US011033359B2

(12) **United States Patent**
Velazquez et al.

(10) **Patent No.: US 11,033,359 B2**
(45) **Date of Patent: Jun. 15, 2021**

(54) **VIRTUAL FILLERS**

(71) Applicant: **Align Technology, Inc.**, San Jose, CA (US)

(72) Inventors: **Israel Velazquez**, Juarez (MX); **Andrey Cherkas**, Krasnoznamensk (RU); **Stephan Albert Alexandre Dumothier**, Houston, TX (US); **Anatoliy Parpara**, Moscow (RU); **Alexey Geraskin**, Moscow (RU); **Yury Slynko**, Moscow (RU)

(73) Assignee: **Align Technology, Inc.**, San Jose, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 497 days.

(21) Appl. No.: **15/726,211**

(22) Filed: **Oct. 5, 2017**

(65) **Prior Publication Data**

US 2019/0105127 A1 Apr. 11, 2019

(51) **Int. Cl.**

A61C 7/00	(2006.01)
G06F 30/20	(2020.01)
A61C 9/00	(2006.01)
A61C 7/08	(2006.01)

(52) **U.S. Cl.**

CPC ***A61C 7/002*** (2013.01); ***A61C 7/08*** (2013.01); ***A61C 9/004*** (2013.01); ***G06F 30/20*** (2020.01)

(58) **Field of Classification Search**

CPC A61C 7/002; A61C 7/08; A61C 13/0004; A61C 7/00; A61C 13/0019; A61C 9/004; G06F 30/20

USPC 700/98, 182, 118, 159; 249/54; 264/19; 433/24

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,790,035	B2	9/2004	Tricca et al.
6,970,760	B2	11/2005	Wolf et al.
7,080,979	B2	7/2006	Rubbert et al.
7,384,266	B2	6/2008	Wen
7,578,673	B2	8/2009	Wen et al.
7,600,999	B2	10/2009	Knopp
7,658,610	B2	2/2010	Knopp
8,359,114	B2	1/2013	Steingart et al.
8,539,114	B2	9/2013	Zawacki et al.
8,738,165	B2	5/2014	Cinader, Jr. et al.
8,849,015	B2	9/2014	Bodony et al.
9,364,296	B2	6/2016	Kuo
9,675,431	B2	6/2017	Orth
10,426,574	B2	10/2019	Raby et al.
10,722,328	B2	7/2020	Velazquez et al.

(Continued)

OTHER PUBLICATIONS

Kusalanukhun, Teeraporn, Chanjira Sinthanayothin, and Wichit Tharanon. "An Algorithm of 3D Objects Connection for Dental Bridge Design." (Year: 2015).*

(Continued)

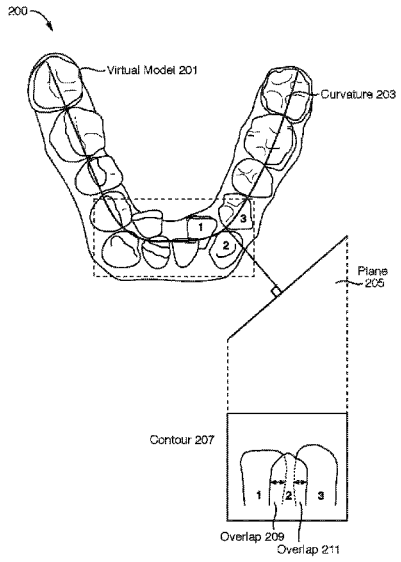
Primary Examiner — Leith S Shafi

(74) *Attorney, Agent, or Firm* — Lowenstein Sandler LLP

(57) **ABSTRACT**

System and methods herein determine two or more adjacent teeth in a virtual model. The system and methods determine a characteristic of the teeth indicative of a spatial relationship between the teeth. The system and methods further determine that the characteristic satisfies a criterion for a virtual filler. The system and methods determine a geometry of the virtual filler based on the spatial relationship between the teeth.

11 Claims, 15 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

2002/0192617	A1	12/2002	Phan et al.	
2006/0068353	A1	3/2006	Abolfathi et al.	
2006/0093982	A1	5/2006	Wen	
2009/0248184	A1	10/2009	Steingart et al.	
2009/0280450	A1	11/2009	Kuo	
2014/0142897	A1	5/2014	Kuo	
2016/0256240	A1	9/2016	Shivapuja et al.	
2017/0071705	A1	3/2017	Kuo	
2018/0085201	A1	3/2018	Wu et al.	
2018/0116762	A1	5/2018	Kopelman	
2018/0189434	A1*	7/2018	Zhou	G06F 30/23
2019/0105127	A1	4/2019	Velazquez et al.	
2019/0314117	A1	10/2019	Morton et al.	
2019/0388189	A1	12/2019	Shivapuja et al.	
2020/0060792	A1	2/2020	Kuo	
2020/0060797	A1	2/2020	Sachdeva et al.	

OTHER PUBLICATIONS

Communication Relating to the Results of the Partial International Search for International Patent Application No. PCT/US2018/054456 dated Dec. 7, 2018, 13 pages.

Wu, Chenglei et al.,"Model-Based Teeth Reconstruction," Disney Research, published Nov. 21, 2016; downloaded from https://www.disneyresearch.com/publication/model-based-teeth-reconstruction/ on Sep. 7, 2018.

International Search Report and Written Opinion of the International Searching Authority for International Application No. PCT/US2018/054456 dated Jan. 28, 2019, 21 pages.

Zhang, Hanzhou. "Mesh generation for voxel-based objects." West Virginia University, (2005).

Kikuchi H., Ikeda M., Araki K., Evaluation of a virtual reality simulation system for porcelain fused to metal crown preparation at Tokyo Medical and Dental University. Journal of dental education. Jun. 2013; 77(6):782-92.

Wang D., Li T., Zhang Y., Hou J., Survey on multisensory feedback virtual reality dental training systems. European Journal of Dental Education. Nov. 2016; 20(4): 248-60.

Roy E., Bakr MM, George R. The need for virtual reality simulators in dental deducation: A review. The Saudi dental journal. Apr. 1, 2017:29(2):41-7.

Huang TH, Yang CH, Hsieh YH, Wang JC, Hung CC. Augmented reality (AR) and virtual reality (VR) applied in lentistry. The Kaohsiung journal of medical sciences. Apr. 1, 2018;34(4):243-8.

Rhienmora, P., Haddawy, P., Khanal, P., Suebnukam, S. and Dailey, M.N., 2010. A virtual reality simulator for teaching and evaluating dental procedures. Methods of information in medicine, 49(04), pp. 396-405.

* cited by examiner

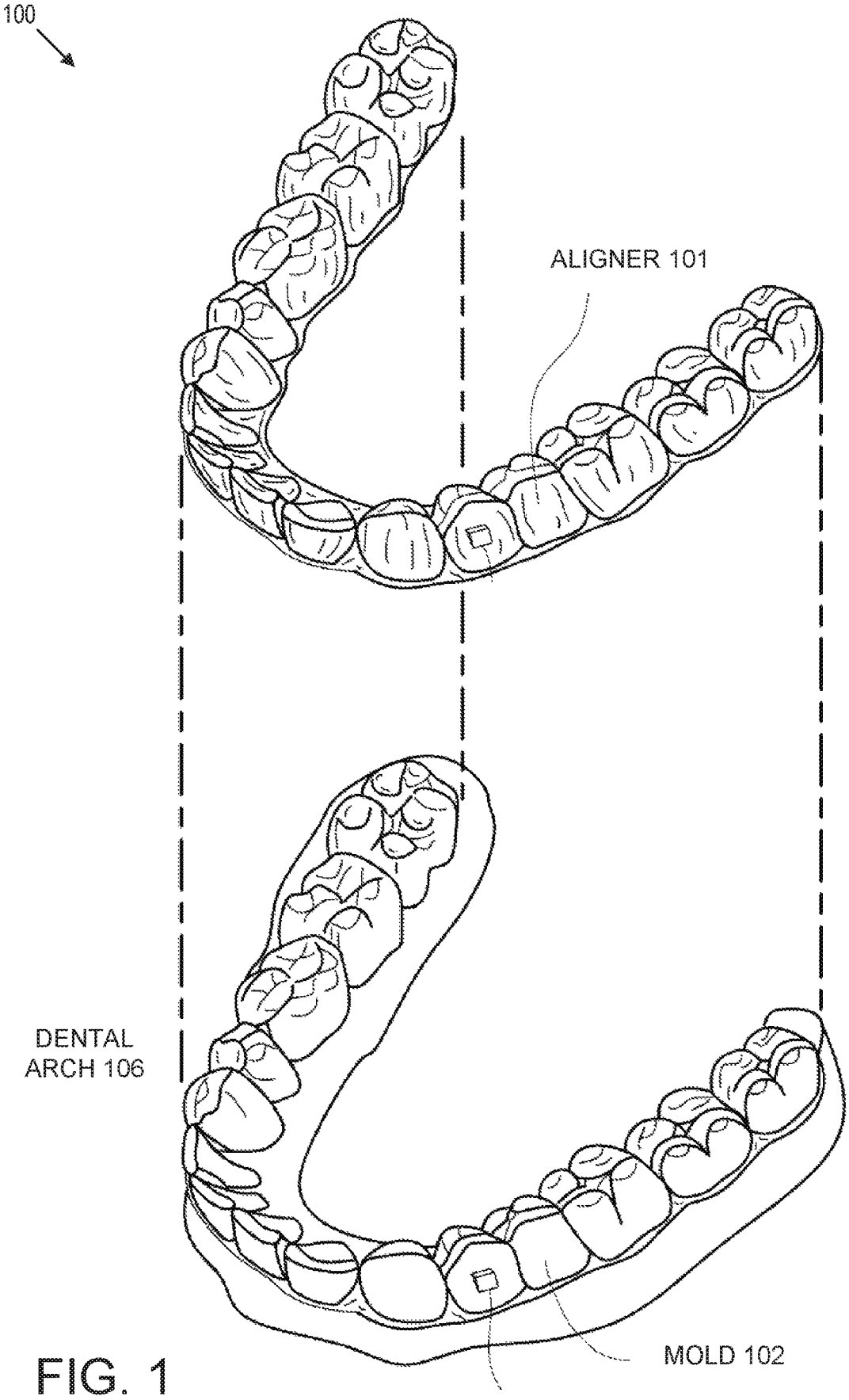


FIG. 1

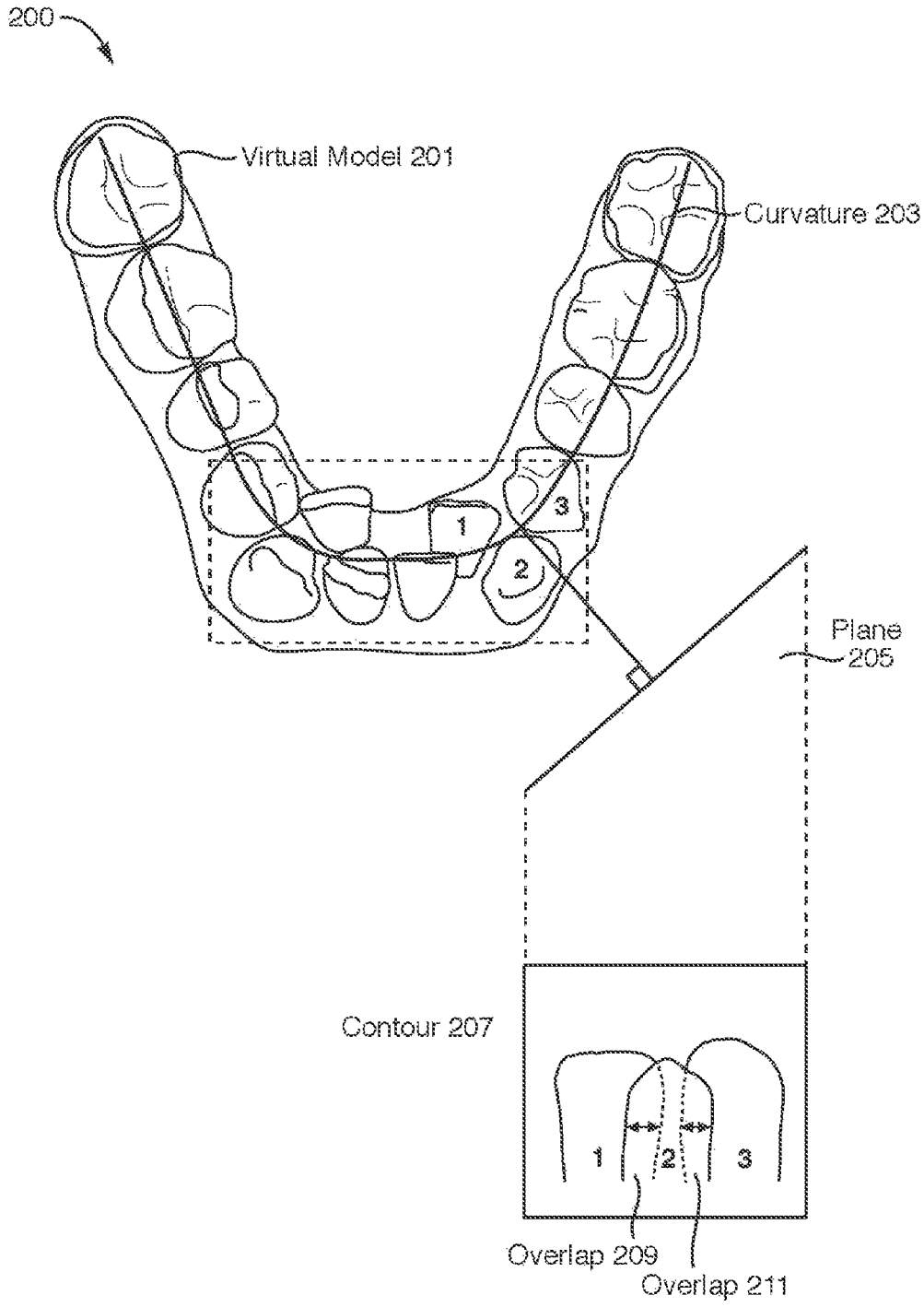

200
Virtual Model 201
Curvature 203
1
2
3
Plane
205
Contour 207
1
2
3
Overlap 209
Overlap 211

FIG. 2

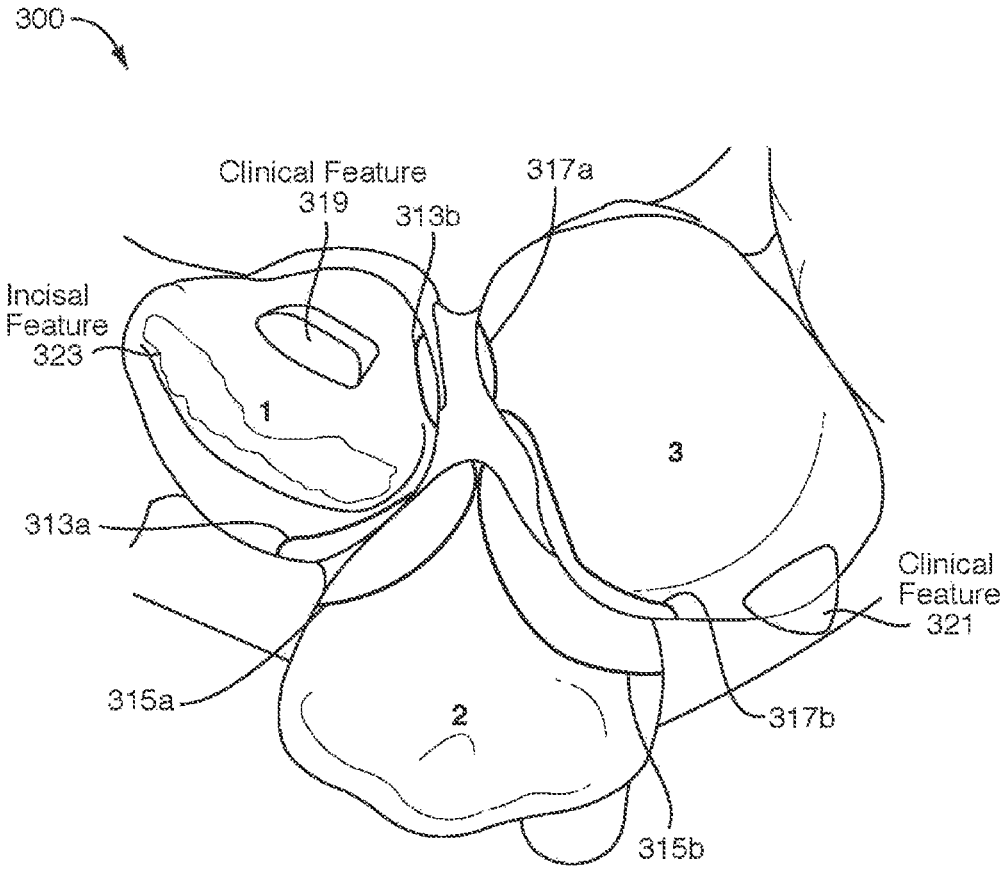

300
Clinical Feature
319
313b
317a
Incisal
Feature
323
1
3
313a
Clinical
Feature
321
315a
2
317b
315b

FIG. 3

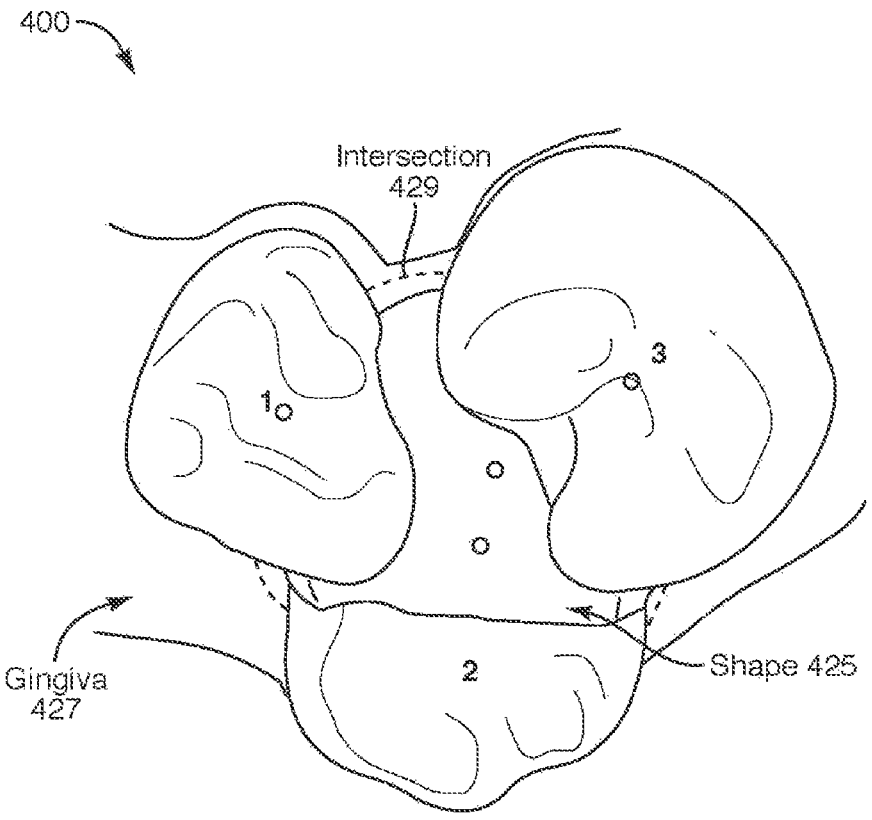


FIG. 4

FIG. 5

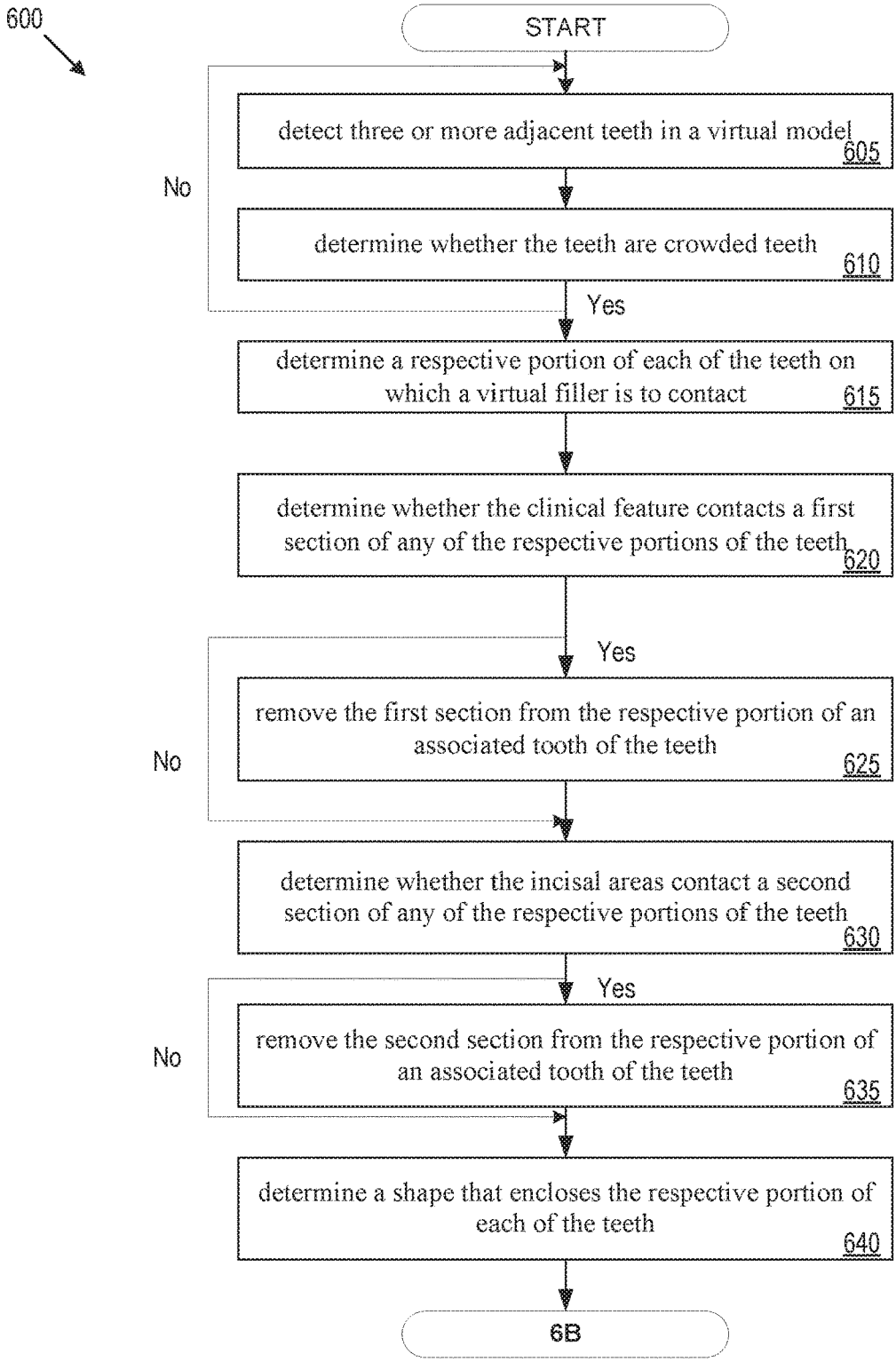

600
START
detect three or more adjacent teeth in a virtual model
605
No
determine whether the teeth are crowded teeth
610
Yes
determine a respective portion of each of the teeth on which a virtual filler is to contact
615
determine whether the clinical feature contacts a first section of any of the respective portions of the teeth
620
Yes
remove the first section from the respective portion of an associated tooth of the teeth
625
No
determine whether the incisal areas contact a second section of any of the respective portions of the teeth
630
Yes
remove the second section from the respective portion of an associated tooth of the teeth
635
No
determine a shape that encloses the respective portion of each of the teeth
640
6B

FIG. 6A

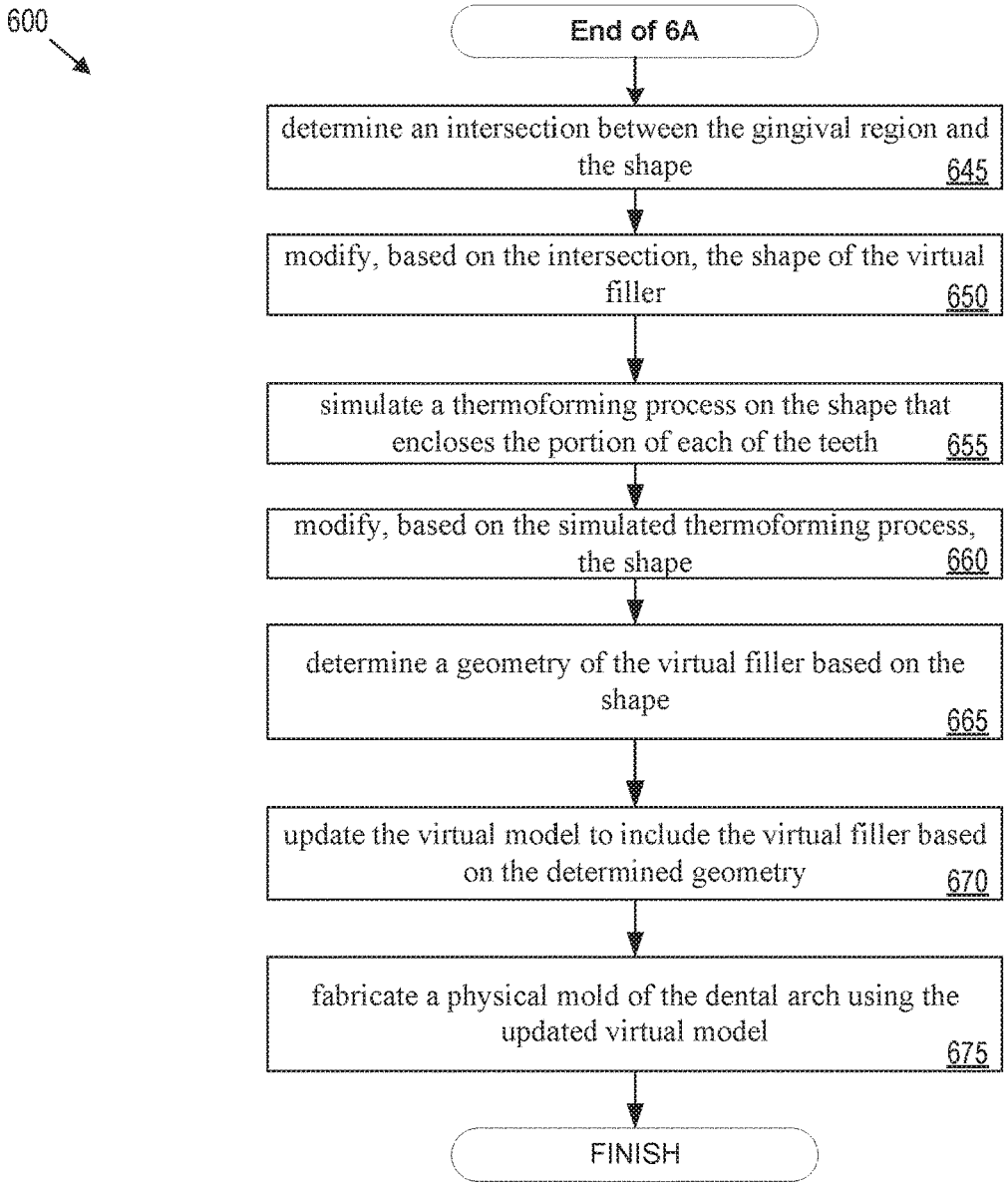

600
End of 6A
determine an intersection between the gingival region and the shape 645
modify, based on the intersection, the shape of the virtual filler 650
simulate a thermoforming process on the shape that encloses the portion of each of the teeth 655
modify, based on the simulated thermoforming process, the shape 660
determine a geometry of the virtual filler based on the shape 665
update the virtual model to include the virtual filler based on the determined geometry 670
fabricate a physical mold of the dental arch using the updated virtual model 675
FINISH

FIG. 6B

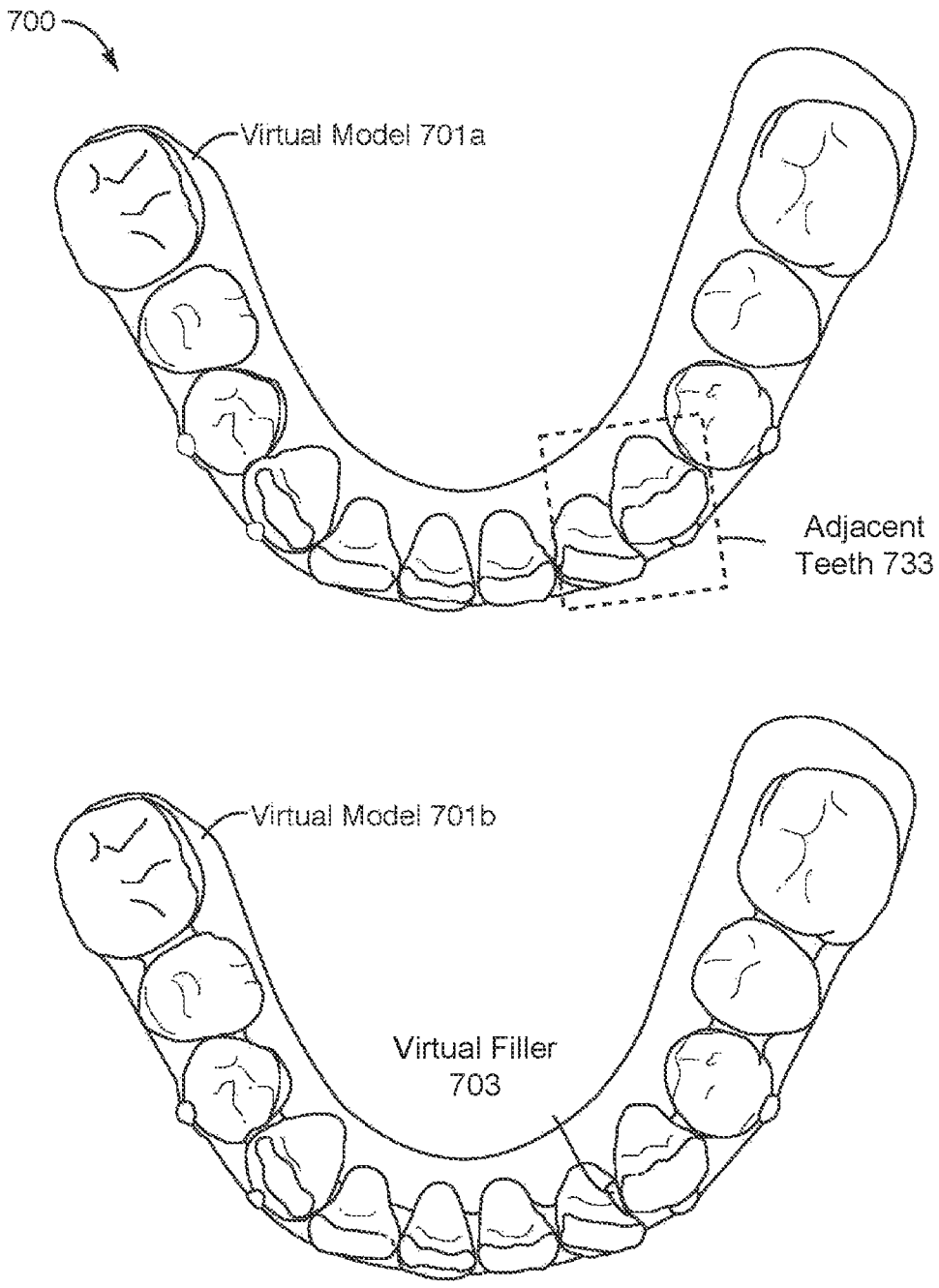

700
Virtual Model 701a
Adjacent Teeth 733
Virtual Model 701b
Virtual Filler 703

FIG. 7

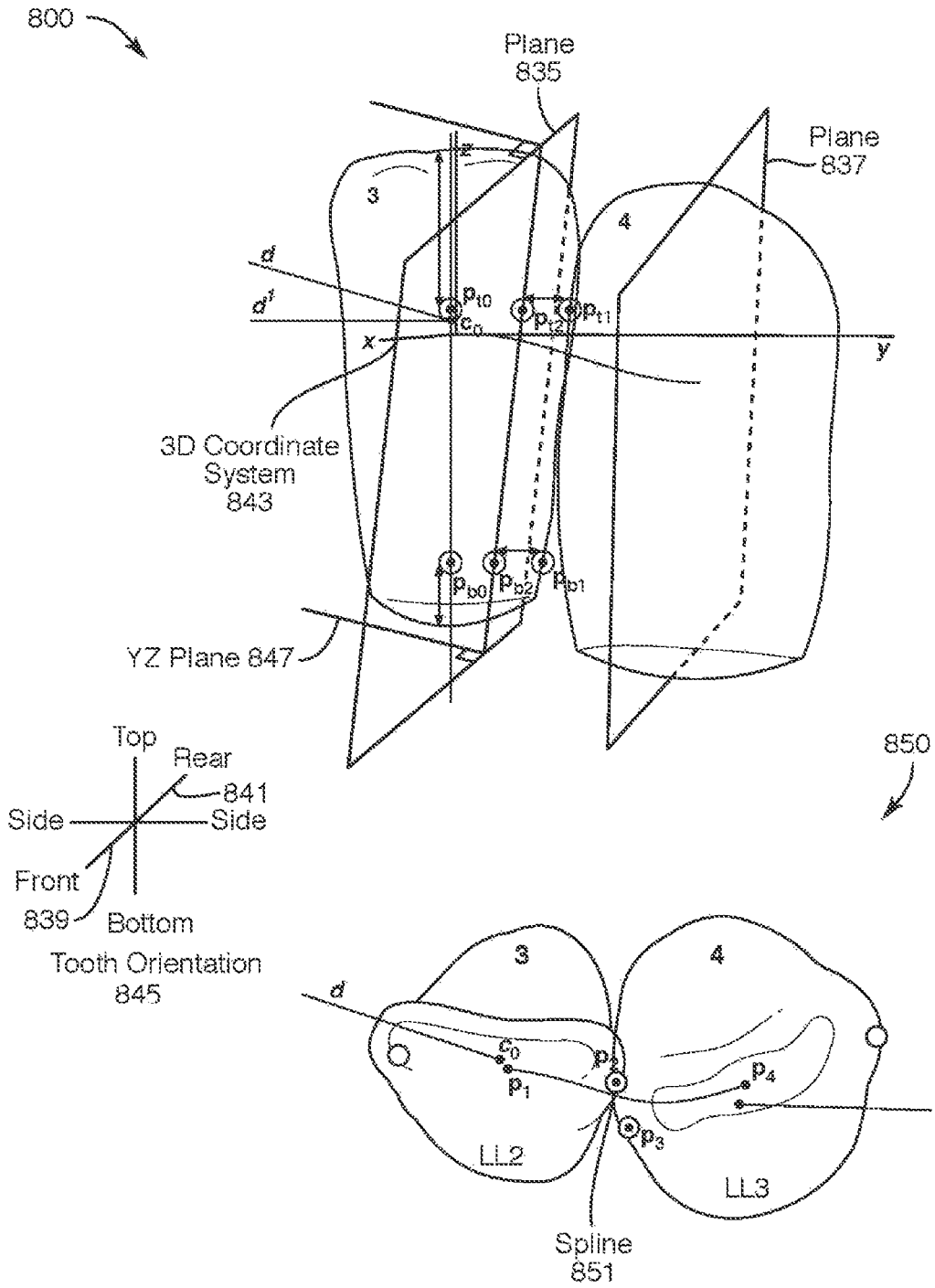

800
Plane
835
Plane
837
3
4
d
d'
p_{t0}
p_{t2}
p_{t1}
c_{t0}
x
y
3D Coordinate
System
843
p_{b0}
p_{b2}
p_{b1}
YZ Plane 847
Top
Rear
841
Side
Side
Front
839
Bottom
Tooth Orientation
845
850
3
4
d
c_0
p_2
p_1
p_4
p_3
LL2
LL3
Spline
851

FIG. 8

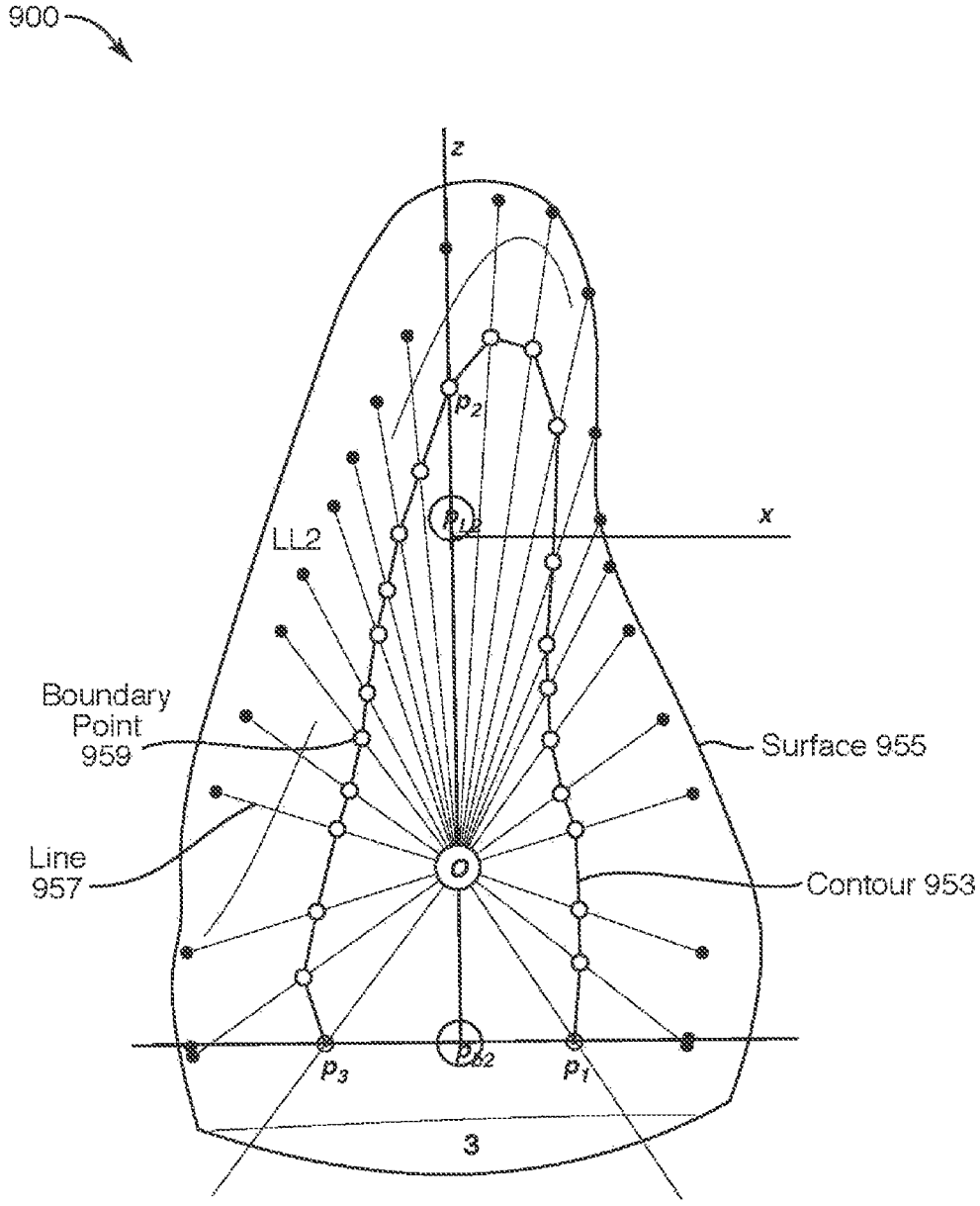

900
z
x
LL2
Boundary Point 959
Surface 955
Line 957
Contour 953
3

FIG. 9

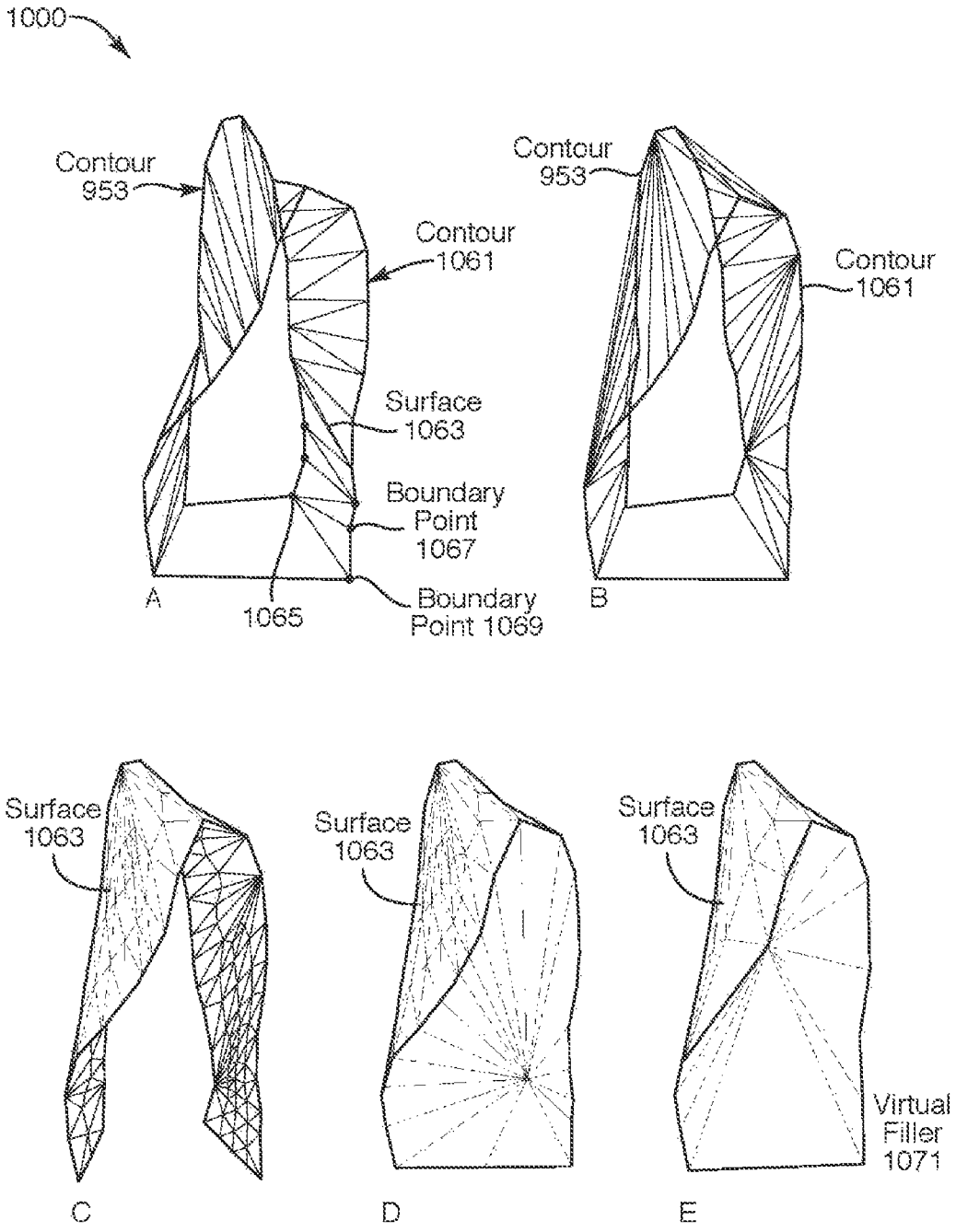

1000
Contour 953
Contour 1061
Surface 1063
Boundary Point 1067
Boundary Point 1069
1065
A
Contour 953
Contour 1061
B
Surface 1063
C
Surface 1063
D
Surface 1063
Virtual Filler 1071
E

FIG. 10

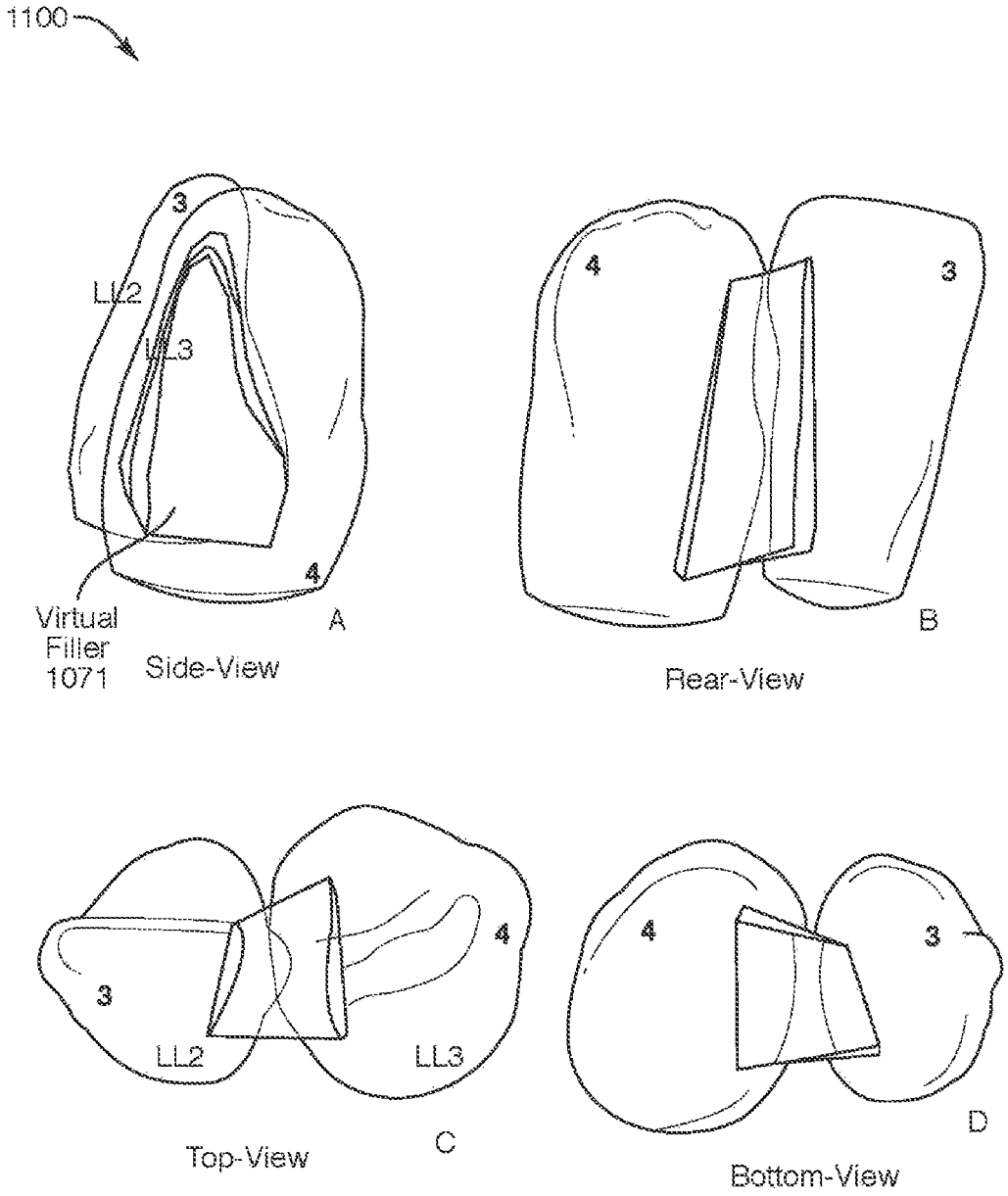

1100
3
LL2
LL3
4
Virtual Filler 1071
A
Side-View
4
3
B
Rear-View
3
4
LL2
LL3
C
Top-View
4
3
D
Bottom-View

FIG. 11

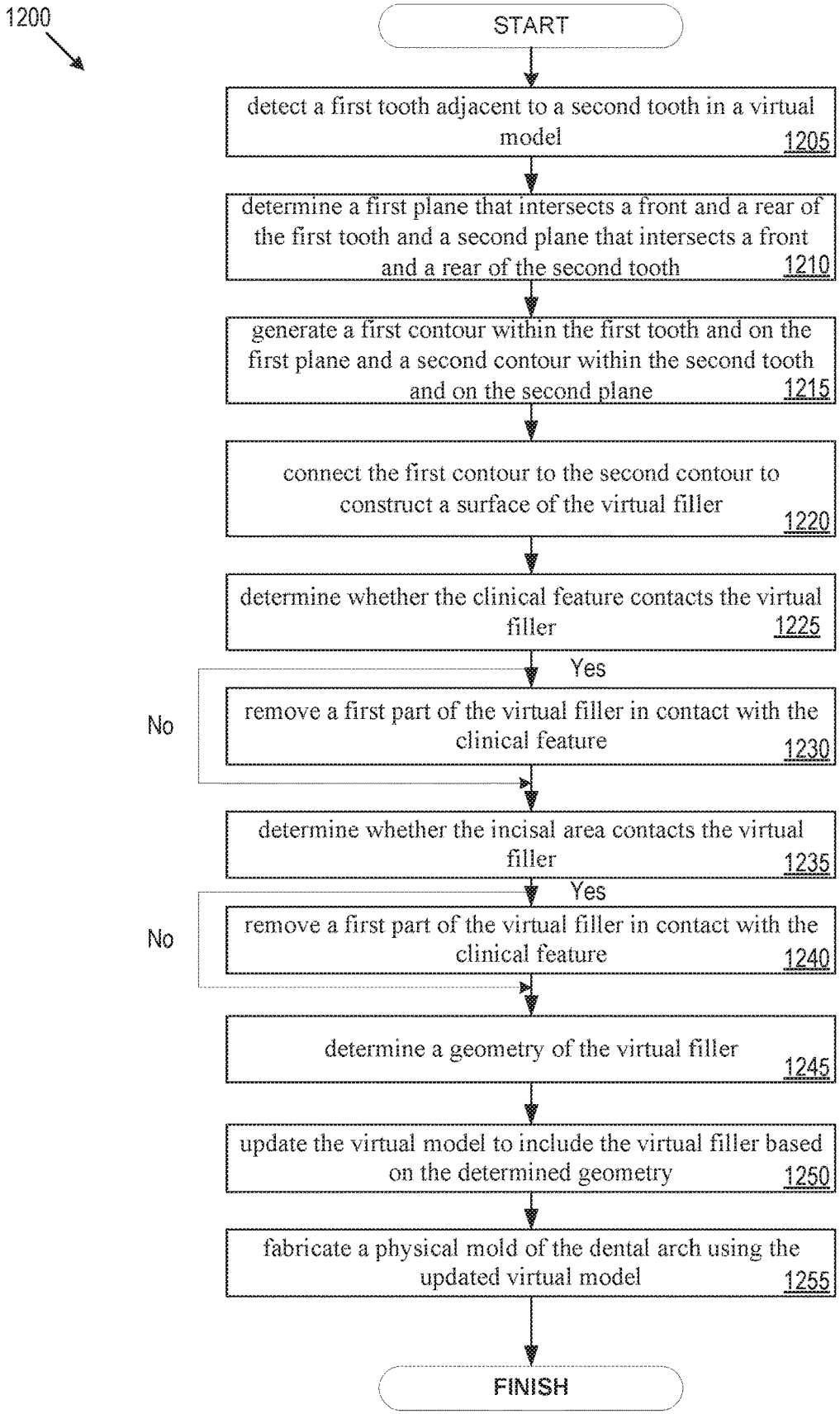

1200
START
detect a first tooth adjacent to a second tooth in a virtual model 1205
determine a first plane that intersects a front and a rear of the first tooth and a second plane that intersects a front and a rear of the second tooth 1210
generate a first contour within the first tooth and on the first plane and a second contour within the second tooth and on the second plane 1215
connect the first contour to the second contour to construct a surface of the virtual filler 1220
determine whether the clinical feature contacts the virtual filler 1225
Yes
No
remove a first part of the virtual filler in contact with the clinical feature 1230
determine whether the incisal area contacts the virtual filler 1235
Yes
No
remove a first part of the virtual filler in contact with the clinical feature 1240
determine a geometry of the virtual filler 1245
update the virtual model to include the virtual filler based on the determined geometry 1250
fabricate a physical mold of the dental arch using the updated virtual model 1255
FINISH

FIG. 12

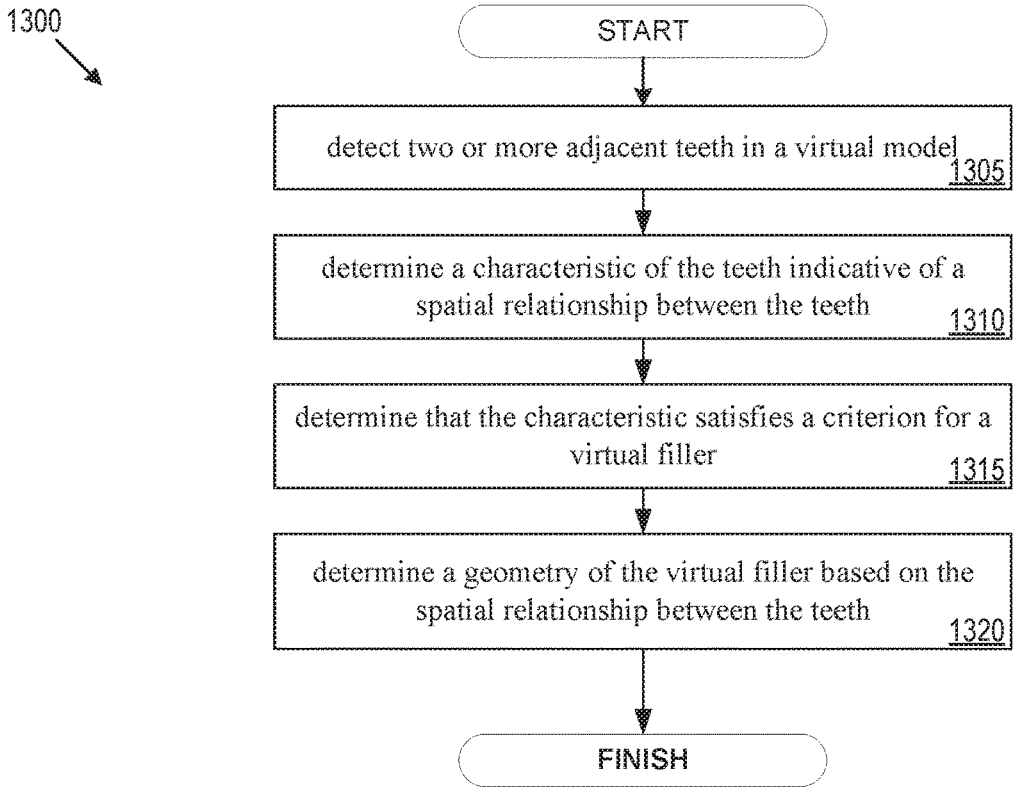

1300
START
detect two or more adjacent teeth in a virtual model
1305
determine a characteristic of the teeth indicative of a spatial relationship between the teeth
1310
determine that the characteristic satisfies a criterion for a virtual filler
1315
determine a geometry of the virtual filler based on the spatial relationship between the teeth
1320
FINISH

FIG. 13

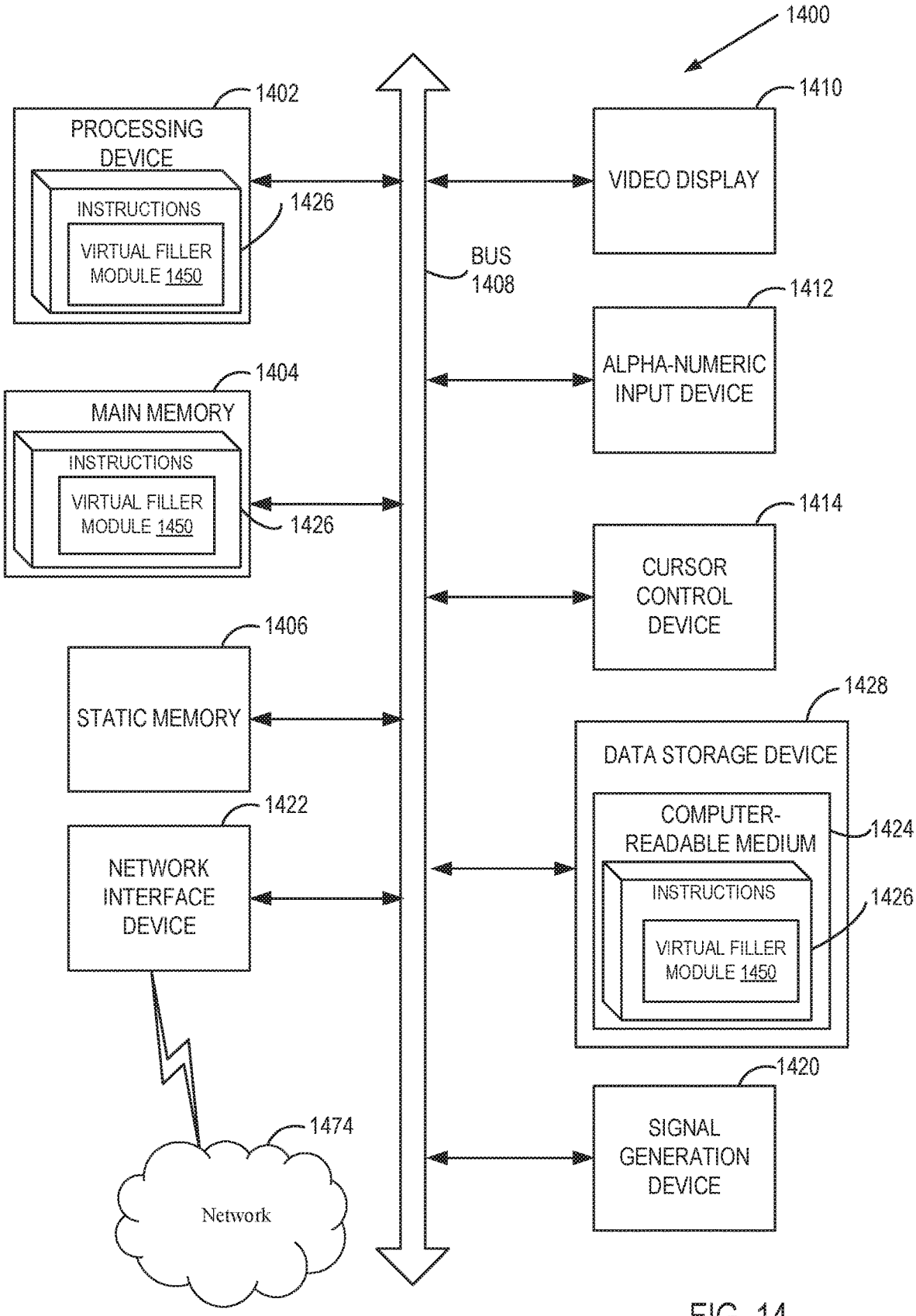

1400
1402
PROCESSING DEVICE
INSTRUCTIONS
VIRTUAL FILLER MODULE 1450
1426
1404
MAIN MEMORY
INSTRUCTIONS
VIRTUAL FILLER MODULE 1450
1426
1406
STATIC MEMORY
1422
NETWORK INTERFACE DEVICE
1474
Network
BUS 1408
1410
VIDEO DISPLAY
1412
ALPHA-NUMERIC INPUT DEVICE
1414
CURSOR CONTROL DEVICE
1428
DATA STORAGE DEVICE
COMPUTER-READABLE MEDIUM
1424
INSTRUCTIONS
VIRTUAL FILLER MODULE 1450
1426
1420
SIGNAL GENERATION DEVICE

FIG. 14

VIRTUAL FILLERS

TECHNICAL FIELD

Embodiments of the present disclosure relate to the field of orthodontics and, in particular, to orthodontic aligners.

BACKGROUND

Orthodontic procedures typically involve repositioning a patient's teeth to a desired arrangement in order to correct malocclusions or improve aesthetics. To achieve these objectives, orthodontic appliances such as braces, retainers, aligners, and the like can be applied to the patient's teeth by an orthodontic practitioner. The appliance is configured to exert force on one or more teeth in order to effect desired tooth movements. The application of force can be periodically adjusted by the practitioner (e.g., by altering the appliance or using different types of appliances) in order to incrementally reposition the teeth to a desired arrangement.

BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings.

FIG. **1** illustrates an orthodontic aligner and physical mold, in accordance with one embodiment.

FIG. **2** illustrates a virtual model of a dental arch with crowded teeth, in accordance with embodiments.

FIG. **3** illustrates portions of crowded teeth on which a virtual filler contacts, in accordance with embodiments.

FIG. **4** illustrates a shape that encloses respective portions of the crowded teeth, in accordance with embodiments.

FIG. **5** illustrates a virtual filler for crowded teeth, in accordance with embodiments.

FIGS. **6**A-**6**B illustrates a flow diagram for a method of creating a virtual filler for crowded teeth, in accordance with one embodiment.

FIG. **7** illustrates a virtual model of dental arches with two adjacent teeth with and without virtual fillers, in accordance with embodiments.

FIG. **8** illustrates a plane that intersects a front and a rear of a tooth of two adjacent teeth, in accordance with some embodiments.

FIG. **9** illustrates a contour on a plane that intersects a front and a rear of a tooth of two adjacent teeth, in accordance with some embodiments.

FIG. **10** illustrates a construction of a surface of a virtual filler, in accordance with some embodiments.

FIG. **11** illustrates a geometry a virtual filler for adjacent teeth, in accordance with some embodiments.

FIG. **12** illustrates a flow diagram for a method of creating a virtual filler for adjacent teeth, in accordance with one embodiment.

FIG. **13** illustrates a flow diagram for a method of creating a virtual filler for adjacent teeth or crowded teeth, in accordance with one embodiment.

FIG. **14** illustrates a block diagram of an example computing device, in accordance with embodiments of the present disclosure.

DETAILED DESCRIPTION

Orthodontic aligners (also referred to as "shell aligners," "plastic aligners," or "aligners" herein) described herein, along with related systems and methods, can be employed as part of an orthodontic treatment procedure in order to reposition one or more teeth, maintain a current position of one or more teeth, or suitable combinations thereof. An orthodontic aligner as described herein may be included in a series of orthodontic aligners so as to provide an orthodontic system for positioning teeth. Such an orthodontic system can include a sequence of orthodontic aligners each including a shell having a one or more cavities shaped to receive at least portions of teeth. The series of orthodontic aligners may be successively worn by a patient to move one or more teeth from a first arrangement to a second arrangement.

For each of the series of orthodontic aligners, a virtual model of a dental arch (also referred to as an "arch" herein) may be created. The virtual model may be used to fabricate a physical mold of the dental arch. In turn, the physical mold of the dental arch may be used to fabricate the particular orthodontic aligner in the series. For instance, a thermoforming process may be used to form a plastic orthodontic aligner on the physical mold of the dental arch. In some cases, the geometry of the physical mold may induce quality issues in the orthodontic aligner during or after the thermoforming process. For instance, the geometry of the physical mold may include retentive areas or stress concentration areas that induce quality issues with the orthodontic aligner, such as holes or pinched areas, degradation of material properties (e.g., compression or stretching), or deformation or tearing of the orthodontic aligner during a removal process (e.g., removal of the orthodontic aligner from the physical mold).

Aspects of the present disclosure address the above-mentioned and other challenges by generating virtual fillers for a virtual model of a dental arch, where the virtual fillers reduce the retentive and stress concentration areas of a resultant physical mold. In embodiments, generating a virtual filler includes determining two or more adjacent teeth in a virtual model of a dental arch and determining a characteristic of the teeth indicative of a spatial relationship between the teeth. A determination may be made as to whether the characteristic satisfies a criterion for a virtual filler (e.g., determining that the teeth are crowded teeth or two adjacent teeth). Responsive to the determination, a geometry (e.g., geometric shape and position in the virtual model) of the virtual filler for either crowded teeth or two adjacent teeth may be determined based on the spatial relationship between the teeth. A virtual filler may refer to a digital feature of or added to a virtual model (such as a virtual model of a dental arch) that presents an additional object between two or more adjacent teeth. In embodiments, the virtual filler of the virtual model changes the geometry of a respective physical mold and reduces the probability of fabrication issues.

Generating virtual fillers for virtual models, as disclosed herein, is advantageous at least because the virtual filler of the virtual model changes the geometry of a respective physical mold to reduce retentive and stress concentration areas, which reduces the probability of quality issues during and after the fabrication of orthodontic aligners. Further, aspects of the present disclosure result in reduction of storage resources and computational (processing) resources at least because the virtual fillers may be used and re-used in the creation of multiple physical molds (e.g., data stored and processing resources are reduced because the number of virtual fillers is also reduced) and the virtual fillers help reduce the number of fabrication processes (e.g., a particular orthodontic aligner may be fabricated once as a result of the

reduction of quality issues). In addition, aspects of the present disclosure result in improvements in the fabrication of orthodontic aligners.

Embodiments are discussed herein with reference to orthodontic aligners. The orthodontic aligners described herein are generally plastic shells that are thermoformed over a physical mold that has been manufactured using a virtual three-dimensional (3D) model of a dental arch. It should be noted that embodiments described herein with reference to orthodontic aligners also apply to other plastic shells worn over a patients teeth, such as sleep apnea appliances, appliances used for surgical stabilization (e.g., for use during and/or after surgery that corrects type I, type II and/or type III malocclusions), orthodontic retainers, orthodontic splints, and so on. Accordingly, any discussion of orthodontic aligners also applies to other such plastic shells that are worn over a patient's teeth.

FIG. **1** illustrates an orthodontic aligner and physical mold, in accordance with one embodiment. Diagram **100** illustrates an example of a tooth repositioning appliance, such as orthodontic aligner **101** that can be worn by a patient in order to achieve an incremental repositioning of individual teeth in the jaw. The orthodontic aligner **101** can include a shell (e.g., a translucent polymeric shell o) having teeth-receiving cavities that receive and resiliently reposition the teeth. The orthodontic aligner **101** or portion(s) thereof may be indirectly fabricated using a physical model or physical mold **102** of the teeth. In embodiments, the physical mold **102** may be a mold of a patient's dental arch **106**. A dental arch may refer to a crescent arrangement of teeth. Each jaw may include two dental arches that constitute a dentition. In embodiments, orthodontic aligner **101** can be formed using a physical mold **102** and a sheet of suitable layers of polymeric material. An orthodontic aligner **101** can fit over all teeth present in an upper or lower jaw (e.g., upper dental arch or lower dental arch), or less than all of the teeth. The orthodontic aligner **101** can be designed specifically to accommodate the teeth of the patient (e.g., the topography of the tooth-receiving cavities matches the topography of the patient's teeth), and may be fabricated based on positive or negative models of the patient's teeth generated by impression, scanning, and the like. Alternatively, the orthodontic aligner **101** can be a generic aligner configured to receive the teeth, but not necessarily shaped to match the topography of the patient's teeth.

In some embodiments, only certain teeth received by an orthodontic aligner **101** will be repositioned by the orthodontic aligner **101** while other teeth can provide a base or anchor region for holding the appliance in place as the orthodontic aligner **101** applies force against the tooth or teeth targeted for repositioning. In some cases, many or most, and even all, of the teeth will be repositioned at some point during treatment. Teeth that are moved can also serve as a base or anchor for holding the orthodontic aligner **101** as the aligner is worn by the patient. Typically, no wires or other means will be provided for holding an orthodontic aligner **101** in place over the teeth. In some cases, however, it may be desirable to provide individual attachments or other anchoring elements (not shown) on teeth with corresponding receptacles or apertures (not shown) in the orthodontic aligner **101** so that the aligner can apply a selected force on the tooth.

In some embodiments, orthodontic aligner **101** may be fabricated by one or more operations. For example, one or more operations may be performed by a processing device executing a computer aided drafting (CAD) program or virtual filler module **1450**. It may be noted that operations described in the disclosure herein may be performed by a virtual filler module **1450**, unless otherwise described. The aligner development and fabrication process is described in the following description. In embodiments, a virtual patient is created. A virtual patient is a digital file, database entry, or data structure that represents a patient. The virtual patient may include patient data, photographs, a virtual model (e.g., virtual three-dimensional (3D) model of a patient's dental arch), x-ray images of a patient's dentition, and so on. The virtual patient may be created based on input data in the form of intraoral scan data, a PVS (polyvinyl siloxane) impression or the like, (e.g., a PVS file or a 3DM file), a sterolithography (STL) file, an align design file (ADF), digital photographs (e.g., JPG files, BMP files, PNG files, and so on), stereo photos, videos (e.g., MPEG files), x-ray images (e.g., cone beam computerized tomography CBCT scan) and/or other input data. If a virtual 3D model of the patient's upper and lower dental arches are not yet included in the virtual patient, then such virtual 3D models may be generated from the input data.

In an example, an intraoral scan of the patient's dental arches may be performed to generate the virtual 3D model of the patient's upper and lower dental arches. For example, a full scan of the mandibular and/or maxillary arches of a patient may be performed to generate virtual 3D models thereof. The intraoral scan may be performed by creating multiple overlapping intraoral images from different scanning stations and then stitching together the intraoral images to provide a composite virtual 3D model. In other applications, virtual 3D models may also be generated based on scans of an object to be modeled or based on use of computer aided drafting techniques (e.g., to design the virtual 3D mold). Alternatively, an initial negative mold may be generated from an actual object to be modeled. The negative mold may then be scanned to determine a shape of a positive mold that will be produced.

In embodiments, an initial dental orientation is defined (e.g., before the start or treatment with orthodontic aligner **101**). The initial dental orientation includes an initial position of the upper and lower jaw, including an initial relationship in position and orientation between the upper and lower jaw. The initial dental orientation is the initial position, orientation, and relationship for and between the upper and lower dental arches before treatment with orthodontic aligner **101**. The initial dental orientation defines the starting point for orthodontic treatment and the initial shapes of the upper and lower dental arches, and the fixed relationship between the upper and lower dental arch, during a post-operative fixation period.

In embodiments, once the initial dental orientation target is defined, a final treatment goal is defined. The final treatment goal is the target dental positions and orientations for the patient's teeth post treatment with orthodontic aligner **101**. In embodiments, a sequence of treatment stages are determined to reposition the teeth from the starting dentition defined from the initial dental orientation to the final treatment goal. This may include determining a number of treatment stages that should be used to cause the teeth to progress from initial positions and orientations to the target final positions and orientations. Each treatment stage may move the patient's teeth slightly toward the final treatment goal. The shape of the final virtual 3D model and each intermediate virtual 3D model may be determined by computing the progression of tooth movement throughout orthodontic treatment from initial tooth placement and orientation to final corrected tooth placement and orientation. For each treatment stage, a separate virtual 3D model of the

patient's dental arches at that treatment stage may be generated. The shape of each virtual 3D model will be different. The original virtual 3D model, the final virtual 3D model and each intermediate virtual 3D model is unique and customized to the patient. A treatment plan may be generated that includes the surgical target, final treatment goal and each of the treatment stages (including the virtual 3D models of the arches at each treatment stage).

In embodiments, multiple different virtual 3D models may be generated for a single patient. A first pair of virtual 3D models may be a unique pair of models of a patient's dental arches and/or teeth as they will exist after the surgery, and a final virtual 3D model may be a model of the patient's dental arch and/or teeth after both surgery and orthodontic correction of one or more teeth and/or a jaw. Multiple intermediate virtual 3D models may be modeled, each of which may be incrementally different from previous virtual 3D models.

In embodiments, orthodontic aligners **101** are fabricated based on the virtual 3D models of the dental arches for one or more treatment stages. In one embodiment, rapid prototyping (e.g., stereo lithography) is performed to form physical molds **102** from the virtual 3D models for one or more treatment stages. One example of a rapid prototyping manufacturing machine is a 3D printer. 3D Printing includes any layer-based additive manufacturing processes. 3D printing may be achieved using an additive process, where successive layers of material are formed in proscribed shapes. 3D printing may be performed using extrusion deposition, granular materials binding, lamination, photopolymerization, continuous liquid interface production (CLIP), or other techniques. 3D printing may also be achieved using a subtractive process, such as milling.

In one embodiment, stereolithography (SLA), also known as optical fabrication solid imaging, is used to fabricate an SLA mold. In SLA, the physical mold **102** is fabricated by successively printing thin layers of a photo-curable material (e.g., a polymeric resin) on top of one another. A platform rests in a bath of a liquid photopolymer or resin just below a surface of the bath. A light source (e.g., an ultraviolet laser) traces a pattern over the platform, curing the photopolymer where the light source is directed, to form a first layer of the physical mold **102**. The platform is lowered incrementally, and the light source traces a new pattern over the platform to form another layer of the physical mold **102** at each increment. This process repeats until the physical mold **102** is completely fabricated. Once all of the layers of the physical mold **102** are formed, the mold may be cleaned and cured.

Materials such as a polyester, a co-polyester, a polycarbonate, a thermoplastic polyurethane, a polypropylene, a polyethylene, a polypropylene and polyethylene copolymer, an acrylic, a cyclic block copolymer, a polyetheretherketone, a polyamide, a polyethylene terephthalate, a polybutylene terephthalate, a polyetherimide, a polyethersulfone, a polytrimethylene terephthalate, a styrenic block copolymer (SBC), a silicone rubber, an elastomeric alloy, a thermoplastic elastomer (TPE), a thermoplastic vulcanizate (TPV) elastomer, a polyurethane elastomer, a block copolymer elastomer, a polyolefin blend elastomer, a thermoplastic co-polyester elastomer, a thermoplastic polyamide elastomer, or combinations thereof, may be used to directly form the physical mold **102**. The materials used for fabrication of the physical mold **102** can be provided in an uncured form (e.g., as a liquid, resin, powder, etc.) and can be cured (e.g., by photopolymerization, light curing, gas curing, laser curing, crosslinking, etc.). The properties of the material before curing may differ from the properties of the material after curing.

In embodiments, orthodontic aligners **101** may be formed from each physical mold **102** to provide forces to move the patient's teeth. The shape of each orthodontic aligner **101** is unique and customized for a particular patient and a particular treatment stage. In an example, the orthodontic aligner **101** can be pressure formed or thermoformed over the physical molds **102**. In one embodiment, a sheet of material is pressure formed or thermoformed over the physical mold **102**. The sheet may be, for example, a sheet of plastic (e.g., an elastic thermoplastic, a sheet of polymeric material, etc.). To thermoform the orthodontic aligner **101** over the physical mold **102**, the sheet of material may be heated to a temperature at which the sheet becomes pliable. Pressure may concurrently be applied to the sheet to form the now pliable sheet around the physical mold **102** with the features that will imprint the markings and/or elements in the orthodontic aligner **101**. Once the sheet cools, it will have a shape that conforms to the physical mold **102**. In one embodiment, a release agent (e.g., a non-stick material) is applied to the physical mold **102** before forming the a orthodontic aligner **101**. This may facilitate later removal of the physical mold **102** from the orthodontic aligner **101**. After thermoforming, the orthodontic aligner **101** may be trimmed at a cut line that is near to a gingival line of the patient.

In embodiments, each physical mold **102** may be used to fabricate an orthodontic aligner **101** that will apply forces to the patient's teeth at a particular stage of the orthodontic treatment. The orthodontic aligners **101** each have teeth-receiving cavities that receive and resiliently reposition the teeth in accordance with a particular treatment stage. The orthodontic aligners **101** may additionally have stabilization features that will maintain target positions and orientation of the upper and lower jaw during the post-operative fixation period.

One of more of the virtual 3D models of the upper and/or lower dental arches may include features (e.g., undercuts, sharp corners, crowded areas, etc.) that will ultimately cause manufacturing difficulties. Such features will be transferred to the physical molds generated from the virtual 3D models. After thermoforming is performed, these features may cause the orthodontic aligner to be retained on the mold, and may make removal of the orthodontic aligner from the mold difficult and/or error prone. Moreover, these features may cause the orthodontic aligners to be too thin in regions, to be damaged during removal of the orthodontic aligners from the physical molds, and so on. Virtual fillers may therefore be added to the virtual 3D models to remove problematic features and/or to mitigate the impact of such problematic features, as set forth herein below. Multiple different techniques for generating virtual fillers are provided herein. A first technique for generating virtual fillers is used for crowded teeth, and a second technique for generating virtual fillers is used for pairs of adjacent teeth.

FIG. **2** illustrates a virtual model of a dental arch with crowded teeth, in accordance with embodiments. Diagram **200** shows a virtual model **201** of a dental arch having crowded teeth. In embodiments, crowded teeth may refer to three or more adjacent teeth (herein after referred to as "teeth" unless otherwise described) having a threshold amount of overlap between the teeth (e.g., teeth **1**, **2**, and **3** are crowded together). The amount of overlap of the teeth may be a characteristic of crowded teeth (e.g., spatial relationship between the teeth). It may be noted that three or

more adjacent teeth may also be considered a characteristic of crowded teeth. In some embodiments, the amount of overlap between the teeth may be compared to a criterion, such as a threshold (e.g., distance in millimeters (mm)), to determine whether the teeth are crowded teeth.

In some embodiments, determining whether the teeth are crowded teeth includes determining a curvature **203** of the dental arch. In embodiments, the curvature **203** may be a line that estimates or approximates the curvature of the dental arch. A plane **205** that is tangential to a point on the curvature **203** may be determined. For example, a point at approximately the center of tooth **2** may be located. A line orthogonal to the center of tooth **2** may be generated. Plane **205** may then be generated, where plane **205** is orthogonal to the line. In embodiments, a similar operation may be performed on each tooth of the virtual model **201** of the dental arch. For example, a plane tangential to a point on each tooth may be generated.

In embodiments, the two-dimensional contours (e.g., outline) of adjacent teeth may be projected on the plane **205**. For the sake of illustration, rather than limitation, the contours **207** of tooth **1**, tooth **2**, and tooth **3** are shown projected on plane **205**. A crowding metric indicative of the amount of overlap between the teeth may be determined. For example, a crowding metric may be determined by measuring the amount of overlap of the contours for each pair of adjacent teeth of the three or more adjacent teeth **1**, **2**, **3**. In some embodiments, the amount of overlap of the contours may be the maximum distance between the intersections of contours for a pair of teeth. For example, the overlap **209** of tooth **1** and tooth **2** may be 2 mm and the overlap **211** of tooth **2** and tooth **3** may be 1 mm. In some embodiments, the crowding metric may be the sum of the overlap between the contours **207**. For example, for teeth **1-3** the crowding metric may be the sum of overlap **209** and overlap **211** (e.g., 3 mm of overlap). The crowding metric (e.g., 3 mm of overlap) may be compared to a threshold (e.g. 2.5 mm). Responsive to determining that the crowding metric is below the threshold, the teeth may be considered uncrowded teeth. Responsive to determining that the crowding metric is equal to or greater than the threshold, the teeth may be considered crowded teeth. In embodiments, the threshold may be predetermined by a developer or adjusted on a per patient basis, for example. In embodiments, each tooth may be examined in similar manner as described to determine if the tooth is part of a crowded teeth structure. It may be noted that tooth **1**, **2**, and **3** as described with respect to FIGS. **2-6**B refer to the respective teeth of virtual model **201** of the dental arch of FIG. **2**.

Once a determination is made that a dental arch includes crowded teeth, one or more operations may be performed to generate a virtual filler (or multiple virtual fillers) that will contact one or more of the crowded teeth. A first set of operations may be performed to determine portions of one or more teeth that will contact a virtual filler. Portions of a tooth an area (e.g., surface area or internal area) of a tooth that will contact a virtual filler or that will be include in a shape that defines the geometry of the virtual filler.

FIG. **3** illustrates portions of crowded teeth on which a virtual filler contacts, in accordance with embodiments. Diagram **300** shows a magnified view of the crowded teeth (tooth **1**, tooth **2**, and tooth **3**) identified in FIG. **2**. In embodiments, responsive to determining that the teeth (i.e., teeth **1-3**) are crowded teeth, a respective portion of each of the teeth on which the virtual filler is to contact is determined. For example, tooth **1** includes portion **313**A and portion **313**B (collectively referred to as portion **313**). Tooth **2** includes portion **315**A and portion **315**B (collectively referred to as portion **315**). Tooth **3** includes portion **317**A and portion **317**B (collectively referred to as portion **317**).

In some embodiments, the portions of the teeth that are to contact a virtual filler are determined by aggregating all the points (i.e., countably additive points) that are less than or equal to a threshold distance from an adjacent tooth. For instance, portion **315**A of tooth **2** includes all the points that are less than or equal to a threshold distance from tooth **1**. Similarly, portion **315**B of tooth **2** includes all the points that are less than or equal to a threshold distance from tooth **3**. In some embodiments, the portions may be determined by calculating distances between all points for a pair of teeth (e.g., distance between all points of tooth **1** to all points of tooth **2**). Points that are below or equal to the threshold are included as part of the portion for a respective tooth, and points greater than the threshold are discarded.

In some embodiments, the portions of the teeth may be adjusted to account for clinical features on the teeth. A clinical feature may be a foreign object located on or attached to a tooth. For example, a clinical feature may include a filling, a bridge, a bracket (of braces), and so forth. Diagram **300** shows clinical feature **319** on tooth **1** and clinical feature **321** on tooth **3**. In embodiments, a clinical feature may be detected on at least one of the teeth. For example, clinical feature **319** may be detected on tooth **1**. A determination may be made whether the clinical feature contacts any section of any portions of the teeth. For example, clinical feature **319** may be examined to determine whether clinical feature **319** contacts any section of any portions **313**, **315**, or **317**. Responsive to determining that a clinical feature contacts a section of a portion of a tooth, the section of the respective portion may be removed from consideration. For example, if clinical feature **319** where determined to overlap a section of portion **313**B (which is not the case in diagram **300**), portion **313**B would be reduced in size so that there is no overlap between clinical feature **319** and portion **313**B. Responsive to determining that a clinical feature does not contact a section of a portion of a tooth, the portion of the tooth is not adjusted.

In some embodiments, the portions of the teeth may be adjusted to account for incisal areas (also referred to as "occlusal areas" herein) of the teeth. An incisal area may be an area of the tooth that is used for eating or an area that contacts with an opposing tooth in the opposing dental arch. In embodiments, an incisal area of each tooth (tooth **1-3**) may be determined. For example, an outline of incisal area **323** of tooth **1** is shown in diagram **300**. A determination is made whether the incisal area contacts a section of any respective portions of the teeth. For example, virtual filler module **1450** may determine whether incisal area **323** contacts any section of portion **313**A or **313**B of tooth **1**. Responsive to determining that the incisal area contacts a section of any portions of a tooth, the section is removed from the respective portion of the tooth. For example, if incisal area **323** were determined to overlap a section of portion **313**A or portion **313**B (which is not the case in diagram **300**), portion **313** would be reduced in size so that there is no overlap between incisal area **323** and the respective section of portion **313**. Responsive to determining that an incisal area does not contact a section of a portion of a tooth, the portion of the tooth is not adjusted.

After the portions of teeth that will contact a virtual filler are determined, a shape of the virtual filler may be determined. FIG. **4** illustrates a shape that encloses respective portions of the crowded teeth **1**, **2**, **3**, in accordance with embodiments. Diagram **400** shows shape **425** that encloses

the respective portion (i.e., portion **313**, **315**, and **317** of FIG. **3**) of each of the teeth **1**, **2**, and **3**. In embodiments, shape **425** may be a convex hull. A convex hull may be a shape (e.g., smallest convex polygon) that includes a set of X points in an affine space that contains the set of X points.

In embodiments, shape **425** may be adjusted in view of gingiva **427** near the teeth. Gingiva (also referred to as "gums" or "gingival region" herein) may be the tissue that lies over the mandible or maxilla and surrounds the base of the teeth. In an embodiment, gingiva **427** may be projected under and slightly around the shape **425**. The virtual filler module **1450** may determine the intersection **429** of the gingiva **427** and the shape **425**. For instance, the intersection **429** may include the gingiva **427** directly under the shape **425**. In some embodiments, the intersection **429** may also include some amount of gingiva **427** around the shape **425** (e.g., some distance X from directly underneath the shape **425**). The points (i.e., countably additive points) of the intersection **429** may be added to the set of points for the portions **313**, **315**, and **317**. Shape **425** may be modified to include the set of points for the portions **313**, **315**, and **317** and the points of the intersection **429** between the gingiva **427** and the shape **425**.

In some embodiments, shape **425** may be adjusted to account for a simulated physical process. For example, the shape **425** may be adjusted to account for the deformation of an orthodontic aligner that undergoes a thermoforming process as part of the fabrication process. In some embodiments, a thermoforming process may be simulated on the shape **425** that encloses the portion of each of the teeth. The shape **425** may be modified based on the simulated thermoforming process. In some embodiments, the thermoforming process may be simulated by simulating a pressure on the outer-facing surface of the shape **425** and a vacuum on the inner-facing surface of the shape **425**. The shape **425** may deform (and often shrink) responsive the simulation of the thermoforming process, and the shape **425** may be adjusted to conform to the simulated deformation. In some embodiments, the shape **425** may be adjusted to account for a simulated physical process after shape **425** is adjusted in view of gingiva **427** near the teeth. In one embodiment, the simulated process applies elastic forces between points on a surface of the shape. These elastic forces may reduce the distance between the points on the surface and thus cause the shape to effectively shrink by some amount. In one embodiment, the points on the surface that contact any of the teeth **1**, **2**, **3** are fixed so that no forces are applied to those points.

FIG. **5** illustrates a virtual filler for crowded teeth, in accordance with embodiments. Diagram **500** shows a virtual filler **531** for the crowded teeth (tooth **1**, **2**, and **3**) after the above described operations have been performed. In embodiments, the geometry of the virtual filler **531** may be based on the shape **425**. In some embodiments, shape **425** may be the geometry of the virtual filler **531**. In other embodiments, the geometry of the virtual filler **531** may be determined by smoothing the shape **425** (e.g., the shape may be smoothed to reduce the number of edges or vertices). In embodiments, the virtual filler **531** is part of a virtual model **201** of a dental arch. The virtual model **201** may be updated to include the virtual filler **531** based on the determined geometry. The geometry may include the 3D shape of the virtual filler **531** as well as the location of the virtual filler with respect to the teeth in the virtual model. It may be noted that the virtual model **201** may be used to determine any number of sets of crowded teeth. For each set of crowded teeth, a virtual filler may be generated as described herein. Each virtual filler for the different sets of crowded teeth may be included in the virtual model **201** of the dental arch. In embodiments, a physical mold of the dental arch may be fabricated based on the virtual model **201** that includes the one or more virtual fillers for crowded teeth.

FIGS. **6**A-**6**B illustrate a flow diagram for a method **600** of creating a virtual filler for crowded teeth, in accordance with one embodiment. One or more operations of method **600** are performed by processing logic of a computing device. The processing logic may include hardware (e.g., circuitry, dedicated logic, programmable logic, microcode, etc.), software (e.g., instructions executed by a processing device), firmware, or a combination thereof. For example, one or more operations of method **600** may be performed by a processing device executing a computer aided drafting (CAD) program or module such as a virtual filler module **1450**. Elements of the previous figures may be used to help illustrate method **600**. It may be appreciated that the in some implementations, method **600** may include the same, different, fewer, or greater operations performed in any order.

In embodiments, processing logic in performing method **600** begins at block **605** by detecting three or more adjacent teeth in a virtual model. For example, processing logic may scan the virtual model **201** to detect a group of three teeth that are directly adjacent to one another. At block **610**, processing logic determines whether the teeth are crowded teeth based on a crowding metric indicative of an amount of overlap between the teeth (e.g., as described with reference to FIG. **2**). Responsive to determining that the teeth are not crowded teeth (e.g., comparing characteristics of the teeth to a criterion), processing logic may return to block **605** to determine whether other teeth of a dental arch are crowded teeth. Responsive to determining that the teeth are crowded teeth, processing logic moves to block **615**. At block **615**, processing logic determines a respective portion of each of the teeth on which a virtual filler is to contact. The portions of the teeth on which the virtual filler is to contact are determined as described with reference to FIG. **3**.

At block **620**, processing logic determines whether a clinical feature contacts a first section of any of the respective portions of the teeth. It may be noted that processing logic may also detect a clinical features on at least one of the teeth prior to the determining of block **620**. For example, a feature of a virtual model **201** may be labeled as a clinical feature and processing logic may use location information to locate the clinical feature on the virtual model. Responsive to determining that a clinical feature does not contact a first section of any of the respective portions of the teeth, processing logic moves to block **630**. Responsive to determining that the clinical feature contacts a first section of any of the respective portions of the teeth, processing logic moves to block **625**. At block **625**, processing logic removes the first section from the respective portion of an associated tooth of the teeth.

At block **630**, processing logic determines whether the incisal areas contact a second section of any of the respective portions of the teeth. It may be noted that processing logic may also determine the incisal areas of the teeth prior to the determining of block **630**. For example, a surface of tooth of a virtual model **201** may be labeled as an incisal area and processing logic may use location information to locate the incisal area on the specific tooth of virtual model. Responsive to determining that an incisal area does not contact a second section of any of the respective portions of the teeth, processing logic moves to block **640**. Responsive to determining that an incisal area contacts a second section of any of the respective portions of the teeth, processing logic moves to block **635**. At block **635**, processing logic removes

the second section from the respective portion of an associated tooth of the teeth. At block **640**, processing logic determines a shape that encloses the respective portion of each of the teeth (after the regions that contacted clinical features and/or incisal areas have been removed). The shape represents an initial shape of the virtual filler.

Method **600** moves from block **640** of FIG. **6**A to block **645** of FIG. **6**B. At block **645**, processing logic determines an intersection between the gingival region and the shape of the virtual filler. At block **650**, processing logic modifies, based on the intersection, the shape of the virtual filler. The shape of the virtual filler is adjusted as described above with reference to FIG. **4**. In one embodiment, at block **655**, processing logic simulates a thermoforming process on the shape that encloses the portion of each of the teeth. At block **660**, processing logic modifies the shape based on the simulated thermoforming process.

At block **665**, processing logic determines a geometry of the virtual filler based on the shape. At block **670**, processing logic updates the virtual model to include the virtual filler based on the determined geometry. Alternatively, the virtual model may be updated at one or more of blocks **640**-**660** to include the virtual model. In such an embodiment, blocks **665** and/or **670** may be omitted. At block **675**, processing logic fabricates a physical mold of the dental arch using the updated virtual model. This may include outputting a file that contains instructions for fabricating the dental arch with the virtual filler to a rapid prototyping machine. The rapid prototyping machine (e.g., an SLA machine) may then manufacture the physical model from the file. The physical mold includes material in an area of the virtual filler.

A second technique for generating virtual fillers may be used for virtual fillers between pairs of adjacent teeth that are not crowded.

FIG. **7** illustrates a virtual model of dental arches with two adjacent teeth with and without virtual fillers, in accordance with embodiments. Diagram **700** shows a virtual model **701**A of a dental arch without virtual fillers and a virtual model **701**B of a dental arch with virtual fillers, such as virtual filler **703**. In embodiments, two adjacent teeth may refer to any two teeth that are directly adjacent to one another (i.e., no intervening teeth). The distance between the two adjacent teeth (also referred to as "adjacent teeth" herein, unless otherwise described) may be a characteristic of the adjacent teeth. Adjacent teeth that are directly adjacent teeth may be another characteristic. Additionally, another characteristic of adjacent teeth may be that the two teeth are not part of a crowded tooth structure, as described herein. In some embodiments, the distance between the adjacent teeth may be compared to a criterion, such as a threshold (e.g., distance in millimeters (mm)), to determine whether the teeth are adjacent teeth. For example, two teeth that are directly adjacent and have a distance between the two teeth of less than X millimeters may be considered adjacent teeth. It may be noted that all the teeth of virtual model **701**A may be checked to determine whether the pairs of adjacent teeth satisfy the criterion for adjacent teeth. Responsive to satisfying the criterion, virtual filler module **1450** may generate a virtual filler for identified pairs of adjacent teeth, as described herein. Adjacent teeth **733** is an example of two adjacent teeth that fulfill the criterion and will be used in the following description to describe the formation of a virtual filler for adjacent teeth.

FIG. **8** illustrates a plane that intersects a front and a rear of a tooth of two adjacent teeth, in accordance with some embodiments. Diagram **800** and **850** show adjacent teeth **733** of FIG. **7** from a front-facing perspective and a top-down perspective, respectively. Adjacent teeth **733** are also referred to as tooth **3** and tooth **4**. In embodiments, a virtual filler module **1450** detects that tooth **3** is adjacent tooth **4** in the virtual model **701**. In embodiments, virtual filler module **1450** determines a plane **835** (e.g., first plane) that intersects a front **839** and a rear **841** of tooth **3** and a plane **837** (e.g., second plane) that intersects the front and rear of tooth **4**. Tooth orientation **845** is provided to illustrate the relative orientation of tooth **3** and tooth **4** with respect to diagram **800**. It may be appreciated that the tooth orientation **845** may be used throughout the disclosure to describe the relative orientation of respective teeth, i.e., top surface, bottom surface, rear **841** surface, front **839** surface, and side surfaces. It may be noted that tooth **3** and **4** as described with respect to FIGS. **7**-**12** refer to the respective teeth (e.g., adjacent teeth **733**) of virtual model **701**B of dental arch of FIG. **7**.

In embodiments, determining a plane **835** that intersects a front **839** (i.e., front surface) and a rear **841** (i.e., rear surface) of tooth **3** includes generating a three-dimensional (3D) coordinate system **843** with respect to the tooth **3**. The z-axis of the 3D coordinate system **843** intersects a bottom portion and a top portion of the tooth **3** (see tooth orientation **845**). The y-axis of the 3D coordinate system **843** extends in a direction of the second tooth. Virtual filler module **1450** determines a first point (e.g., P_{t2}) and a second point (e.g., P_{b2}) within the tooth **3**. The first point (e.g., P_{t2}) and a second point (e.g., P_{b2}) lay along the yz-plane **847**. Virtual filler module **1450** may generate plane **835** so that it contains the first point (e.g., P_{t2}) and a second point (e.g., P_{b2}) and is perpendicular to yz-plane **847**. It may be noted that similar operations may be performed on tooth **4** to find plane **837**.

In embodiments, determining a plane **835** that intersects a front **839** and a rear **841** of tooth **3** includes generating a three-dimensional (3D) coordinate system **843** with respect to the tooth **3**. Virtual filler module **1450** may generate a spline **851** using at least four control points: two points at the centers of tooth **3** and tooth **4** (P_1 and P_4, respectively) and the proximal points (P_2 and P_3). The proximal points may be a point on each tooth **3** and **4** that would touch or otherwise align if tooth **3** and **4** where properly aligned (e.g., target positions). Of note, "d" may be the inverse of spline direction and "c_0" may be the center of the tooth offset from the top surface of the tooth (e.g., ⅓ the distance from top to bottom of the tooth). A line through c_0 may be drawn that is parallel the z-axis. Virtual filler module **1450** may find points (P_{b0} and P_{t0}) that intersect the top and bottom surface of tooth **3** and lay along a line drawn through c_0. Point P_{to} may be shifted down from the top of tooth **3** (e.g., shift of 7.0 mm but no more than ⅓ tooth height). Point Pbo may be shifted from the bottom of tooth (e.g., shift of 1.5 mm but no more than ⅓ tooth height). Virtual filler module **1450** may project direction d onto the tooth xy-plane obtaining direction d'. Virtual filler module **1450** may project p_m and p_{b0} onto the surface of tooth **3** along d' to obtain points p_{t1} and p_{b1}. Points p_{t1} and p_{b1} may be shifted towards the center of tooth **3** along d to obtain points p_{t2} and p_{b2}. For example, points p_{t1} and p_{b1} may be shifted towards the center 20% of tooth width along d' to obtain points p_{t2} and p_{b2}. Plane **835** may be generated so that plane **835** contains points p_{t2} and p_{b2} and is perpendicular to plane containing p_{t2}, p_{b2} and d' (e.g., yz-plane **847**). It may be noted that similar operations may be performed on tooth **4** to find plane **837**.

FIG. **9** illustrates a contour on a plane that intersects a front and a rear of a tooth of two adjacent teeth, in accordance with some embodiments. Diagram **900** shows contour **953** that is projected on plane **834** of FIG. **8** within tooth **3**.

It may be noted that for purposes of illustration, the contour **953** of tooth **3** is described, and the operations described herein may be applied to generate another contour for tooth **4**. It may also be noted that the contours, such as contour **953**, may form the sides of the virtual filler, and are approximately aligned parallel with the sides of the respective tooth. In embodiments, virtual filler module **1450** generates a first contour (e.g., contour **953**) within tooth **3** and on the plane **834** and a second contour within tooth **4** and on plane **837** of FIG. **8**. In embodiments, generating a contour **953** within tooth **3** where contour **953** is on plane **834** includes determining a third point (e.g., origin point "o") that is between the first point (e.g., p_{t2}) and the second point (p_{b2}) and on the yz-plane **847** of FIG. **8**. Virtual filler module **1450** may determine multiple lines (e.g., line **957**) from the third point (e.g., point "o") to a surface **955** of tooth **3**. Each of the multiple lines extends from the third point (e.g., point "o") to a different point on the surface **955** of the tooth **3**. Virtual filler module **1450** determines multiple boundary points (e.g., boundary point **959**). Each of the boundary points are located on a respective one of the lines a distance from the surface **955** of tooth **3**. Virtual filler module **1450** connects the boundary points to form the contour **953**.

In some embodiments, virtual filler module **1450** may determine the contour **953** by letting the z-axis be a projection of tooth basis z-axis onto plane **835**. Virtual filler module **1450** may let the y-axis plane be the plane normal to plane **835** and pointing from the tooth **3** to tooth **4**. Virtual filler module **1450** may define an operator (e.g., project (point, angle)) as follows: Virtual filler module **1450** may take a ray laying in the plane **835** with origin in point (e.g., point origin "o") and having an angle between x axis and ray's direction. Point may refer to the projection center, while angle may refer to arbitrary parameters (e.g., selected by an administrator). Virtual filler module **1450** projects the ray onto the surface **955** of the tooth **3** and takes the projection point (e.g., point that intersects the surface **955** of tooth **3**). Virtual filler module **1450** may shift the projection point back towards point a distance from the surface **955** but not more than a proportion of the distance from point to the surface **955** along the ray.

In embodiments, virtual filler module **1450** may obtain points p_1=project (p_{b2}, 0), p_2=project (p_{b2}, $\pi/2$), and p_3=project (p_{b2}, π). Virtual filler module **1450** may find the projection center o=HEIGHT_PROPORTION*p_{b2}+(1−HEIGHT_PROPORTION)*p_{t2}, where HEIGHT_PROPORTION=1/3. Virtual filler module **1450** lets α_i be the angle between the ray o−p_i and the x-axis. Virtual filler module **1450** obtains other boundary points using a recursive algorithm as follows: take two angles β_1 and β_2 (the algorithm is invoked twice for pairs a_1, π and π, α_3) with corresponding boundary points b_1 and b_2. If cos ($\beta_2-\beta_1$)<MAX_COS=0.99 and $|b_2-b_1|$>MESH_EDGE_LENGTH=1 mm, then calculate $\beta=(\beta_2-\beta_1)$ and a new boundary point b=project (o, β). The same algorithm is applied to angle pairs β_1, β and β, β_2.

FIG. **10** illustrates a construction of a surface of a virtual filler, in accordance with some embodiments. Diagram **1000** shows multiple stages (e.g., stages A-E) of constructing a surface of a virtual filler **1071** by connecting contour **953** of tooth **3** to contour **1061** of tooth **2**. It may be noted that some or all the stages may be implemented in some embodiments. In one embodiment, connecting contour **953** to contour **1061** to construct a surface **1063** of a virtual filler **1071** includes connecting boundary points (e.g., boundary point **1065**) of contour **953** with boundary points of contour **1061** (e.g., stage A). Virtual filler module **1450** may perform stage C to smooth surface **1063** of the virtual filler **1071** (e.g., reduce rough edges or vertices). Virtual filler module **1450** may perform stage D to fill the surface **1063** of virtual filler **1071**. In embodiments, the connecting of the contours **953** and **1061** and generation of the surface forms or completes the geometry of virtual filler **1071**.

In some embodiments, to connect contour **953** to the contour **1061** to construct a surface **1063** of the virtual filler **1071**, virtual filler module **1450** may connect the boundary points on contour **953** with the boundary points on contour **1061** so that the bottom boundary points (e.g., boundary point **1065** and boundary point **1069**) are pairwise connected and the other boundary points (e.g., boundary point **1067**) are paired based on the distance between the boundary points (e.g., stage A). At stage B, the connecting edges are flipped until the surface **1063** has a minimal surface area. Flipping a connecting edge may refer to replacing an edge by another edge. For example, given two adjacent triangles ABC and BCD (sharing edge BC), edge BC may be flipped by replacing edge BC with another edge AD. At stage C, the surface **1063** of virtual filler **1071** is refined and smoothed. In embodiments, refined may include splitting in half all edges longer than a threshold (e.g., 1 mm), starting from the longest edge until there are no edges longer than the threshold. In embodiments, smoothing may include multiple iterations (e.g., **10** iterations) of smoothing, such as Lapacian smoothing. At stage D, the virtual filler **1071** is filled. At stage E, the surface **1063** of virtual filler **1071** is decimated with a mesh tolerance (e.g., mesh tolerance=0.1 mm) to remove extra vertices. In embodiments, decimation of a mesh may include removing some vertices so that the surface **1063** is similar to the surface **1063** at stage C, for example. In embodiments, the completion of one or more of the stages A-D forms or completes the geometry (e.g. initial geometry) of virtual filler **1071**. In other embodiments, the geometry of the virtual filler **1071** may be further updated or modified, as described below.

In some embodiments, the geometry of the virtual filler **1071** may be modified in view of a clinical feature. In an embodiment, virtual filler module **1450** may detect a clinical feature on tooth **3** or tooth **4**. Virtual filler module **1450** may determine if the clinical features contact the virtual filler **1071**. Responsive to determining the clinical feature contacts the virtual filler **1071**, virtual filler module **1450** may remove the part of the virtual filler **1071** that is in contact with the clinical feature.

In some embodiments, the geometry of the virtual filler **1071** may be modified in view of an incisal area. In an embodiment, virtual filler module **1450** may determine an incisal area on tooth **3** or tooth **4**. Virtual filler module **1450** may determine whether the incisal area contacts the virtual filler **1071**. Responsive to determining that the incisal area contacts the virtual filler **1071**, virtual filler module **1450** may remove the part of the virtual filler **1071** that contacts the incisal area.

FIG. **11** illustrates a geometry a virtual filler for adjacent teeth, in accordance with some embodiments. Diagram **1100** illustrates multiple views of the virtual filler **1071** of FIG. **10** orientated within tooth **3** and tooth **4**. Diagram **1100**A shows a side-view of virtual filler **1071** with tooth **3** in front of tooth **4**. It may be noted that the virtual filler **1071** is encased by tooth **3** and tooth **4** on the respective ends of the virtual filler **1071**. The gap between the tooth **3** and tooth **4** may be an area of the virtual filler **1071** that is exposed externally. Diagram **1100**B show a rear-view of the virtual filler **1071**. Diagram **1100**C shows a top-view of virtual filler **1071** and diagram **1100**D shows the bottom-view of the virtual filler **1071**. It may be noted that diagram **1100** illustrates the

geometry (e.g., shape) of the virtual filler **1071**, which may also include the location of the virtual filler **1071** with respect to tooth **3** and tooth **4** as well as the location of virtual filler **1071** with respect to the greater dental arch. In some embodiments, the location of the virtual filler **1071** in the virtual model may be determined based on the plane **835** and **837** of FIG. **8**.

It may be noted that the geometry (e.g., sides of the virtual filler **1071** are located within the tooth **3** and **4**) allows virtual filler **1071** to be used for the fabrication of multiple sequential physical molds in a series. For example, as the teeth shift position from one physical mold to the next, the gap between the teeth also changes. Virtual filler **1071** may be re-used as the gap changes. For instance, as the gap between the teeth increases more of virtual filler **1071** is exposed.

FIG. **12** illustrates a flow diagram for a method of creating a virtual filler for adjacent teeth, in accordance with one embodiment. One or more operations of method **1200** are performed by processing logic of a computing device. The processing logic may include hardware (e.g., circuitry, dedicated logic, programmable logic, microcode, etc.), software (e.g., instructions executed by a processing device), firmware, or a combination thereof. For example, one or more operations of method **1200** may be performed by a processing device executing a computer aided drafting (CAD) program or module such as a virtual filler module **1450**. Elements of the previous figures may be used to help illustrate method **1200**. It may be appreciated that the in some implementations, method **1200** may include the same, different, fewer, or greater operations performed in any order.

In an embodiment, processing logic implementing method **1200** begins at block **1205** where processing logic detects a first tooth adjacent to a second tooth in a virtual model. At block **1210**, processing logic determines a first plane that intersects a front and a rear of the first tooth and a second plane that intersects a front and a rear of the second tooth (e.g., as described with reference to FIG. **8**). At block **1215**, processing logic generates a first contour within the first tooth and on the first plane and a second contour within the second tooth and on the second plane (e.g., as described with reference to FIG. **9**). The first contour and the second contour are respective sides of the virtual filler. At block **1220**, processing logic connects the first contour to the second contour to construct a surface of the virtual filler (e.g., as described with reference to FIG. **10**).

At block **1225**, processing logic detects a clinical feature and determines whether the clinical feature contacts the virtual filler. Responsive to determining that the clinical feature does not contact the virtual filler, processing logic moves to block **1235**. Responsive to determining that the clinical feature does contact the virtual filler, processing logic moves to block **1230**. At block **1230**, processing logic removes a first part of the virtual filler in contact with the clinical feature (e.g., as described with reference to FIG. **10**).

At block **1235**, processing logic detects an incisal area of the first tooth and the second tooth and determines whether the incisal area contacts the virtual filler. Responsive to determining that the incisal area does not contact the virtual filler, processing logic moves to block **1245**. Responsive to determining that the incisal area does contact the virtual filler, processing logic moves to block **1240**. At block **1240**, processing logic, removes the second part of the virtual filler in contact with the incisal area (e.g., as described with reference to FIG. **10**).

At block **1245**, processing logic determines the geometry of the virtual filler. At block **1250**, processing logic updates the virtual model to include the virtual filler based on the determined geometry. At block **1255**, processing logic fabricates a physical mold of the dental arch using the updated virtual model. The physical mold includes material in an area of the virtual filler.

FIG. **13** illustrates a flow diagram for a method of creating a virtual filler for adjacent teeth or crowded teeth, in accordance with one embodiment. One or more operations of method **1300** are performed by processing logic of a computing device. The processing logic may include hardware (e.g., circuitry, dedicated logic, programmable logic, microcode, etc.), software (e.g., instructions executed by a processing device), firmware, or a combination thereof. For example, one or more operations of method **1300** may be performed by a processing device executing a computer aided drafting (CAD) program or module such as a virtual filler module **1450**. Elements of the previous figures may be used to help illustrate method **1300**. It may be appreciated that the in some implementations, method **1300** may include the same, different, fewer, or greater operations performed in any order.

In an embodiment, processing logic performing the method **1300** begins at block **1305** to detect two or more adjacent teeth in a virtual model. At block **1310**, processing logic determines a characteristic of the teeth indicative of a spatial relationship between the teeth. At block **1315**, processing logic determines that the characteristic satisfies a criterion for a virtual filler. For example, processing logic may determine that the characteristics satisfy a criterion for crowded teeth or adjacent teeth. At block **1315**, processing logic determines a geometry of the virtual filler based on the spatial relationship between the teeth. For example, processing logic may determine the geometry of the virtual filler for crowded teeth or adjacent teeth, as described herein. For adjacent teeth that satisfy a first adjacent teeth virtual filler criterion, method **1200** may be performed to generate a virtual filler. For adjacent teeth that satisfy a second crowded teeth virtual filler criterion, method **600** may be performed to generate a virtual filler. Notably, method **1200** may be performed to generate one or more virtual fillers for a virtual 3D model of a dental arch and method **600** may be performed to generate one or more virtual fillers for the same dental arch.

FIG. **14** illustrates a diagrammatic representation of a machine in the example form of a computing device within which a set of instructions, for causing the machine to perform any one or more of the methodologies discussed with reference to the methods **600**, **1200**, or **1300** of FIG. **6**A-B, **12**, or **13**, respectively. In embodiments, the machine may be connected (e.g., networked) to other machines in a Local Area Network (LAN), an intranet, an extranet, or the Internet. For example, the machine may be networked to a rapid prototyping apparatus such as a 3D printer or SLA apparatus. The machine may operate in the capacity of a server or a client machine in a client-server network environment, or as a peer machine in a peer-to-peer (or distributed) network environment. The machine may be a personal computer (PC), a tablet computer, a set-top box (STB), a Personal Digital Assistant (PDA), a cellular telephone, a web appliance, a server, a network router, switch or bridge, or any machine capable of executing a set of instructions (sequential or otherwise) that specify actions to be taken by that machine. Further, while only a single machine is illustrated, the term "machine" shall also be taken to include any collection of machines (e.g., computers) that individually or

jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein.

The example computing device **1400** includes a processing device **1402**, a main memory **1404** (e.g., read-only memory (ROM), flash memory, dynamic random access memory (DRAM) such as synchronous DRAM (SDRAM), etc.), a static memory **1406** (e.g., flash memory, static random access memory (SRAM), etc.), and a secondary memory (e.g., a data storage device **1428**), which communicate with each other via a bus **1408**.

Processing device **1402** represents one or more general-purpose processors such as a microprocessor, central processing unit, or the like. More particularly, the processing device **1402** may be a complex instruction set computing (CISC) microprocessor, reduced instruction set computing (RISC) microprocessor, very long instruction word (VLIW) microprocessor, processor implementing other instruction sets, or processors implementing a combination of instruction sets. Processing device **1402** may also be one or more special-purpose processing devices such as an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a digital signal processor (DSP), network processor, or the like. Processing device **1402** is configured to execute the processing logic (instructions **1426**) for performing operations discussed herein.

The computing device **1400** may further include a network interface device **1422** for communicating with a network **1464**. The computing device **1400** also may include a video display unit **1410** (e.g., a liquid crystal display (LCD) or a cathode ray tube (CRT)), an alphanumeric input device **1412** (e.g., a keyboard), a cursor control device **1414** (e.g., a mouse), and a signal generation device **1420** (e.g., a speaker).

The data storage device **1428** may include a machine-readable storage medium (or more specifically a non-transitory computer-readable storage medium) **1424** on which is stored one or more sets of instructions **1426** embodying any one or more of the methodologies or functions described herein. A non-transitory storage medium refers to a storage medium other than a carrier wave. The instructions **1426** may also reside, completely or at least partially, within the main memory **1404** and/or within the processing device **1402** during execution thereof by the computer device **1400**, the main memory **1404** and the processing device **1402** also constituting computer-readable storage media.

The computer-readable storage medium **1424** may also be used to store one or more virtual 3D models (also referred to as electronic models) and/or a virtual filler module **1450**, which may perform one or more of the operations of methods **600**, **1200**, or **1300** described with reference to FIG. **6**A-B, **12**, or **13**. The computer readable storage medium **1424** may also store a software library containing methods that call a virtual filler module **750**. While the computer-readable storage medium **1424** is shown in an example embodiment to be a single medium, the term "computer-readable storage medium" should be taken to include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) that store the one or more sets of instructions. The term "computer-readable storage medium" shall also be taken to include any medium that is capable of storing or encoding a set of instructions for execution by the machine and that cause the machine to perform any one or more of the methodologies of the present disclosure. The term "computer-readable storage medium" shall accordingly be taken to include, but not be limited to, solid-state memories, and optical and magnetic media.

In the foregoing description, numerous details are set forth. It will be apparent, however, to one of ordinary skill in the art having the benefit of this disclosure, that the present disclosure may be practiced without these specific details. In some instances, well-known structures and devices are shown in block diagram form, rather than in detail, in order to avoid obscuring the present disclosure.

Some portions of the detailed description have been presented in terms of algorithms and symbolic representations of operations on data bits within a computer memory. These algorithmic descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of operations leading to a result. The operations are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. It has proven convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like.

It may be borne in mind, however, that all of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise, it is appreciated that throughout the description, discussions utilizing terms such as "detecting," "updating," "determining," "fabricating," "removing," "modifying," "simulating," "projecting," "connecting," or the like, refer to the actions and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (e.g., electronic) quantities within the computer system memories or registers into other data similarly represented as physical quantities within the computer system memories or registers or other such information storage, transmission or display devices.

The present disclosure also relates to an apparatus for performing the operations herein. This apparatus may be specially constructed for the required purposes, or it may include a general purpose computer selectively activated or reconfigured by a computer program stored in the computer. Such a computer program may be stored in a computer readable storage medium, such as, but not limited to, any type of disk including a floppy disk, an optical disk, a compact disc read-only memory (CD-ROM), a magnetic-optical disk, a read-only memory (ROM), a random access memory (RAM), an erasable programmable read-only memory (EPROM), an electrically erasable programmable read-only memory (EEPROM), a magnetic or optical card, or any type of media suitable for storing electronic instructions.

The words "example" or "exemplary" are used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as "example" or "exemplary" is not necessarily to be construed as preferred or advantageous over other aspects or designs. Rather, use of the words "example" or "exemplary" is intended to present concepts in a concrete fashion. As used in this application, the term "or" is intended to mean an inclusive "or" rather than an exclusive "or." That is, unless specified otherwise, or clear from context, "X includes A or B" is intended to mean any of the natural inclusive permutations. That is, if X

includes A; X includes B; or X includes both A and B, then "X includes A or B" is satisfied under any of the foregoing instances. In addition, the articles "a" and "an" as used in this application and the appended claims may generally be construed to mean "one or more" unless specified otherwise or clear from context to be directed to a singular form. Moreover, use of the term "an implementation" or "one implementation" or "an implementation" or "one implementation" throughout is not intended to mean the same implementation or implementation unless described as such. The terms "first," "second," "third," "fourth," etc. as used herein are meant as labels to distinguish among different elements and may not necessarily have an ordinal meaning according to their numerical designation.

It is to be understood that the above description is intended to be illustrative, and not restrictive. Many other embodiments will be apparent upon reading and understanding the above description. Although embodiments of the present disclosure have been described with reference to specific example embodiments, it will be recognized that the disclosure is not limited to the embodiments described, but can be practiced with modification and alteration within the spirit and scope of the appended claims. Accordingly, the specification and drawings are to be regarded in an illustrative sense rather than a restrictive sense. The scope of the disclosure should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

What is claimed is:

1. A method comprising:

determining three or more adjacent teeth in a virtual model of a dental arch;

determining whether the teeth are crowded teeth based on a crowding metric indicative of an amount of overlap between the teeth;

responsive to determining that the teeth are crowded teeth, determining a respective portion of each of the teeth on which a virtual filler is to contact;

determining a shape that encloses the respective portion of each of the teeth;

determining, by a processing device, a geometry of the virtual filler based on the shape;

updating the virtual model to include the virtual filler based on the determined geometry; and

fabricating a physical mold of the dental arch using the updated virtual model, wherein the physical mold comprises material in an area of the virtual filler,

wherein the physical mold of the dental arch designed fabricated based on the updated virtual model reduces retentive or stress areas corresponding to a fabrication of orthodontic aligners with the physical mold.

2. The method of claim **1**, further comprising:

determining a clinical feature on at least one of the teeth;

determining whether the clinical feature contacts a first section of any of the respective portions of the teeth; and

responsive to determining that the clinical feature contacts the first section, removing the first section from the respective portion of an associated tooth of the teeth.

3. The method of claim **1**, wherein the virtual model comprises a gingival region, the method further comprising:

determining an intersection between the gingival region and the shape; and

modifying, based on the intersection, the shape of the virtual filler to determine the geometry of the virtual filler.

4. The method of claim **1**, further comprising:

simulating a thermoforming process on the shape that encloses the portion of each of the teeth; and

modifying, based on the simulated thermoforming process, the shape to determine the geometry of the virtual filler.

5. The method of claim **1**, wherein the virtual model is a virtual model of a dental arch, and wherein determining whether the teeth are crowded teeth comprises:

determining a curvature of the dental arch;

determining a plane tangential to a point on the curvature;

projecting contours of the teeth on the plane;

determining the crowding metric by measuring an amount of overlap of the contours of the teeth; and

comparing the crowding metric to a threshold, wherein determining the crowding metric is greater than the threshold indicates the teeth are crowded teeth.

6. A method comprising:

determining a first tooth adjacent to a second tooth in a virtual model of a dental arch;

determining a first plane that intersects a front and a rear of the first tooth and a second plane that intersects a front and a rear of the second tooth;

generating a first contour within the first tooth and on the first plane and a second contour within the second tooth and on the second plane, wherein the first contour and the second contour are respective sides of a virtual filler;

connecting the first contour to the second contour to construct a surface of the virtual filler;

determining, by a processing device, a geometry of the virtual filler based on the first contour, the second contour and the surface;

updating the virtual model to include the virtual filler based on the determined geometry; and

fabricating a physical mold of the dental arch using the updated virtual model, wherein the physical mold comprises material in an area of the virtual filler,

wherein the physical mold of the dental arch designed fabricated based on the updated virtual model reduces retentive or stress areas corresponding to a fabrication of orthodontic aligners with the physical mold.

7. The method of claim **6**, further comprising

determining a location of the virtual filler in the virtual model based on the determining of the first plane and the second plane.

8. The method of claim **6**, wherein determining a first plane that intersects a front and a rear of the first tooth comprises:

generating a three-dimensional (3D) coordinate system with respect to the first tooth, wherein a z-axis of the 3D coordinate system intersects a bottom portion and a top portion of the tooth, and wherein a y-axis of the 3D coordinate system extends in a direction of the second tooth;

determining a first point and a second point within the first tooth, wherein the first point and the second point lay along a yz-plane; and

generating the first plane containing the first point and the second point, wherein the first plane is perpendicular to the yz-plane.

9. The method of claim **8**, wherein generating a first contour within the first tooth and on the first plane, comprises:

determining a third point that is between the first point and the second point and on the yz-plane;

determining a plurality of lines from the third point to a surface of the first tooth, wherein each of the plurality of lines extends from the third point to a different point on the surface of the first tooth;

determining a plurality of boundary points, wherein each of the boundary points are located on a respective one of the lines a distance from the surface of the tooth; and

connecting the boundary points to form the first contour.

10. The method of claim **6**, wherein connecting the first contour to the second contour to construct a surface of the virtual filler, comprises:

connecting first boundary points of the first contour to second boundary points of the second contour;

smoothing the surface of the virtual filler; and

filling the surface of the virtual filler.

11. The method of claim **6**, further comprising:

determining a clinical feature on at least one of the first tooth or the second tooth;

determining whether the clinical feature contacts the virtual filler; and

responsive to determining that the clinical feature contacts the virtual filler, removing a first part of the virtual filler in contact with the clinical feature.

* * * * *