conventional method did not work because the image was too big to be resliced.

Breakthroughs

The new method for file conversion resulted in significantly smaller file sizes and shorter processing times, while maintaining comparable print times.

Conventional G-Code generation software typically has a file size limit of approximately 1 Gb, so any STL file larger than 1 Gb could not be converted into G-Code using our conventional method. This limited the number of layers we could print to around 10, because the CT scans used were of such high resolution. On the other hand, the computer program handled 1000 (30 micron resolution) images, which converts to 303 layers, with relative ease, converting the DICOM to G-Code in less than half a minute. Similarly, while typical software could not often handle the re-slicing of the clinical resolution skull, the computer program generated the G-Code in a couple minutes.

Conclusion

This study introduced a novel method of directly converting DICOM images from a CT or MRI into the G-Code instructions interpreted by a 3D printer. This approach could substantially reduce the time between a patient taking a scan and obtaining a 3D print from the images. Furthermore, this new program allows for significant improvements in potential for customizability, from changing print speeds in the middle of a print to allowing for different extrusion amounts for either increased porosity or better adhesion. This makes bio printing for medical purposes more feasible and efficient.

Figure 5 is a block diagram of an example system **500** for 3D printing from medical images. The system **500** includes a 3D printing computer system **502**, a medical imaging system **504** configured to image a patient **506**, and a 3D printer **508**. The computer system **502**, medical imaging system **504**, and 3D printer **508** can communicate using any appropriate technology, e.g., over a digital communications network **510**.

The computer system **502** includes at least one processor **512** and memory **514** storing executable instructions for the processor **512**. The computer system **502** receives a 3D image **516** of a structure in the patient **506** from the medical imaging system **504**. For example, receiving the 3D image **516** can include receiving a magnetic resonance (MR) image or a computed tomographic (CT) image of a bone structure of the patient **506**.

The computer system **518** includes a 3D printing converter **518** implemented using the processor(s) **512** and memory **514**. The 3D printing converter **518** can include an image preparer **520** for preparing the 3D image **516**, a slice-by-slice converter **522** for converting the 3D image **516** into 3D printing instructions, and a 3D printer controller **524** for controlling the 3D printer **508**.

The image preparer **520** can perform one or more of various appropriate tasks to prepare the 3D image **516** for conversion. For example, the image preparer **520** can be configured for thresholding the 3D image **516** to generate a binary image. The image preparer **520** can be configured for segmenting, from the 3D image **516**, a portion of the 3D image **516** depicting the structure. The image preparer **520** can be configured for resampling the 3D image **516** to a resolution compatible with the 3D printer **508**.

The slice-by-slice converter **522** is configured to, for each two dimensional (2D) slice of the 3D image **516**, to convert, row-by-row for each row of the 2D slice, voxels of the 2D slice into 3D printing instructions for the 2D slice. Converting voxels of each 2D slice into 3D printing instructions can include converting intensity data in the 3D image to density instructions for 3D printing. As a result, the 3D printer controller **524** can use the 3D printer **508** for variable density printing.

The 3D printer controller **524** is configured for 3D printing, using the 3D printer **508**, a model based on the structure by 3D printing, slice by slice, each 2D slice using the 3D printing instructions. In some examples, the 3D printer **508** is a 3D printing extruder. Converting voxels of each 2D slice into 3D printing instructions can include specifying, for the 3D printing extruder, an extrusion direction or extrusion angle or both for the 2D slice. Converting voxels of each 2D slice into 3D printing instructions can include specifying, for the 3D printing extruder, an extrusion speed or extrusion temperature or both for the 2D slice.

Figure 6 is a flow diagram of an example method **600** for 3D printing from medical images. The method includes receiving, from a medical imaging device, a multi-dimensional image of a structure (**602**). The multi-dimensional image may be an original image of the structure or a modified image of the structure. For example, the multi-dimensional image may be a re-sampled image that was re-sampled from an original image. The method includes, for each two dimensional (2D) slice of the multi-dimensional image, converting, row-by-row for each row of the 2D slice, voxels of the 2D slice into 3D printing instructions for the 2D slice (**604**). The method includes 3D printing, by controlling a 3D printing extruder, a physical model based on the structure by 3D printing, slice by slice, each 2D slice using the 3D printing instructions (**606**).

Although specific examples and features have been described above, these examples and features are not intended to limit the scope of the present disclosure, even where only a single example is described with respect to a particular feature. Examples of features provided in the disclosure are intended to be illustrative rather than restrictive unless stated otherwise. The above description is intended to cover such alternatives, modifications, and equivalents as would be apparent to a person skilled in the art having the benefit of this disclosure.

The scope of the present disclosure includes any feature or combination of features disclosed in this specification (either explicitly or implicitly), or any generalization of features disclosed, whether or not such features or generalizations mitigate any or all of the problems described in

this specification. Accordingly, new claims may be formulated during prosecution of this application (or an application claiming priority to this application) to any such combination of features. In particular, with reference to the appended claims, features from dependent claims may be combined with those of the independent claims and features from respective independent claims may be combined in any appropriate manner and not merely in the specific combinations enumerated in the appended claims.

References

The disclosure of each of the following references is incorporated herein by reference in its entirety.

1. Tokiwa Y, Calabia BP, Ugwu CU, Aiba S. Biodegradability of Plastics. *International Journal of Molecular Sciences*. 2009;10(9):3722-3742. doi:10.3390/ijms10093722.
2. Grevera G, Udupa J, Odhner D, et al. CAVASS: A Computer-Assisted Visualization and Analysis Software System. *Journal of Digital Imaging*. 2007;20(Suppl 1):101-118. doi:10.1007/s10278-007-9060-5.

CLAIMS

What is claimed is:

1. A method for 3D printing from multi-dimensional images, the method comprising:

receiving at least one multi-dimensional image of a structure;

for each two dimensional (2D) slice of a plurality of 2D slices of the multi-dimensional image, converting, row-by-row for each row of a plurality of rows of the 2D slice, voxels of the 2D slice into 3D printing instructions for the 2D slice; and

3D printing a physical model based on the structure by 3D printing, slice by slice, each 2D slice using the 3D printing instructions.

2. The method of claim 1, wherein receiving the multi-dimensional image of the structure comprises segmenting, from the multi-dimensional image, a portion of the multi-dimensional image depicting the structure.

3. The method of claim 1, wherein receiving the multi-dimensional image of the structure comprises pre-processing the multi-dimensional image to generate a binary image.

4. The method of claim 1, wherein receiving the multi-dimensional image of the structure comprises resampling the multi-dimensional image to a resolution compatible with a 3D printer.

5. The method of claim 1, wherein receiving the multi-dimensional image of the structure comprises receiving a magnetic resonance (MR) image or a computed tomographic (CT) image of a structure of a patient.

6. The method of claim 1, wherein converting voxels of each 2D slice into 3D printing instructions comprises converting intensity data in the multi-dimensional image to density instructions for 3D printing.

7. The method of claim 1, wherein 3D printing the physical model comprises using at least one 3D printing extruder.

8. The method of claim 7, wherein converting voxels of each 2D slice into 3D printing instructions comprises specifying, for the 3D printing extruder, an extrusion direction or extrusion angle or both for the 2D slice.

9. The method of claim 7, wherein converting voxels of each 2D slice into 3D printing instructions comprises specifying, for the 3D printing

extruder, an extrusion speed or extrusion temperature or both for each print segment of a plurality of print segments.

10. The method of claim 1, wherein 3D printing the physical model comprises controlling a plurality of extruders to each cover a respective portion of each 2D slice using a respective material for the portion.

11. The method of claim 1, wherein 3D printing the physical model comprises altering, while printing at least one segment of at least one 2D slice, one or more of: speed, density, porosity, adhesion, and gap distance between print locations.

12. A system for 3D printing from multi-dimensional images, the system comprising:

at least one processor; and

a 3D printing converter implemented on the at least one processor and configured to perform operations comprising:

receiving at least one multi-dimensional image of a structure;

for each two dimensional (2D) slice of a plurality of 2D slices of the multi-dimensional image, converting, row-by-row for each row of a plurality of rows of the 2D slice, voxels of the 2D slice into 3D printing instructions for the 2D slice; and

3D printing a physical model based on the structure by 3D printing, slice by slice, each 2D slice using the 3D printing instructions.

13. The system of claim 12, wherein receiving the multi-dimensional image of the structure comprises segmenting, from the multi-dimensional image, a portion of the multi-dimensional image depicting the structure.

14. The system of claim 12, wherein receiving the multi-dimensional image of the structure comprises pre-processing the multi-dimensional image to generate a binary image.

15. The system of claim 12, wherein receiving the multi-dimensional image of the structure comprises resampling the multi-dimensional image to a resolution compatible with a 3D printer.

16. The system of claim 12, wherein receiving the multi-dimensional image of the structure comprises receiving a magnetic resonance (MR) image or a computed tomographic (CT) image of a structure of a patient.

17. The system of claim 12, wherein converting voxels of each 2D slice into 3D printing instructions comprises converting intensity data in the multi-dimensional image to density instructions for 3D printing.

18. The system of claim 12, wherein 3D printing the physical model comprises using at least one 3D printing extruder.

19. The system of claim 18, wherein converting voxels of each 2D slice into 3D printing instructions comprises specifying, for the 3D printing extruder, an extrusion direction or extrusion angle or both for the 2D slice.

20. The system of claim 18, wherein converting voxels of each 2D slice into 3D printing instructions comprises specifying, for the 3D printing extruder, an extrusion speed or extrusion temperature or both for each print segment of a plurality of print segments.

21. The system of claim 12, wherein 3D printing the physical model comprises controlling a plurality of extruders to each cover a respective portion of each 2D slice using a respective material for the portion.

22. The system of claim 12, wherein 3D printing the physical model comprises altering, while printing at least one segment of at least one 2D slice, one or more of: speed, density, porosity, adhesion, and gap distance between print locations.

23. A non-transitory computer readable medium storing executable instructions that when executed by at least one processor of a computer control the computer to perform operations comprising:

receiving at least one multi-dimensional image of a structure;

for each two dimensional (2D) slice of a plurality of 2D slices of the multi-dimensional image, converting, row-by-row for each row of a plurality of rows of the 2D slice, voxels of the 2D slice into 3D printing instructions for the 2D slice; and

3D printing a physical model based on the structure by 3D printing, slice by slice, each 2D slice using the 3D printing instructions.

24. A system for 3D printing from multi-dimensional images, the system comprising:

a medical imaging device;

at least one 3D printing extruder; and

a computer system programmed for:

receiving, from the medical imaging device, a multi-dimensional image of a structure;

for each two dimensional (2D) slice of a plurality of 2D slices of the multi-dimensional image, converting, row-by-row for each row of a plurality of rows of the 2D slice, voxels of the 2D slice into 3D printing instructions for the 2D slice; and

3D printing, by controlling the 3D printing extruder, a physical model based on the structure by 3D printing, slice by slice, each 2D slice using the 3D printing instructions.

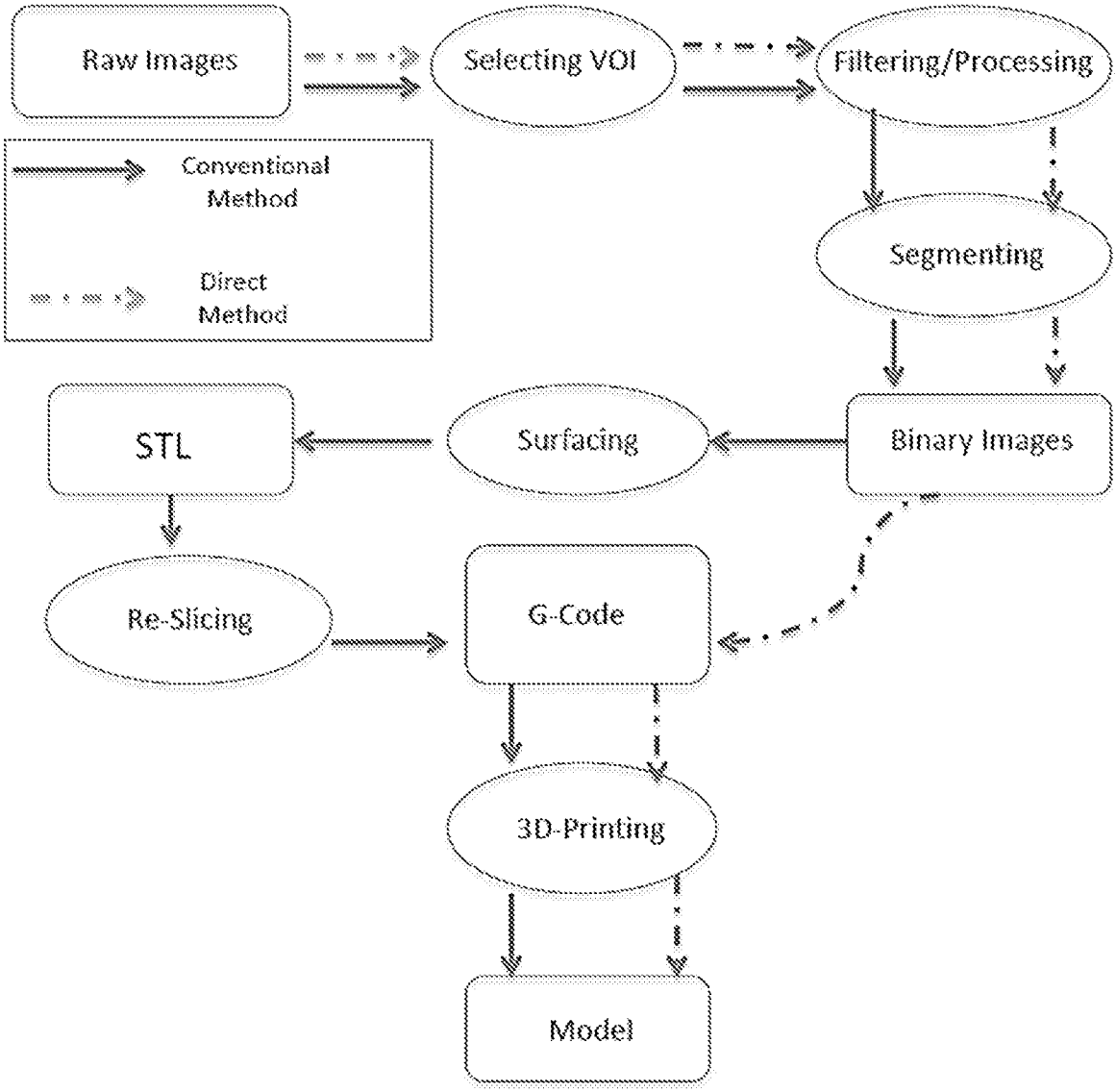
Raw Images
Selecting VOI
Filtering/Processing
Conventional Method
Direct Method
Segmenting
STL
Surfacing
Binary Images
Re-Slicing
G-Code
3D-Printing
Model

FIG. 1

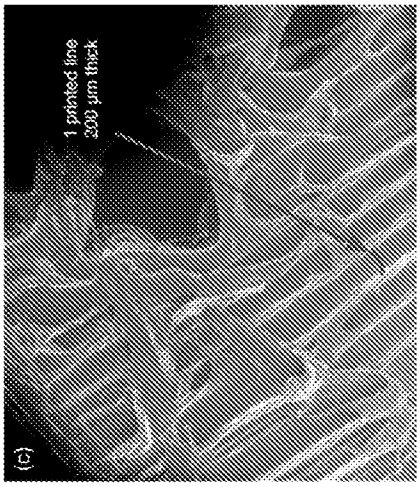

FIG. 2C

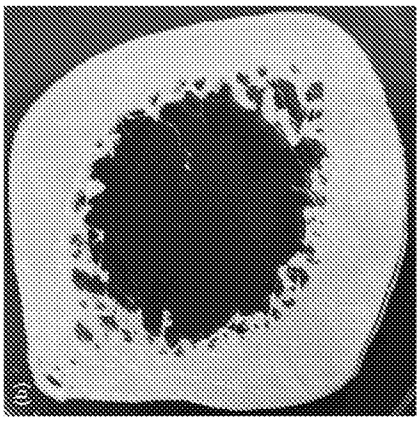

FIG. 2B

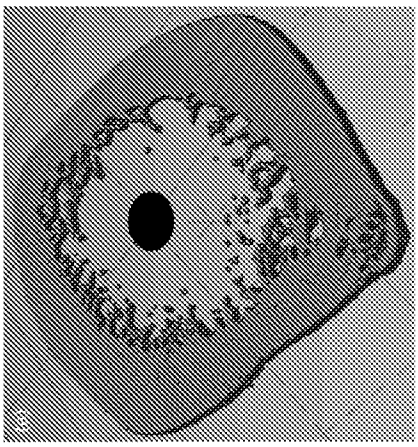

FIG. 2A

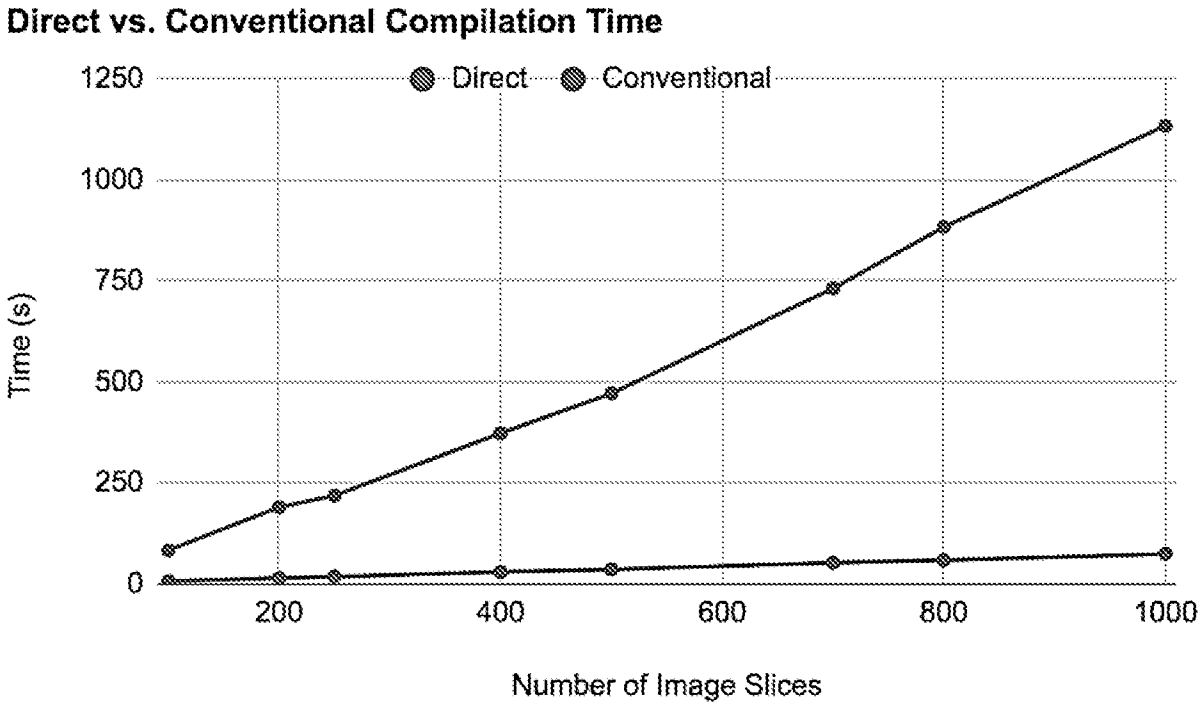
Direct vs. Conventional Compilation Time
Direct
Conventional
1250
1000
750
500
250
0
Time (s)
200
400
600
800
1000
Number of Image Slices

FIG. 3

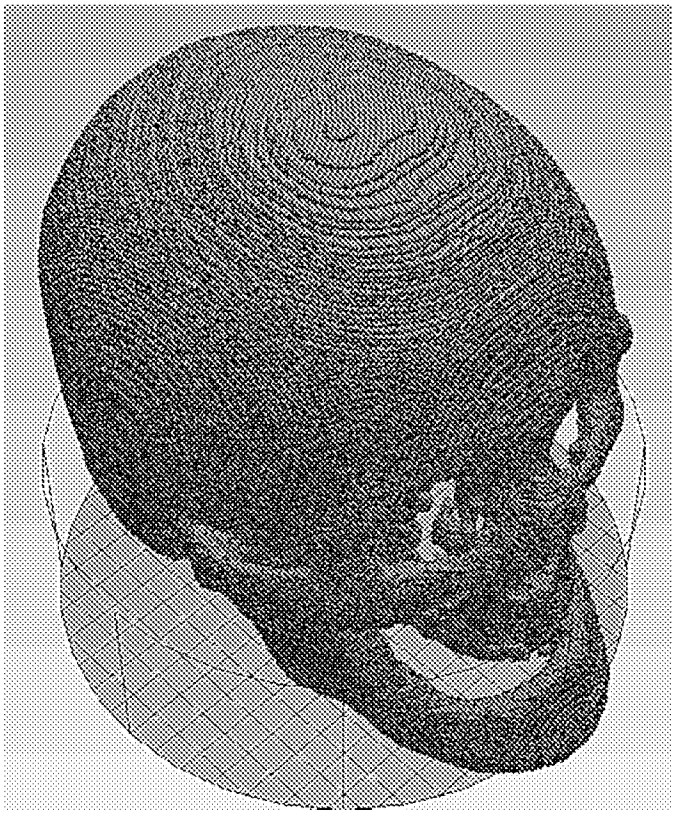

FIG. 4

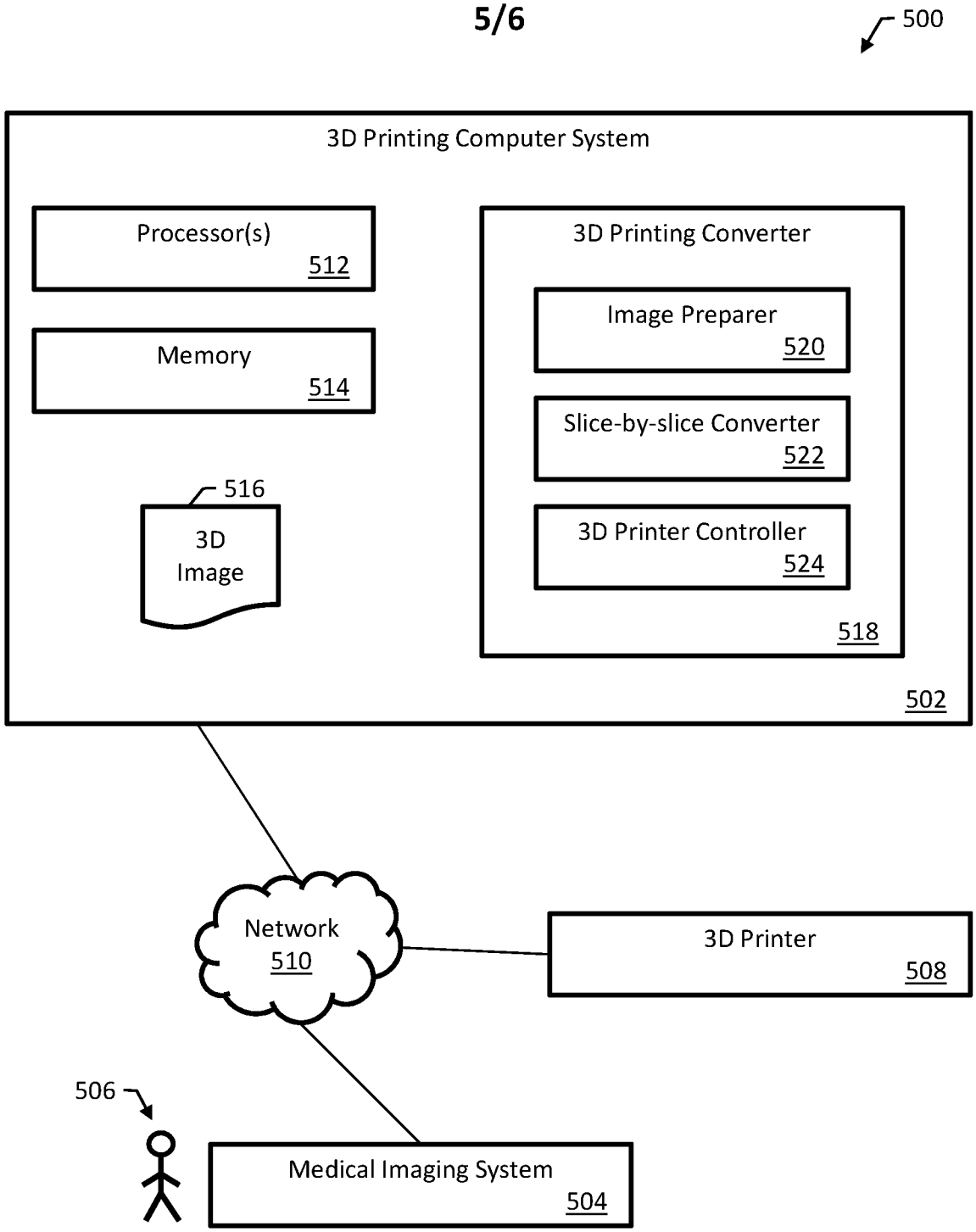
500
3D Printing Computer System
Processor(s)
512
Memory
514
516
3D
Image
3D Printing Converter
Image Preparer
520
Slice-by-slice Converter
522
3D Printer Controller
524
518
502
Network
510
3D Printer
508
506
Medical Imaging System
504

FIG. 5

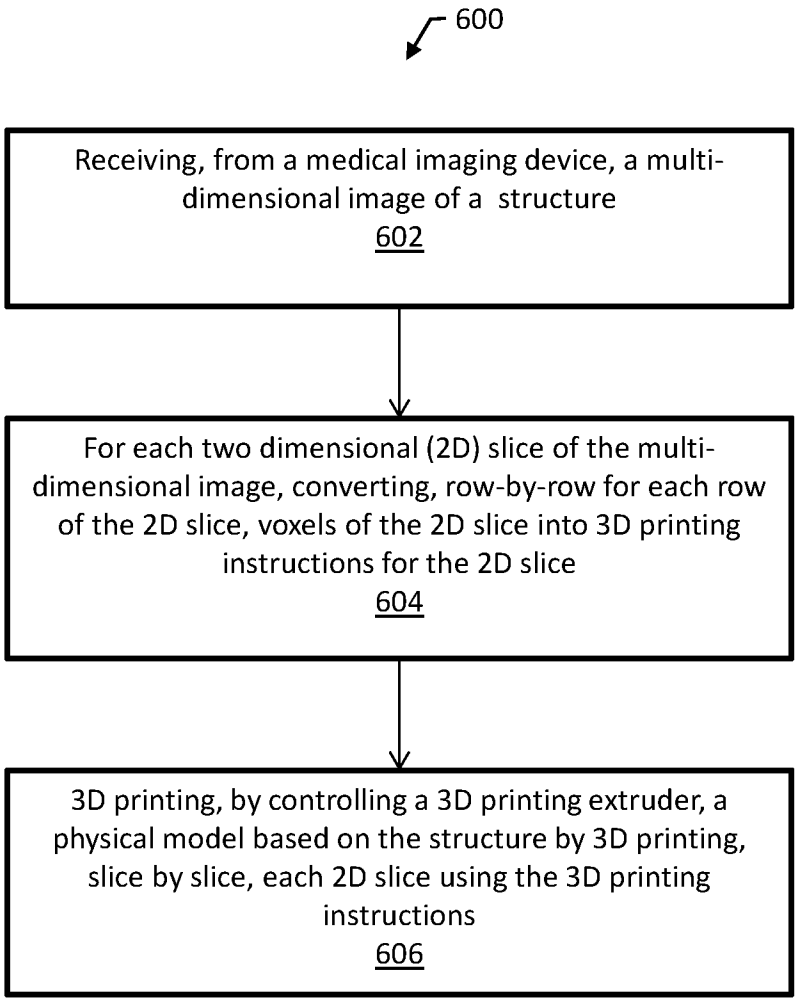
600
Receiving, from a medical imaging device, a multi-dimensional image of a structure
602
For each two dimensional (2D) slice of the multi-dimensional image, converting, row-by-row for each row of the 2D slice, voxels of the 2D slice into 3D printing instructions for the 2D slice
604
3D printing, by controlling a 3D printing extruder, a physical model based on the structure by 3D printing, slice by slice, each 2D slice using the 3D printing instructions
606

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 18/64134

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - A61F 2/02 (2019.01)
CPC - G06T 17/20, G06T 19/00, G06T 17/00, G06T 17/10, G06T 17/005, G06T 15/08, G06T 15/06, G06T 15/40

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History Document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
See Search History Document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History Document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2017/0181798 A1 (Intuitive Surgical Operations, INC.) 29 June 2017 (29.06.2017), entire document especially abstract; para [0002], [0012], [0106], [0144]-[0147]	1-24
Y	US 2015/0076739 A1 (Stratasys, Inc.) 19 March 2015 (19.03.2015), entire document especially abstract; para [0006], [0044], [0045], [0061]	1-24
Y	US 2016/0331467 A1 (ConforMIS, INC.) 17 November 2016 (17.11.2016), entire document especially para [0300], [0307]	1-24

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 February 2019 (15.02.2019)	08 MAR 2019
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

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