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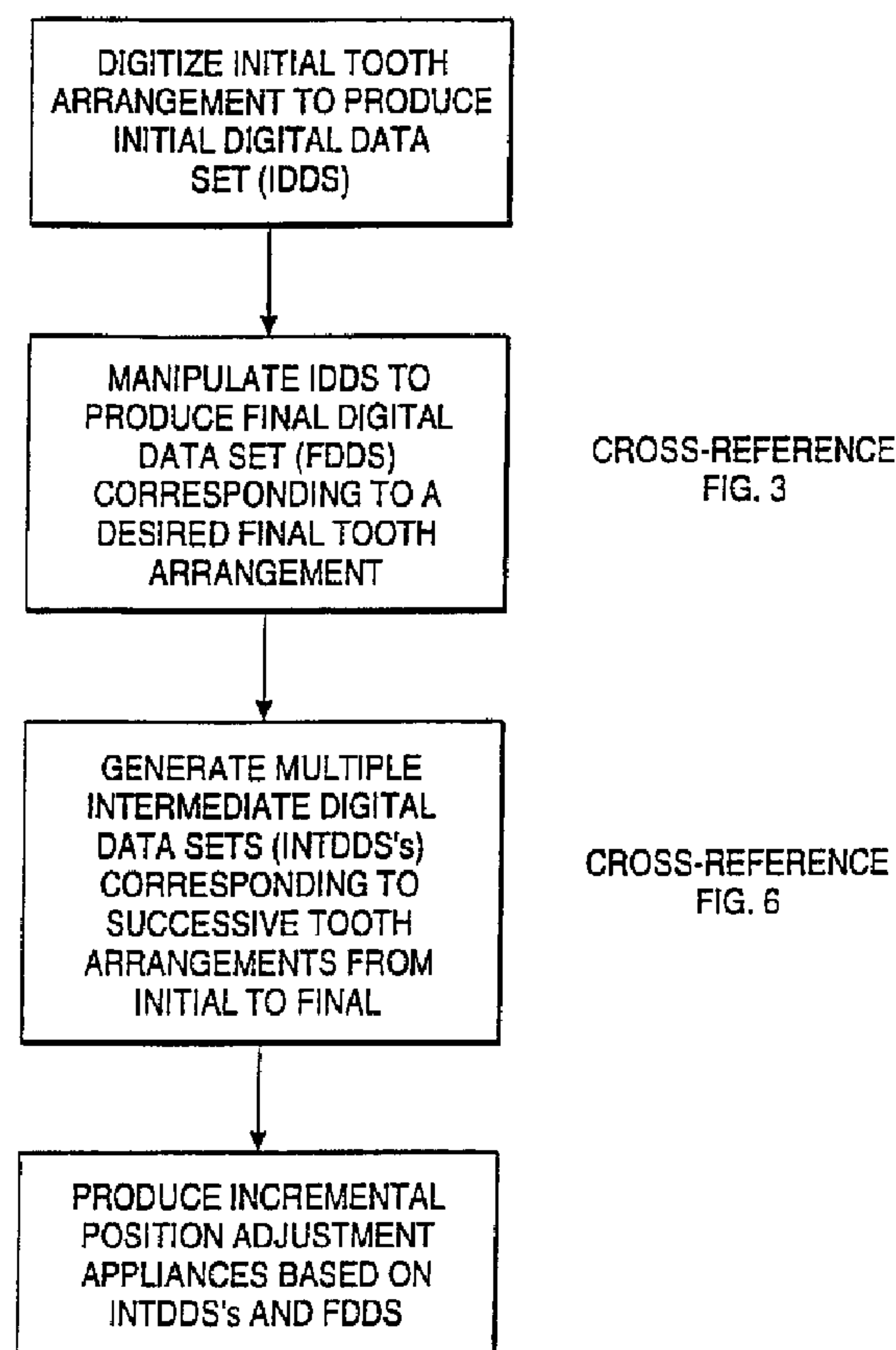
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(54) Titre : PROCÉDE ET SYSTÈME DE REPOSITIONNEMENT PROGRESSIF DES DENTS

(54) Title: METHOD AND APPARATUS FOR PRODUCING A DATA SET REPRESENTING A TOOTH ARRANGEMENT



(57) Abrégé/Abstract:

A method and apparatus for producing a data set representing a desired tooth arrangement is disclosed. The method involves providing a first data set representing an initial tooth arrangement, presenting an image based on the first data set, manipulating the image to reposition individual teeth in the image, and producing a second data set representing the desired tooth arrangement with the repositioned teeth as observed in the image.

ABSTRACT

A method and apparatus for producing a data set representing a desired tooth arrangement is disclosed. The method involves providing a first data set representing an initial tooth arrangement, presenting an image based on the first data set, manipulating the image to reposition individual teeth in the image, and producing a second data set representing the desired tooth arrangement with repositioned teeth as observed in the image.

METHOD AND APPARATUS FOR PRODUCING A DATA SET REPRESENTING A TOOTH ARRANGEMENT

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

The present invention is related generally to the field of orthodontics. More particularly, the present invention is related to a method and system for incrementally moving teeth from an initial tooth arrangement to a final tooth arrangement.

DESCRIPTION OF RELATED ART

Repositioning teeth for aesthetic or other reasons is accomplished conventionally by wearing what are commonly referred to as "braces". Braces comprise a variety of appliances such as brackets, archwires, ligatures, and O-rings. Attaching the appliances to a patient's teeth is a tedious and time consuming enterprise requiring many meetings with the treating orthodontist. Consequently, conventional orthodontic treatment limits an orthodontist's patient capacity and makes orthodontic treatment quite expensive.

Before fastening braces to a patient's teeth, at least one appointment is typically scheduled with the orthodontist, dentist, and/or X-ray laboratory so that X-rays and photographs of the patient's teeth and jaw structure can be taken. Also during this preliminary meeting, or possibly at a later meeting, an alginate mold of the patient's teeth is typically made. This mold provides a model of the patient's teeth that the orthodontist uses in conjunction with the X-rays and photographs to formulate a treatment strategy. The orthodontist then typically schedules one or more appointments during which braces will be attached to the patient's teeth.

At the meeting during which braces are first attached, the teeth surfaces are initially treated with a weak acid. The acid optimizes the adhesion properties of the teeth surfaces

for brackets and bands that are to be bonded to them. The brackets and bands serve as anchors for other appliances to be added later. After the acid step, the brackets and bands are cemented to the patient's teeth using a suitable bonding material. No force-inducing appliances are added until the cement is set. For this reason, it is common for the
5 orthodontist to schedule a later appointment to ensure that the brackets and bands are well bonded to the teeth.

The primary force-inducing appliance in a conventional set of braces is the archwire. The archwire is resilient and is attached to the brackets by way of slots in the brackets. The
10 archwire links the brackets together and exerts forces on them to move the teeth over time. Twisted wires or elastomeric O-rings are commonly used to reinforce attachment of the archwire to the brackets. Attachment of the archwire to the brackets is known in the art of orthodontia as "ligation" and wires used in this procedure are called "ligatures."
The elastomeric O-rings are called "plastics."

15 After the archwire is in place, periodic meetings with the orthodontist are required, during which the patient's braces will be adjusted by installing a different archwire having different force-inducing properties or by replacing or tightening existing ligatures. Typically, these meetings are scheduled every three to six weeks.

20 As the above illustrates, the use of conventional braces is a tedious and time consuming process and requires many visits to the orthodontist's office. Moreover, from the patient's perspective, the use of braces is unsightly, uncomfortable, presents a risk of infection, and makes brushing, flossing, and other dental hygiene procedures difficult.

25 For these reasons, it would be desirable to provide alternative methods and systems for repositioning teeth. Such methods and systems should be economical, and in particular should reduce the amount of time required by the orthodontist in planning and overseeing each individual patient. The methods and systems should also be more acceptable to the
30 patient, in particular being less visible, less uncomfortable, less prone to infection, and

more compatible with daily dental hygiene. At least some of these objectives will be met by the methods and systems of the present invention described hereinafter.

DESCRIPTION OF THE BACKGROUND ART

5 Tooth positioners for finishing orthodontic treatment are described by Kesling in the Am. J. Orthod. Oral. Surg. 31: 297-304 (1945) and 32: 285-293 (1946). The use of silicone positioners for the comprehensive orthodontic realignment of a patient's teeth is described in Warunek et al. (1989) J. Clin. Orthod. 23: 694-700. Clear plastic retainers for finishing and maintaining tooth positions are commercially available from Raintree Essix, Inc.,
10 New Orleans, Louisiana 70125, and Tru-Tain Plastics, Rochester, Minnesota 55902. The manufacture of orthodontic positioners is described in U. S. Patent Nos. 5,186,623; 5,059,118; 5,055,039; 5,035,613; 4,856,991; 4,798,534; and 4,755,139.

Other publications describing the fabrication and use of dental positioners include
15 Kleemann and Janssen (1996) J. Clin. Orthodon. 30: 673-680; Cureton (1996) J. Clin. Orthodon. 30: 390-395; Chiappone (1980) J. Clin. Orthodon. 14: 121-133; Shilliday (1971) Am. J. Orthodontics 59: 596-599; Wells (1970) Am. J. Orthodontics 58: 351-366; and Cottingham (1969) Am. J. Orthodontics 55: 23-31.

20 Kuroda et al. (1996) Am. J. Orthodontics 110: 365-369 describes a method for laser scanning a plaster dental cast to produce a digital image of the cast. See also U. S. Patent No. 5,605,459.

U. S. Patent Nos. 5,533,895; 5,474,448; 5,454,717; 5,447,432; 5,431,562; 5,395,238;
25 5,368,478; and 5,139,419, assigned toOrmco Corporation, describe methods for manipulating digital images of teeth for designing orthodontic appliances.

U. S. Patent No. 5,011,405 describes a method for digitally imaging a tooth and determining optimum bracket positioning for orthodontic treatment. Laser scanning of a
30 molded tooth to produce a three-dimensional model is described in U. S. Patent No.

5,338,198. U. S. Patent NO. 5,452,219 describes a method for laser scanning a tooth model and milling a tooth mold. Digital computer manipulation of tooth contours is described in U. S. Patent Nos. 5,607,305 and 5,587,912. Computerized digital imaging of the jaw is described in U. S. Patent Nos. 5,342,202 and 5,340,309. Other patents of interest include U. S. Patent Nos. 5,549,476; 5,382,164; 5,273,429; 4,936,862; 3,860,803; 3,660,900; 5,645,421; 5,055,039; 4,798,534; 4,856,991; 5,035,613; 5,059,118; 5,186,623; and 4,755,139.

SUMMARY OF THE INVENTION

10 In one aspect, the present invention provides improved methods and systems for repositioning teeth from an initial tooth arrangement to a final tooth arrangement. Repositioning is accomplished with a system comprising a series of appliances configured to receive the teeth in a cavity and incrementally reposition individual teeth in a series of at least three successive steps, usually including at least four successive steps, 15 often including at least ten steps, sometimes including at least twenty-five steps, and occasionally including forty or more steps. Often, the methods and systems will reposition teeth in from ten to twenty-five successive steps, although complex cases involving many of the patient's teeth may take forty or more steps. The successive use of a number of such appliances permits each appliance to be configured to move individual 20 teeth in small increments, typically less than 2 mm, preferably less than 1 mm, and more preferably less than 0.5 mm. These limits refer to the maximum linear translation of any point on a tooth as a result of using a single appliance. The movements provided by successive appliances, of course, will usually not be the same for any particular tooth. Thus, one point on a tooth may be moved by a particular distance as a result of the use of one appliance and thereafter moved by a different distance and/or in a different direction 25 by a later appliance.

The individual appliances may comprise a polymeric shell having the teeth-receiving cavity formed therein, typically by molding as described below. Each individual 30 appliance will be configured so that its tooth-receiving cavity has a geometry

corresponding to an intermediate or end tooth arrangement intended for that appliance. That is, when an appliance is first worn by the patient, certain of the teeth will be misaligned relative to an undeformed geometry of the appliance cavity. The appliance, however, is sufficiently resilient to accommodate or conform to the misaligned teeth, and will apply sufficient resilient force against such misaligned teeth in order to reposition the teeth to the intermediate or end arrangement desired for that treatment step.

Systems according to the present invention may include at least a first appliance having a geometry selected to reposition a patient's teeth from the initial tooth arrangement to a first intermediate arrangement where individual teeth will be incrementally repositioned. The system may further comprise at least one intermediate appliance having a geometry selective to progressively reposition teeth from the first intermediate arrangement to one or more successive intermediate arrangements. The system may still further comprise a final appliance having a geometry selected to progressively reposition teeth from the last intermediate arrangement to the desired final tooth arrangement. In some cases, it will be desirable to form the final appliance or several appliances to over correct the final tooth position, as discussed in more detail below.

As will be described in more detail below in connection with the methods of the present invention, the systems may be planned and all individual appliances fabricated at the outset of treatment, and the appliances may thus be provided to the patient as a single package or system. The order in which the appliances are to be used may be clearly marked, (e. g. by sequential numbering) so that the patient can place the appliances over his or her teeth at a frequency prescribed by the orthodontist or other treating professional. Unlike braces, the patient need not visit the treating professional every time an adjustment in the treatment is made. While the patients will usually want to visit their treating professionals periodically to assure that treatment is going according to the original plan, eliminating the need to visit the treating professional each time an adjustment is to be made allows the treatment to be carried out in many more, but smaller, successive steps while still reducing the time spent by the treating professional

with the individual patient. Moreover, the ability to use polymeric shell appliances which are more comfortable, less visible, and removable by the patient, greatly improves patient compliance, comfort, and satisfaction.

5 According to a method of the present invention, a patient's teeth are repositioned from an initial tooth arrangement to a final tooth arrangement by placing a series of incremental position adjustment appliances in the patient's mouth. Conveniently, the appliances are not affixed and the patient may place and replace the appliances at any time during the procedure. The first appliance of the series will have a geometry selected to reposition
10 the teeth from the initial tooth arrangement to a first intermediate arrangement. After the first intermediate arrangement is approached or achieved, one or more additional (intermediate) appliances will be successively placed on the teeth, where such additional appliances have geometries selected to progressively reposition teeth from the first intermediate arrangement through successive intermediate arrangement (s). The
15 treatment will be finished by placing a final appliance in the patient's mouth, where the final appliance has a geometry selected to progressively reposition teeth from the last intermediate arrangement to the final tooth arrangement. The final appliance or several appliances in the series may have a geometry or geometries selected to over correct the tooth arrangement, i.e. have a geometry which would (if fully achieved) move individual
20 teeth beyond the tooth arrangement which has been selected as the final. Such over correction may be desirable in order to offset potential relapse after the repositioning method has been terminated, i.e. to permit some movement of individual teeth back toward their pre-corrected positions. Over correction may also be beneficial to speed the rate of correction, i.e. by having an appliance with a geometry that is positioned beyond a
25 desired intermediate or final position, the individual teeth will be shifted toward the position at a greater rate. In such cases, treatment can be terminated before the teeth reach the positions defined by the final appliance or appliances. The method will usually comprise placing at least two additional appliances, often comprising placing at least ten additional appliances, sometimes placing at least twenty-five additional appliances, and
30 occasionally placing at least forty or more additional appliances. Successive appliances

will be replaced when the teeth either approach (within a preselected tolerance) or have reached the target end arrangement for that stage of treatment, typically being replaced at an interval in the range from 2 days to 20 days, usually at an interval in the range from 5 days to 10 days.

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Often, it may be desirable to replace the appliances at a time before the end tooth arrangement of that treatment stage is actually achieved. It will be appreciated that as the teeth are gradually repositioned and approach the geometry defined by a particular appliance, the repositioning force on the individual teeth will diminish greatly. Thus, it may be possible to reduce the overall treatment time by replacing an earlier appliance with the successive appliance at a time when the teeth have been only partially repositioned by the earlier appliance. Thus, the FDDS can actually represent an over correction of the final tooth position. This both speeds the treatment and can offset patient relapse.

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In general, the transition to the next appliance can be based on a number of factors. Most simply, the appliances can be replaced on a predetermined schedule or at a fixed time interval (i.e. number of days for each appliance) determined at the outset based on an expected or typical patient response. Alternatively, actual patient response can be taken into account, e. g. a patient can advance to the next appliance when that patient no longer perceives pressure on their teeth from a current appliance, i.e. the appliance they have been wearing fits easily over the patient's teeth and the patient experiences little or no pressure or discomfort on his or her teeth. In some cases, for patients whose teeth are responding very quickly, it may be possible for a treating professional to decide to skip one or more intermediate appliances, i.e. reduce the total number of appliances being used below the number determined at the outset. In this way, the overall treatment time for a particular patient can be reduced.

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In another aspect, methods of the present invention comprise repositioning teeth using appliances comprising polymeric shells having cavities shaped to receive and resiliently

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reposition teeth to produce a final tooth arrangement. The present invention provides improvements to such methods which comprise determining at the outset of treatment geometries for at least three of the appliances which are to be worn successively by a patient to reposition teeth from an initial tooth arrangement to the final tooth arrangement. Preferably, at least four geometries will be determined in the outset, often at least ten geometries, frequently at least twenty-five geometries, and sometimes forty or more geometries. Usually, the tooth positions defined by the cavities in each successive geometry differ from those defined by the prior geometry by no more than 2 mm, preferably no more than 1 mm, and often no more than 0.5 mm, as defined above.

In yet another aspect, methods are provided for producing a digital data set representing a final tooth arrangement. The methods comprise providing an initial data set representing an initial tooth arrangement, and presenting a visual image based on the initial data set. The visual image is then manipulated to reposition individual teeth in the visual image. A final digital data set is then produced which represents the final tooth arrangement with repositioned teeth as observed in the visual image. Conveniently, the initial digital data set may be provided by conventional techniques, including digitizing X-ray images, images produced by computer-aided tomography (CAT scans), images produced by magnetic resonance imaging (MRI), and the like. Preferably, the images will be three-dimensional images and digitization may be accomplished using conventional technology. Usually, the initial digital data set is provided by producing a plaster cast of the patient's teeth (prior to treatment) by conventional techniques. The plaster cast so produced may then be scanned using laser or other scanning equipment to produce a high resolution digital representation of the plaster cast of the patient's teeth. Use of the plaster cast is preferred since it does not expose the patient to X-rays or subject the patient to the inconvenience of an MRI scan.

In one embodiment, a wax bite is also obtained from the patient using standard methods. The wax bite allows plaster casts of a patient's upper and lower dentition to be placed relative to one another in the centric occlusal position. The pair of casts are then scanned

to provide information on the relative position of the jaw in this position. This information is then incorporated into the IDDS for both arches.

Once the digital data set is acquired, an image can be presented and manipulated on a
5 suitable computer system equipped with computer-aided design software, as described in
greater detail below. The image manipulation will usually comprise defining boundaries
about at least some of the individual teeth, and causing the images of the teeth to be
moved relative to the jaw and other teeth by manipulation of the image via the computer.
Methods are also provided for detecting cusp information for the teeth. The image
10 manipulation can be done entirely subjectively, i.e. the user may simply reposition teeth
in an aesthetically and/or therapeutically desired manner based on observation of the
image alone. Alternatively, the computer system could be provided with rules and
algorithms which assist the user in repositioning the teeth. In some instances, it will be
possible to provide rules and algorithms which reposition the teeth in a fully automatic
15 manner, i.e. without user intervention. Once the individual teeth have been repositioned,
a final digital data set representing the desired final tooth arrangement will be generated
and stored.

One method for determining the final tooth arrangement is for the treating professional to
20 define the final tooth positions, e. g. by writing a prescription. The use of prescriptions
for defining the desired outcomes of orthodontic procedures is well known in the art.
When a prescription or other final designation is provided, the image can then be
manipulated to match the prescription. In some cases, it would be possible to provide
software which could interpret the prescription in order to generate the final image and
25 thus the digital data set representing the final tooth arrangement.

In yet another aspect, methods according to the present invention are provided for
producing a plurality of digital data sets representing a series of discrete tooth
arrangements progressing from an initial tooth arrangement to a final tooth arrangement.
30 Such methods comprise providing a digital data set representing an initial tooth

arrangement (which may be accomplished according to any of the techniques set forth above). A digital data set representing a final tooth arrangement is also provided. Such final digital data set may be determined by the methods described previously. The plurality of successive digital data sets are then produced based on the initial digital data set and the final digital data set. Usually, the successive digital data sets are produced by determining positional differences between selected individual teeth in the initial data set and in the final data set and interpolating said differences. Such interpolation may be performed over as many discrete stages as may be desired, usually at least three, often at least four, more often at least ten, sometimes at least twenty-five, and occasionally forty or more. Many times, the interpolation will be linear interpolation for some or all of the positional differences. Alternatively, the interpolation may be non-linear. In a preferred embodiment, non-linear interpolation is computed automatically by the computer using path scheduling and collision detection techniques to avoid interferences between individual teeth. The positional differences will correspond to tooth movements where the maximum linear movement of any point on a tooth is 2 mm or less, usually being 1 mm or less, and often being 0.5 mm or less.

Often, the user will specify certain target intermediate tooth arrangements, referred to as key frames, which are incorporated directly into the intermediate digital data sets. The methods of the present invention then determine successive digital data sets between the key frames in the manner described above, e. g. by linear or non-linear interpolation between the key frames. The key frames may be determined by a user, e. g. the individual manipulating a visual image at the computer used for generating the digital data sets, or alternatively may be provided by the treating professional as a prescription in the same manner as the prescription for the final tooth arrangement.

In still another aspect, methods according to the present invention provide for fabricating a plurality of dental incremental position adjustment appliances. Said methods comprise providing an initial digital data set, a final digital data set, and producing a plurality of successive digital data sets representing the target successive tooth arrangements,

generally as just described. The dental appliances are then fabricated based on at least some of the digital data sets representing the successive tooth arrangements. Preferably, the fabricating step comprises controlling a fabrication machine based on the successive digital data sets to produce successive positive models of the desired tooth arrangements.

5 The dental appliances are then produced as negatives of the positive models using conventional positive pressure or vacuum fabrication techniques. The fabrication machine may comprise a stereolithography or other similar machine which relies on selectively hardening a volume of non-hardened polymeric resin by scanning a laser to selectively harden the resin in a shape based on the digital data set.

10 Other fabrication machines which could be utilized in the methods of the present invention include tooling machines and wax deposition machines.

In still another aspect, methods of the present invention for fabricating a dental appliance

15 comprise providing a digital data set representing a modified tooth arrangement for a patient. A fabrication machine is then used to produce a positive model of the modified tooth arrangement based on the digital data set. The dental appliance is then produced as a negative of the positive model. The fabrication machine may be a stereolithography or other machine as described above, and the positive model is produced by conventional

20 pressure or vacuum molding techniques.

In a still further aspect, methods for fabricating a dental appliance according to the present invention comprise providing a first digital data set representing a modified tooth arrangement for a patient. A second digital data set is then produced from the first digital

25 data set, where the second data set represents a negative model of the modified tooth arrangement. The fabrication machine is then controlled based on the second digital data set to produce the dental appliance. The fabrication machine will usually rely on selectively hardening a non- hardened resin to produce the appliance. The appliance typically comprises a polymeric shell having a cavity shape to receive and resiliently

30 reposition teeth from an initial tooth arrangement to the modified tooth arrangement.

In accordance with one aspect of the invention there is provided a method for producing a data set representing a desired tooth arrangement. The method involves receiving at a computer, a first data set representing an initial tooth arrangement, presenting an image representing the initial tooth arrangement based on the first data set, causing the computer to manipulate the image of the initial tooth arrangement to reposition individual teeth in the image to produce an image representing the desired tooth arrangement, and causing the computer to produce a second data set representing the desired tooth arrangement with repositioned teeth as observed in the image.

The method may involve producing a plurality of intermediate data sets representing a series of successive tooth arrangements progressing from the initial tooth arrangement toward the desired tooth arrangement.

The method may involve fabricating a plurality of successive tooth repositioning appliances, at least some of which may be related to at least some of the produced data sets.

Receiving the first data set representing the initial tooth arrangement may involve scanning a three-dimensional model of a patient's teeth.

Causing the computer to manipulate the image may involve defining tooth boundaries about at least some of the individual teeth, and moving at least some of the tooth boundaries relative to the other teeth in the image.

Fabricating the plurality of successive tooth repositioning appliances may involve fabricating a plurality of polymeric shell appliances.

The method may involve producing a plurality of intermediate data sets representing a series of successive tooth arrangements progressing from the initial tooth arrangement to

the desired tooth arrangement, and providing a plurality of the intermediate data sets to a fabrication operation for fabricating a series of successive tooth repositioning appliances to facilitate repositioning teeth.

5 The intermediate and second data sets may represent substantially accurate shapes of a patient's actual teeth.

10 The method may involve fabricating a plurality of successive tooth repositioning appliances based on at least a plurality of the intermediate data sets provided to the fabrication operation.

Fabricating the plurality of successive tooth repositioning appliances may involve fabricating polymeric shell appliances.

15 The desired tooth arrangement may include a first desired tooth arrangement and the method may further involve causing the computer to manipulate the image representing the first desired tooth arrangement to produce an image representing a second desired tooth arrangement, and causing the computer to produce a third data set representing the second desired tooth arrangement with repositioned teeth as observed in the image
20 representing a second desired tooth arrangement.

The second data set and the third data set may be produced at different times.

25 In accordance with another aspect of the invention there is provided a method for producing a plurality of data sets representing a series of discrete tooth arrangements progressing from an initial tooth arrangement toward a desired tooth arrangement. The method involves receiving at a computer, a first data set representing the initial tooth arrangement, causing the computer to produce a second data set representing the desired tooth arrangement, and causing the computer to produce a plurality of successive data
30 sets based on the first and second data sets, the plurality of successive data sets

representing a series of successive tooth arrangements progressing from the initial tooth arrangement toward the desired tooth arrangement.

5 The method may involve fabricating a plurality of dental incremental adjustment appliances based on at least some of the plurality of successive data sets.

Receiving the first data set representing the initial tooth arrangement may involve scanning a three-dimensional model of a patient's teeth.

10 Causing the computer to produce the second data set representing the desired tooth arrangement may involve defining tooth boundaries about at least some of the individual teeth, and moving at least some of the tooth boundaries relative to the other teeth in an image based on the first data set to produce the second data set.

15 Causing the computer to produce the plurality of successive data sets may involve determining positional differences between the first data set and the second data set and interpolating the positional differences.

The interpolating step may involve linear interpolation.

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The interpolating step may involve non-linear interpolation.

The method may involve defining one or more key frames between the initial tooth arrangement and desired tooth arrangement and interpolating between the key frames.

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Fabricating may involve controlling a fabrication machine based on the successive data sets to produce successive positive models of the successive tooth arrangements, and producing the dental appliances as negatives of the positive models.

Controlling the fabrication machine may involve, for each of the successive positive models providing a volume of non-hardened polymeric resin, and scanning a laser to selectively harden the resin in a shape based on the respective successive data set to produce the respective successive positive model.

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Producing the dental appliances may involve modeling the dental appliances over the positive models.

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Fabricating the dental appliances may involve fabricating a series of successive appliances.

Fabricating the dental appliances may involve fabricating polymeric shell appliances.

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Causing the computer to produce the plurality of successive data sets may involve causing the computer to produce a plurality of successive data sets based on both of the first and second data sets, the plurality of successive data sets representing substantially accurate shapes of a patient's actual teeth in a series of successive tooth arrangements progressing from the initial tooth arrangement toward the desired tooth arrangement.

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The dental appliances may be fabricated based on corresponding individual ones of the plurality of successive data sets.

The method may involve annotating the successive data sets to add text or numbering.

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Fabricating appliances based on at least some of the produced data sets may involve fabricating dental appliances having the text or numbering appearing on the dental appliances.

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The numbering appearing on the dental appliances may indicate the order of use of each of the dental appliances.

The desired tooth arrangement may include a first desired tooth arrangement and the method may further involve causing the computer to produce a third data set representing a second desired tooth arrangement, and causing the computer to produce a further plurality of successive data sets based on the second and third data sets, the further plurality of successive data sets represent a further series of successive tooth arrangements progressing from the first desired tooth arrangement toward the second desired tooth arrangement.

The second data set and the third data set may be produced at different times.

In accordance with another aspect of the invention there is provided a dental appliance fabricated in accordance with any one of methods above for use in repositioning at least some of a patient's teeth.

In accordance with another aspect of the invention there is provided a computer readable medium encoded with codes for directing a processor to execute any of the above methods.

In accordance with another aspect of the invention there is provided an apparatus for producing a data set representing a desired tooth arrangement. The apparatus includes a processor circuit operably configured to, in response to receiving a first data set representing an initial tooth arrangement, present an image representing the initial tooth arrangement based on the first data set, manipulate the image of the initial tooth arrangement to reposition individual teeth in the image to produce an image representing the desired tooth arrangement, and produce a second data set representing the desired tooth arrangement with repositioned teeth as observed in the image.

The first data set may include a scanned three-dimensional model of a patient's teeth.

The processor may be operably configured to define tooth boundaries about at least some of the individual teeth, and move at least some of the tooth boundaries relative to the other teeth in the image.

5 In accordance with another aspect of the invention there is provided an apparatus for producing a plurality of data sets representing a series of discrete tooth arrangements progressing from an initial tooth arrangement toward a desired tooth arrangement. The apparatus includes a processor circuit operably configured to, in response to receiving a first data set representing the initial tooth arrangement, produce a second data set
10 representing the desired tooth arrangement, and produce a plurality of successive data sets based on the first and second data sets, the plurality of successive data sets representing a series of successive tooth arrangements progressing from the initial tooth arrangement toward the desired tooth arrangement.

15 The first data set may include a scanned three-dimensional model of a patient's teeth.

The processor circuit may be operably configured to define tooth boundaries about at least some of the individual teeth, and move at least some of the tooth boundaries relative to the other teeth in an image based on first data set to produce the second data set.

20 The processor circuit may be operably configured to determine positional differences between the first data set and the second data set and interpolate the positional differences.

25 The processor circuit may be operably configured to linearly interpolate the positional differences.

The processor circuit may be operably configured to non-linearly interpolate the positional differences.

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The processor circuit may be operably configured to define one or more key frames between the initial tooth arrangement and the desired tooth arrangement and to interpolate between the key frames.

5 In accordance with another aspect of the invention there is provided an apparatus for producing a data set representing a desired tooth arrangement. The apparatus includes provisions for receiving a first data set representing an initial tooth arrangement, provisions for presenting an image representing the initial tooth arrangement based on the first data set, provisions for manipulating the image of the initial tooth arrangement to
10 reposition individual teeth in the image to produce an image representing the desired tooth arrangement, and provisions for producing a second data set representing the desired tooth arrangement with repositioned teeth as observed in the image.

In accordance with another aspect of the invention there is provided an apparatus for
15 producing a plurality of data sets representing a series of discrete tooth arrangements progressing from an initial tooth arrangement toward a desired tooth arrangement. The apparatus includes provisions for receiving a first data set representing the initial tooth arrangement, provisions for producing a second data set representing the desired tooth arrangement, and provisions for producing a plurality of successive data sets based on the
20 first and second data sets, the plurality of successive data sets representing a series of successive tooth arrangements progressing from the initial tooth arrangement toward the desired tooth arrangement.

In accordance with another aspect of the invention there is provided an apparatus for
25 fabricating a plurality of dental incremental position adjustment appliances. The apparatus includes provisions for receiving a first data set representing an initial tooth arrangement, provisions for receiving a second data set representing a desired tooth arrangement, provisions for producing a plurality of successive data sets based on both of the first and second data sets, the plurality of successive data sets representing a series of
30 successive tooth arrangements progressing from the initial tooth arrangement toward the

desired tooth arrangement. The apparatus also includes provisions for fabricating the dental appliances based on at least some of the plurality of successive data sets.

5 In accordance with another aspect of the invention there is provided a method for producing a plurality of successive data sets representing a series of discrete tooth arrangements progressing from an initial tooth arrangement toward a desired tooth arrangement. The method involves providing a computer system having at least one processor and memory, receiving at the computer system the initial tooth arrangement based on an initial data set, receiving at the computer system the desired tooth
10 arrangement based on a second data set, and producing a series of successive tooth arrangements progressing from the initial tooth arrangement toward the desired tooth arrangement by producing a plurality of successive data sets based on both of the first and second data sets.

15 Receiving the initial tooth arrangement may involve receiving an initial tooth arrangement produced by scanning a three-dimensional model of a patient's teeth.

Receiving the desired tooth arrangement may involve defining boundaries about at least some of the individual teeth on an image provided by the computer system, and moving
20 at least some of the tooth boundaries relative to the other teeth in the image to produce the desired tooth arrangement.

Producing the series of successive tooth arrangements may involve determining positional differences between the initial tooth arrangement and the desired tooth
25 arrangement and interpolating the positional differences.

The interpolating step may involve linear interpolation.

The interpolating step may involve non-linear interpolation.

The method may involve defining one or more key frames between the initial tooth arrangement and desired tooth arrangement and interpolating between the key frames.

The method may involve annotating the successive data sets to add text or numbering.

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Annotating may involve adding a sequence number to each of the successive data sets.

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The desired tooth arrangement may include a first desired tooth arrangement and the method may further involve producing a further plurality of successive data sets representing a further series of discrete tooth arrangements progressing from the first desired tooth arrangement toward a second desired tooth arrangement, the second desired tooth arrangement being based on a third data set and the further plurality of successive data sets being based on both of the second and third data sets.

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The series of successive tooth arrangements progressing from the initial tooth arrangement toward the first desired tooth arrangement and the further series of successive tooth arrangements progressing from the first desired tooth arrangement toward the second desired tooth arrangement may be produced at different times.

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BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A illustrates a patient's jaw and provides a general indication of how teeth may be moved by the methods and apparatus of the present invention.

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Fig. 1B illustrates a single tooth from Fig. 1A and defines how tooth movement distances are determined.

Fig. 1C illustrates the jaw of Fig. 1A together with an incremental position adjustment appliance which has been configured according to the methods of the present invention.

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Fig. 2 is a block diagram illustrating the steps of the present invention for producing a system of incremental position adjustment appliances.

Fig. 3 is a block diagram setting forth the steps for manipulating an initial digital data set representing an initial tooth arrangement to produce a final digital data set corresponding to a desired final tooth arrangement.

Fig. 4A is a flow chart illustrating an eraser tool for the methods herein.

Fig. 4B illustrates the volume of space which is being erased by the program of Fig. 4A.

Fig. 5 is a flow chart illustrating a program for matching high-resolution and low-resolution components in the manipulation of data sets of Fig. 3.

Fig. 6A is a flow chart illustrating a program for performing the "detection" stage of the cusp detection algorithm.

Fig. 6B is a flow chart illustrating a program for performing the "rejection" stage of the cusp detection algorithm.

Fig. 7 illustrates the method for generating multiple intermediate digital data sets which are used for producing the adjustment appliances of the present invention.

Fig. 8A is a flow chart illustrating the steps performed by the path scheduling algorithm.

Fig. 8B is a flow chart illustrating the steps for performing the "visibility" function according to one embodiment of the present invention.

- Fig. 8C is a flow chart illustrating the steps for performing the "children" function according to one embodiment of the present invention.
- 5 Fig. 8D is a flow chart illustrating the steps for performing path scheduling step 128 of Fig. 8A.
- Fig. 9A is a flow chart illustrating the steps for performing recursive collision testing during collision detection.
- 10 Fig. 9B is a flow chart illustrating node splitting performed during collision detection according to an embodiment of the present invention.
- Fig. 9C is a flow chart illustrating steps for providing additional motion information to the collision detection process.
- 15 Fig. 10 illustrates alternative processes for producing a plurality of appliances according to the methods of the present invention utilizing digital data sets representing the intermediate and final appliance designs.
- 20 Fig. 11 is a simplified block diagram of a data processing system incorporating an embodiment of the present invention.

DESCRIPTION OF SPECIFIC EMBODIMENTS

- 25 According to the present invention, systems and methods are provided for incrementally moving teeth using a plurality of discrete appliances, where each appliance successively moves one or more of the patient's teeth by relatively small amounts. The tooth movements will be those normally associated with orthodontic treatment, including translation in all three orthogonal directions relative to a vertical centerline, rotation of
- 30 the tooth centerline in the two orthodontic directions ("root angulation" and "torque"), as well as rotation about the centerline.

Referring now to Fig. 1A, a representative jaw **100** includes sixteen teeth **102**. The present invention is intended to move at least some of these teeth from an initial tooth arrangement to a final tooth arrangement. To understand how the teeth may be moved, an arbitrary centerline (CL) is drawn through one of the teeth **102**. With reference to this centerline (CL), the teeth may be moved in the orthogonal directions represented by axes **104, 106**, and **108** (where **104** is the centerline). The centerline may be rotated about the axis **108** (root angulation) and **104** (torque) as indicated by arrows **110** and **112**, respectively. Additionally, the tooth may be rotated about the centerline, as represented by arrow **114**. Thus, all possible free-form motions of the tooth can be performed.

Referring now to Fig. 1B, the magnitude of any tooth movement achieved by the methods and devices of the present invention will be defined in terms of the maximum linear translation of any point P on a tooth **102**. Each point P_1 will undergo a cumulative translation as that tooth is moved in any of the orthogonal or rotational directions defined in Fig. 1A. That is, while the point will usually follow a non-linear path, there will be a linear distance between any point in the tooth when determined at any two times during the treatment. Thus, an arbitrary point P_1 may in fact undergo a true side-to-side translation as indicated by arrow d_1 , while a second arbitrary point P_2 may travel along an arcuate path, resulting in a final translation d_2 . Many aspects of the present invention are defined in terms of the maximum permissible movement of a point P_1 induced by the methods in any particular tooth. Such maximum tooth movement, in turn, is defined as the maximum linear translation of that point P_1 on the tooth which undergoes the maximum movement for that tooth in any treatment step.

Referring now to Fig. 1C, systems according to the present invention will comprise a plurality of incremental position adjustment appliances. The appliances are intended to effect incremental repositioning of individual teeth in the jaw as described generally above. In a broadest sense, the methods of the present invention can employ any of the known positioners, retainers, or other removable appliances which are known for finishing and maintaining teeth positions in connection with conventional orthodontic

treatment. The systems of the present invention, in contrast with prior apparatus and systems, will provide a plurality of such appliances intended to be worn by a patient successively in order to achieve the gradual tooth repositioning as described herein. A preferred appliance **100** will comprise a polymeric shell having a cavity shaped to receive and resiliently reposition teeth from one tooth arrangement to a successive tooth arrangement. The polymeric shell will preferably, but not necessarily, fit over all teeth present in the upper or lower jaw. Often, only certain one (s) of the teeth will be repositioned while others of the teeth will provide a base or anchor region for holding the repositioning appliance in place as it applies the resilient repositioning force against the tooth or teeth to be repositioned. In complex cases, however, many or most of the teeth will be repositioned at some point during the treatment. In such cases, the teeth which are moved can also serve as a base or anchor region for holding the repositioning appliance. Additionally, the gums and/or the palette can serve as an anchor region, thus allowing all or nearly all of the teeth to be repositioned simultaneously.

The polymeric appliance **100** of Fig. 1C is preferably formed from a thin sheet of a suitable elastomeric polymeric, such as Tru-Tain **0.03** in. thermal forming dental material, Tru-Tain Plastics, Rochester, Minnesota **55902**. Usually, no wires or other means will be provided for holding the appliance in place over the teeth. In some cases, however, it will be desirable or necessary to provide individual anchors on teeth with corresponding receptacles or apertures in the appliance **100** so that the appliance can apply an upward force on the tooth which would not be possible in the absence of such an anchor. Specific methods for producing the appliances **100** are described hereinafter.

Referring now to Fig. **2**, the overall method of the present invention for producing the incremental position adjustment appliances for subsequent use by a patient to reposition the patient's teeth will be described. As a first step, a digital data set representing an initial tooth arrangement is obtained, referred to hereinafter as the IDDS. The IDDS may be obtained in a variety of ways. For example, the patient's teeth may be scanned or imaged using well known technology, such as X- rays, three-dimensional X-rays,

computer-aided tomographic images or data sets, magnetic resonance images, etc. Methods for digitizing such conventional images to produce data sets useful in the present invention are well known and described in the patent and medical literature.

5 Usually, however, the present invention will rely on first obtaining a plaster cast of the patient's teeth by well known techniques, such as those described in Graber, Orthodontics: Principle and Practice, Second Edition, Saunders, Philadelphia, **1969**, pp. **401-415**. After the tooth casting is obtained, it can be digitally scanned using a conventional laser scanner or other range acquisition system to produce the IDDS.

10

The data set produced by the range acquisition system may, of course, be converted to other formats to be compatible with the software which is used for manipulating images within the data set, as described in more detail below. General techniques for producing plaster casts of teeth and generating digital models using laser scanning techniques are described, for example, in U. S. Patent No. **5,605,459**.

15

There are a variety of range acquisition systems, generally categorized by whether the process of acquisition requires contact with the three dimensional object. A contact-type range acquisition system utilizes a probe, having multiple degrees of translational and/or rotational freedom. By recording the physical displacement of the probe as it is drawn across the sample surface, a computer-readable representation of the sample object is made. A non-contact-type range acquisition device can be either a reflective-type or transmissive-type system. There are a variety of reflective systems in use. Some of these reflective systems utilize non-optical incident energy sources such as microwave radar or sonar. Others utilize optical energy. Those non- contact-type systems working by reflected optical energy further contain special instrumentation configured to permit certain measuring techniques to be performed (e. g., imaging radar, triangulation and interferometry).

20

25

A preferred range acquisition system is an optical, reflective, non-contact-type scanner. Non-contact-type scanners are preferred because they are inherently nondestructive (i. e., do not damage the sample object), are generally characterized by a higher capture resolution and scan a sample in a relatively short period of time. One such scanner is the
5 Cyberware Model 15 manufactured by Cyberware, Inc., Monterey, California.

Either non-contact-type or contact-type scanners may also include a color camera, that when synchronized with the scanning capabilities, provides a means for capturing, in digital format, a color representation of the sample object. The importance of this further
10 ability to capture not just the shape of the sample object but also its color is discussed below.

In a preferred embodiment, a wax bite is also obtained from a patient. The wax bite enables scanning of the relative positions of the upper and lower dentition in centric
15 occlusion. This is usually accomplished by first placing the lower cast in front of the scanner, with the teeth facing upwards, then placing the wax bite on top of the lower cast, and finally by placing the upper cast on top of the lower cast, with the teeth downwards, resting on the wax bite. A cylindrical scan is then acquired for the lower and upper casts in their relative positions. The scanned data provides a digital model of medium
20 resolution representing an object which is the combination of the patient's arches positioned in the same relative configuration as in the mouth.

The digital model acts as a template guiding the placement of the two individual digital models (one per arch). More precisely, using software, for example the CyberWare alignment software, each digital arch is in turn aligned to the pair scan. The individual
25 models are then positioned relative to each other corresponding to the arches in the patient's mouth.

The methods of the present invention will rely on manipulating the IDDS at a computer or workstation having a suitable graphical user interface (GUI) and software appropriate
30 for viewing and modifying the images. Specific aspects of the software will be described

in detail hereinafter. While the methods will rely on computer manipulation of digital data, the systems of the present invention comprising multiple dental appliances having incrementally differing geometries may be produced by non-computer-aided techniques. For example, plaster casts obtained as described above may be cut using knives, saws, or other cutting tools in order to permit repositioning of individual teeth within the casting. The disconnected teeth may then be held in place by soft wax or other malleable material, and a plurality of intermediate tooth arrangements can then be prepared using such a modified plaster casting of the patient's teeth. The different arrangements can be used to prepare sets of multiple appliances, generally as described below, using pressure and vacuum molding techniques. While such manual creation of the appliance systems of the present invention will generally be much less preferred, systems so produced will come within the scope of the present invention.

Referring again to Fig. 2, after the IDDS has been obtained, the digital information will be introduced to the computer or other workstation for manipulation. In the preferred approach, individual teeth and other components will be "cut" to permit their individual repositioning or removal from the digital data. After thus "freeing" the components, the user will often follow a prescription or other written specification provided by the treating professional. Alternatively, the user may reposition them based on the visual appearance or using rules and algorithms programmed into the computer. Once the user is satisfied with the final arrangement, the final tooth arrangement is incorporated into a final digital data set (FDDS).

Based on both the IDDS and the FDDS, a plurality of intermediate digital data sets (INTDDS's) are generated to correspond to successive intermediate tooth arrangements. The system of incremental position adjustment appliances can then be fabricated based on the INTDDS's, as described in more detail below.

Fig. 3 illustrates a representative technique for manipulating the IDDS to produce the FDDS on the computer. Usually, the data from the digital scanner will be in a high

resolution form. In order to reduce the computer time necessary to generate images, a parallel set of digital data set representing the IDDS at a lower resolution will be created. The user will manipulate the lower resolution images while the computer will update the high resolution data set as necessary. The user can also view/manipulate the high resolution model if the extra detail provided in that model is useful. The IDDS will also be converted into a quad edge data structure if not already present in that form. A quad edge data structure is a standard topological data structure defined in *Primitives for the Manipulation of General Subdivisions and the Computation of Voronoi Diagrams*, ACM Transactions of Graphics, Vol. 4, No. 2, April 1985, pp. 74-123. Other topological data structures, such as the winged-edge data structure, could also be used.

As an initial step, while viewing the three-dimensional image of the patient's jaw, including the teeth, gingivae, and other oral tissue, the user will usually delete structure which is unnecessary for image manipulation and/or final production of an appliance. These unwanted sections of the model may be removed using an eraser tool to perform a solid modeling subtraction. The tool is represented by a graphic box. The volume to be erased (the dimensions, position, and orientation of the box) are set by the user employing the GUI. Typically, unwanted sections would include extraneous gum area and the base of the originally scanned cast. Another application for this tool is to stimulate the extraction of teeth and the "shaving down" of tooth surfaces. This is necessary when additional space is needed in the jaw for the final positioning of a tooth to be moved. The treating professional may choose to determine which teeth will be shaved and/or which teeth will be extracted. Shaving allows the patient to maintain their teeth when only a small amount of space is needed. Typically, extraction and shaving, of course, will be utilized in the treatment planning only when the actual patient teeth are to be extracted and/or shaved prior to initiating repositioning according to the methods of the present invention.

Removing unwanted and/or unnecessary sections of the model increases data processing speed and enhances the visual display. Unnecessary sections include those not needed for

creation of the tooth repositioning appliance. The removal of these unwanted sections reduces the complexity and size of the digital data set, thus accelerating manipulations of the data set and other operations.

5 After the user positions and sizes the eraser tool and instructs the software to erase the unwanted section, all triangles within the box set by the user will be removed and the border triangles are modified to leave a smooth, linear border. The software deletes all of the triangles within the box and clips all triangles which cross the border of the box. This requires generating new vertices on the border of the box. The holes created in the model
10 at the faces of the box are re-triangulated and closed using the newly created vertices.

The saw tool is used to define the individual teeth (or possibly groups of teeth) to be moved. The tool separates the scanned image into individual graphic components enabling the software to move the tooth or other component images independent of
15 remaining portions of the model. In one embodiment, the saw tool defines a path for cutting the graphic image by using two cubic B-spline curves lying in space, possibly constrained to parallel planes, either open or closed. A set of lines connects the two curves and shows the user the general cutting path. The user may edit the control points on the cubic B-splines, the thickness of the saw cut, and the number of erasers used, as
20 described below.

In an alternate preferred embodiment, the teeth are separated by using the saw as a "coring" device, cutting the tooth from above with vertical saw cuts. The crown of the tooth, as well as the gingivae tissue immediately below the crown are separated from the
25 rest of the geometry, and treated as an individual unit, referred to as a tooth. When this model is moved, the gingivae tissue moves relative to the crown, creating a first order approximation of the way that the gingivae will reform within a patient's mouth.

Each tooth may also be separated from the original trimmed model. Additionally, a base
30 may be created from the original trimmed model by cutting off the crowns of the teeth.

The resulting model is used as a base for moving the teeth. This facilitates the eventual manufacture of a physical mold from the geometric model, as described below.

Thickness: When a cut is used to separate a tooth, the user will usually want the cut to be as thin as possible. However, the user may want to make a thicker cut, for example, when shaving down surrounding teeth, as described above. Graphically, the cut appears as a curve bounded by the thickness of the cut on one side of the curve.

Number of Erasers: A cut is comprised of multiple eraser boxes arranged next to each other as a piecewise linear approximation of the Saw Tool's curve path. The user chooses the number of erasers, which determines the sophistication of the curve created-the greater the number of segments, the more accurately the cutting will follow the curve. The number of erasers is shown graphically by the number of parallel lines connecting the two cubic B-spline curves. Once a saw cut has been completely specified the user applies the cut to the model. The cut is performed as a sequence of erasings. A preferred algorithm is set forth in Fig. 4A. Fig. 4B shows a single erasing iteration of the cut as described in the algorithm for a open ended B-spline curve. For a vertical cut, the curves are closed with $P_A [O]$ and $P_A [S]$ the same point and $P_B [O]$ and $P_B [S]$ being the same point.

In one embodiment, the software may automatically partition the saw tool into a set of erasers based upon a smoothness measure input by the user. The saw is adaptively subdivided until an error metric measures the deviation from the ideal representation to the approximate representation to be less than a threshold specified by the smoothness setting. The preferred error metric used compares the linear length of the subdivided curve to the arclength of the ideal spline curve. When the difference is greater than a threshold computed from the smoothness setting, a subdivision point is added along the spline curve.

A preview feature may also be provided in the software. The preview feature visually displays a saw cut as the two surfaces that represent opposed sides of the cut. This allows the user to consider the final cut before applying it to the model data set.

5 After the user has completed all desired cutting operations with the saw tool, multiple graphic solids exist. However, at this point, the software has not determined which triangles of the quad edge data structure belong to which components. The software chooses a random starting point in the data structure and traverses the data structure using adjacency information to find all of the triangles that are attached to each other,
10 identifying an individual component. This process is repeated starting with the triangle whose component is not yet determined. Once the entire data structure is traversed, all components have been identified.

To the user, all changes made to the high resolution model appear to occur
15 simultaneously in the low resolution model, and vice versa. However, there is not a one-to-one correlation between the different resolution models. Therefore, the computer "matches" the high resolution and low resolution components as best as it can subject to defined limits. The algorithm is described in Fig. 5.

20 Cusp detection: In a preferred embodiment, the software provides the ability to detect cusps for a tooth. Cusps are pointed projections on the chewing surface of a tooth. Cusp detection can be performed either before or after the cutting phase has been performed. The algorithm used for cusp detection is composed of two stages: (1) "detection" stage, during which a set of points on the tooth are determined as candidates for cusp locations;
25 and (2) "rejection" stage, during which candidates from the set of points are rejected if they do not satisfy a set of criteria associated with cusps.

A preferred algorithm for the "detection" stage is set forth in Fig. 6A. In the detection stage, a possible cusp is viewed as an "island" on the surface of the tooth, with the
30 candidate cusp at the highest point on the island. "Highest" is measured with respect to

the coordinate system of the model, but could just as easily be measured with respect to the local coordinate system of each tooth if detection is performed after the cutting phase of treatment.

5 The set of all possible cusps is determined by looking for all local maxima on the tooth model that are within a specified distance of the top of the bounding box of the model. First, the highest point on the model is designated as the first candidate cusp. A plane is passed through this point, perpendicular to the direction along which the height of a point is measured. The plane is then lowered by a small predetermined distance along the Z
10 axis. Next, all vertices connected to the tooth and which are above the plane and on some connected component are associated with the candidate cusp as cusps. This step is also referred to as the "flood fill" step. From each candidate cusp point, outward "flooding" is performed, marking each vertex on the model visited in this manner as "part of" the corresponding candidate cusp. After the flood fill step is complete, every vertex on the
15 model is examined. Any vertex that is above the plane and has not been visited by one of the flood fills is added to the list of candidate cusps. These steps are repeated until the plane is traveled a specified distance.

While this iterative approach can be more time consuming than a local maximum search,
20 the approach described above leads to a shorter list of candidate cusps. Since the plane is lowered a finite distance at each step, very small local maxima that can occur due to noisy data are skipped over.

After the "detection" stage, the cusp detection algorithm proceeds with the "rejection"
25 stage. A preferred algorithm for the "rejection" stage is set forth in Fig. 6B. In this stage, the local geometries around each of cusp candidates are analyzed to determine if they possess "non-cusp-like features." Cusp candidates that exhibit "non-cusp-like features" are removed from the list of cusp candidates.

Various criteria may be used to identify "non-cusp-like features." According to one test, the local curvature of the surface around the cusp candidate is used to determine whether the candidate possesses non-cusp-like features. As depicted in Fig. 6B, the local curvature of the surface around the cusp candidate is approximated, and then analyzed to determine if it is too large (very pointy surface) or too small (very flat surface), in which case the candidate is removed from the list of cusp candidates. Conservative values are used for the minimum and maximum curvatures values to ensure that genuine cusps are not rejected by mistake.

According to an alternate test, a measure of smoothness is computed based on the average normal in an area around the candidate cusp. If the average normal deviates from the normal at the cusp by more than a specified amount, the candidate cusp is rejected. In a preferred embodiment, the deviation of a normal vector N from the cusp normal CN is approximated by the formula:

$$1 - \text{Abs}(N \cdot CN),$$

which is zero at no deviation, and 1 when N and CN are perpendicular.

Once the teeth have been separated, the FDDS can be created from the IDDS. The FDDS is created by following the orthodontists prescription, moving the teeth into their final prescription. In one embodiment, the prescription is entered into a computer, which algorithmically computes the final position of the teeth. In alternate embodiments, a user may move the teeth into their final positions by independently manipulating one or more teeth while satisfying the constraints of the prescription. It should be appreciated that various combinations of the above described techniques may also be used to arrive at the final teeth position.

The preferred method for creating the FDDS involves moving the teeth in a specified sequence. First, the centers of each of the teeth are aligned to a standard arch. Then, the teeth are rotated until their roots are in the proper vertical position. Next, the teeth are rotated around their vertical axis into the proper orientation. The teeth are then observed

from the side, and translated vertically into their proper vertical position. Finally, the two arches are placed together, and the teeth moved slightly to ensure that the upper and lower arches properly mesh together. The meshing of the upper and lower arches together is visualized using the collision detection algorithm to highlight the contacting points of the teeth in red.

After the teeth and other components have been placed or removed so that the final tooth arrangement has been produced, it is necessary to generate a treatment plan, as illustrated in Fig. 7. The treatment plan will ultimately produce the series of INTDDS's and FDDS as described previously. To produce these data sets, it is necessary to define or map the movement of selected individual teeth from the initial position to the final position over a series of successive steps. In addition, it may be necessary to add other features to the data sets in order to produce desired features in the treatment appliances. For example, it may be desirable to add wax patches to the image in order to define cavities or recesses for particular purposes. For example, it may be desirable to maintain a space between the appliance and particular regions of the teeth or jaw in order to reduce soreness of the gums, avoid periodontal problems, allow for a cap, and the like. Additionally, it will often be necessary to provide a receptacle or aperture intended to accommodate an anchor which is to be placed on a tooth in order to permit the tooth to be manipulated in a manner that requires the anchor, e. g. lifted relative to the jaw.

Some methods for manufacturing the tooth repositioning appliances require that the separate, repositioned teeth and other components be unified into a single continuous structure in order to permit manufacturing. In these instances, "wax patches" are used to attach otherwise disconnected components of the INTDDS's. These patches are added to the data set underneath the teeth and above the gum so that they do not effect the geometry of the tooth repositioning appliances. The application software provides for a variety of wax patches to be added to the model, including boxes and spheres with adjustable dimensions. The wax patches that are added are treated by the software as additional pieces of geometry, identical to all other geometries. Thus, the wax patches

can be repositioned during the treatment path as well as the teeth and other components. The preferred method of separating the teeth using vertical coring, as described above, removes the need for most of these "wax patches".

5 In the manufacturing process, which relies on generation of positive models to produce the repositioning appliance, adding a wax patch to the graphic model will generate a positive mold that has the same added wax patch geometry. Because the mold is a positive of the teeth and the appliance is a negative of the teeth, when the appliance is formed over the mold, the appliance will also form around the wax patch that has been
10 added to the mold. When placed in the patient's mouth, the appliance will thus allow for a space between the inner cavity surface of the appliance and the patient's teeth or gums. Additionally, the wax patch may be used to form a recess or aperture within the appliance which engages an anchor placed on the teeth in order to move the tooth in directions which could not otherwise be accomplished.

15 In addition to such wax patches, an individual component, usually a tooth, can be scaled to a smaller or larger size which will result in a manufactured appliance having a tighter or looser fit, respectively.

20 Treatment planning is extremely flexible in defining the movement of teeth and other components. The user may change the number of treatment stages, as well as individually control the path and speed of components.

25 Number of Treatment Stages: The user can change the number of desired treatment stages from the initial to the target states of the teeth. Any component that is not moved is assumed to remain stationary, and thus its final position is assumed to be the same as the initial position (likewise for all intermediate positions, unless one or more key frames are defined for that component).

Key frames: The user may also specify "key frames" by selecting an intermediate state and making changes to component position (s). Unless instructed otherwise, the software automatically linearly interpolates between all user-specified positions (including the initial position, all key frame positions, and the target position). For example, if only a final position is defined for a particular component, each subsequent stage after the initial stage will simply show the component an equal linear distance and rotation (specified by a quaternion) closer to the final position. If the user specifies two key frames for that component, it will "move" linearly from the initial position through different stages to the position defined by the first key frame. It will then move, possibly in a different direction, linearly to the position defined by the second key frame. Finally, it will move, possibly in yet a different direction, linearly to the target position.

The user can also specify non-linear interpolation between the key frames. A spline curve is used to specify the interpolating function in a conventional manner.

These operations may be done independently to each component, so that a key frame for one component will not affect another component, unless the other component is also moved by the user in that key frame. One component may accelerate along a curve between stages 3 and 8, while another moves linearly from stage 1 to 5, and then changes direction suddenly and slows down along a linear path to stage 10. This flexibility allows a great deal of freedom in planning a patient's treatment.

In one embodiment, the software automatically determines the treatment path, based upon the IDDS and the FDDS. This is usually accomplished using a path scheduling algorithm which determines the rate at which each component, i. e. a tooth, moves along a straight path from the initial position to the final position. The path scheduling algorithm used by the present invention determines the treatment path while avoiding "round-tripping" which is the term used by orthodontists referring to moving a tooth along a distance greater than absolutely necessary to straighten the teeth. Such motion is highly undesirable, and has potential negative side effects on the patient. In order to avoid

"round- tripping", the path scheduling algorithm schedules or stages the movements of all the teeth by constraining them to the shortest straight-line path between the initial and final position, while avoiding all interferences between separate teeth.

5 The path scheduling algorithm utilizes a randomized search technique to find an unobstructed path through a configuration space which describes possible treatment plans. A preferred embodiment of the algorithm for scheduling motion between two user defined global keyframes is described below. Scheduling over a time interval which includes intermediate keyframes is accomplished by dividing the time interval into
10 subintervals which do not include intermediate keyframes, scheduling each of these intervals independently, and then concatenating the resulting schedules.

Flow chart **120** in Fig. **8A** depicts a simplified path scheduling algorithm according to one embodiment of the present invention. As shown in Fig. **8A**, first step **122** involves
15 construction of the "configuration space" description. A "configuration," in this context, refers to a given set of positions of all the teeth being considered for movement. Each of these positions may be described in multiple ways. In a preferred embodiment of the present invention, the positions are described by one affine transformation to specify change in location and one rotational transformation to specify the change in orientation
20 of a tooth from its initial position to its final position. The intermediate positions of each tooth are described by a pair of numbers which specify how far to interpolate the location and orientation between the two endpoints. A "configuration" thus consists of two numbers for each tooth being moved, and the "configuration space" refers to the space of all such number pairs. Thus, the configuration space is a Cartesian space, any location in
25 which can be interpreted as specifying the positions of all teeth.

The affine transformation describing the movement of each tooth from its starting position to its ending position is decomposed into translational and rotational components; these transformations are independently interpolated with scalar parameters
30 which are considered two dimensions of the configuration space. The entire configuration

space thus consists of two dimensions per moved tooth, all of which are treated equivalently during the subsequent search.

The configuration space is made of "free space" and "obstructed space." "Free" configurations are those which represent valid, physically realizable positions of teeth, while "obstructed" configurations are those which do not. To determine whether a configuration is free or obstructed, a model is created for the positions of the teeth which the configuration describes. A collision detection algorithm is then applied to determine if any of the geometries describing the tooth surfaces intersect. If there are no obstructions, the space is considered free; otherwise it is obstructed. The collision detect algorithm is discussed below in more detail.

At step **124**, a "visibility" function $V(s_1, s_2)$ is defined which takes two vectors in the configuration space, " s_1 " and " s_2 ", as input and returns a true or false boolean value. The visibility function returns a true value if and only if a straight line path connecting s_1 and s_2 passes entirely through a free and unobstructed region of the configuration space. A preferred algorithm for the visibility function is set forth in Fig. **8B**. The visibility function is approximately computed by testing the teeth model for interferences at discretely sampled points along the line s_1 - s_2 . Techniques, such as early termination on failure or choosing the order of sample points by recursively subdividing the interval to be tested, may be used to increase the efficiency of the visibility function.

At step **126** of Fig. **8A**, a "children" function $C(s)$ is defined whose input parameter, " s ", is a vector in the configuration space and which returns a set of vectors, " s_c " in the configuration space. Fig. **8C** depicts a simplified flow chart illustrating the steps followed for computing children function $C(s)$. Each vector within set s_c satisfies the property that $V(s, s_c)$ is true and that each of its components are greater than or equal to the corresponding component of " s ." This implies that any state represented by such a vector is reachable from " s " without encountering any interferences and without performing any motion which is not in the direction prescribed by treatment. Each vector of set " s_c " is

created by perturbing each component of "s" by some random, positive amount. The visibility function $V(s, s_c)$ is then computed and "s" added to the set " s_c " if the visibility function returns a true boolean value. Additionally, for each such vector generated, a pointer to its parent "s" is recorded for later use.

5

After the configuration space has been defined, at step **128**, path scheduling is performed between an initial state " s_{init} " and a final state " s_{final} ". Fig. 8D depicts a preferred flow chart for performing step **128** depicted in Fig. 8A. As illustrated in Fig. 8D, at step **128a**, a set of states "W" is defined to initially contain only the initial state s_{init} . Next, at step **128b**, the visibility function is invoked to determine if $V(s, s_{final})$ is true for at least one state s_i in W. If the visibility function returns a false boolean value, at step **128c**, the set of states "W" is replaced with the union of $C(s_i)$ for all s_i in W. Steps **128b** and **128c** are repeated until $V(s_i, s_{final})$ returns a true boolean value for any s_i belonging to W.

10

15

At step **128d**, for each s_i for which $V(s_i, s_{final})$ is true, an unobstructed path P_i is constructed from s_i to s_{init} by following the parent pointers back to s_{init} . At step **128e**, the path from s_{init} to s_{final} is then constructed by concatenating the paths P_i with the final step from s_i to s_{final} . If there are multiple paths from s_{init} to s_{final} , the total length of each path is computed at step **128f**. Finally, at step **128g**, the path with the shortest length is then chosen as the final path. The length of the chosen path corresponds to the total time and stages required for a treatment plan.

20

25

The resulting final path consists of a series of vectors, each of which represents a group of values of the interpolation parameters of the translational and rotational components of the transformations of the moving teeth. Taken together, these constitute a schedule of tooth movement which avoids tooth-to-tooth interferences.

Collision detect algorithm: The collision or interference detection algorithm employed by the present invention is based on the algorithm described in SIGGRAPH article, Stefan

Gottschalk et al. (1996): *"OBBTree: A Hierarchical Structure for Rapid Interference Detection."* The contents of the SIGGRAPH article are herein incorporated by reference.

The algorithm is centered around a recursive subdivision of the space occupied by an object, which is organized in a binary-tree like fashion. Triangles are used to represent the teeth in the DDS. Each node of the tree is referred to as an oriented bounding box (OBB) and contains a subset of triangles appearing in the node's parent. The children of a parent node contain between them all of the triangle data stored in the parent node.

The bounding box of a node is oriented so it tightly fits around all of the triangles in that node. Leaf nodes in the tree ideally contain a single triangle, but can possibly contain more than one triangle. Detecting collisions between two objects involves determining if the OBB trees of the objects intersect. Fig. 9A sets forth a flow chart depicting a simplified version of a recursive collision test to check if a node "N1" from a first object intersects with node "N2" of a second object. If the OBBs of the root nodes of the trees overlap, the root's children are checked for overlap. The algorithm proceeds in a recursive fashion until the leaf nodes are reached. At this point, a robust triangle intersection routine is used to determine if the triangles at the leaves are involved in a collision.

The present invention provides several enhancements to the collision detection algorithm described in the SIGGRAPH article. In one embodiment, the present invention provides a unique method of building OBB trees in a lazy fashion to save memory and time. This approach stems from the observation that there are parts of the model which will never be involved in a collision, and consequently the OBB tree for such parts of the model need not be computed. The OBB trees are expanded by splitting the internal nodes of the tree as necessary during the recursive collision determination algorithm, as depicted in Fig. 9B.

In another embodiment of the present invention, the triangles in the model which are not required for collision data may also be specifically excluded from consideration when

building an OBB tree. As depicted in Fig. 9C, additional information is provided to the collision algorithm to specify objects in motion. Motion may be viewed at two levels. Objects may be conceptualized as "moving" in a global sense, or they may be conceptualized as "moving" relative to other objects. The additional information improves the time taken for the collision detection by avoiding recomputation of collision information between objects which are at rest relative to each other since the state of the collision between such objects does not change.

The software of the present invention may also incorporate and the user may at any point use a "movie" feature to automatically animate the movement from initial to target states. This is helpful for visualizing overall component movement throughout the treatment process.

Above it was described that the preferred user interface for component identification is a three dimensional interactive GUI. A three-dimensional GUI is also preferred for component manipulation. Such an interface provides the treating professional or user with instant and visual interaction with the digital model components. It is preferred over interfaces that permit only simple low-level commands for directing the computer to manipulate a particular segment. In other words, a GUI adapted for manipulation is preferred over an interface that accepts directives, for example, only of the sort: "translate this component by 0.1 mm to the right. "Such low-level commands are useful for fine-tuning, but, if they were the sole interface, the processes of component manipulation would become a tiresome and time-consuming interaction.

Before or during the manipulation process, one or more tooth components may be augmented with template models of tooth roots. Manipulation of a tooth model augmented with a root template is useful, for example, in situations where impacting of teeth below the gumline is a concern. These template models could, for example, comprise a digitized representation of the patient's teeth x-rays.

The software also allows for adding annotations to the datasets which can comprise text and/or the sequence number of the apparatus. The annotation is added as recessed text (i. e. it is 3-D geometry), so that it will appear on the printed positive model. If the annotation can be placed on a part of the mouth that will be covered by a repositioning appliance, but is unimportant for the tooth motion, the annotation may appear on the delivered repositioning appliance (s).

The above-described component identification and component manipulation software is designed to operate at a sophistication commensurate with the operator's training level. For example, the component manipulation software can assist a computer operator, lacking orthodontic training, by providing feedback regarding permissible and forbidden manipulations of the teeth. On the other hand, an orthodontist, having greater skill in intraoral physiology and teeth-moving dynamics, can simply use the component identification and manipulation software as a tool and disable or otherwise ignore the advice.

Once the intermediate and final data sets have been created, the appliances may be fabricated as illustrated in Fig. 10. Preferably, fabrication methods will employ a rapid prototyping device **200** such as a stereolithography machine. A particularly suitable rapid prototyping machine is Model SLA-250/50 available from 3D System, Valencia, California. The rapid prototyping machine **200** will selectively harden a liquid or other non-hardened resin into a three-dimensional structure which can be separated from the remaining non-hardened resin, washed, and used either directly as the appliance or indirectly as a mold for producing the appliance. The prototyping machine **200** will receive the individual digital data sets and produce one structure corresponding to each of the desired appliances. Generally, because the rapid prototyping machine **200** may utilize a resin having non-optimum mechanical properties and which may not be generally acceptable for patient use, it will be preferred to use the prototyping machine to produce molds which are, in effect, positive tooth models of each successive stage of the treatment.

After the positive models are prepared, a conventional pressure or vacuum molding machine may be used to produce the appliances from a more suitable material, such as 0.03 inch thermal forming dental material, available from Tru-Tain Plastics, Rochester, Minnesota **55902**. Suitable pressure molding equipment is available under the tradename BIOSSTAR from Great Lakes Orthodontics, Ltd., Tonawanda, New York **14150**. The molding machine **250** produces each of the appliances directly from the positive tooth model and the desired material. Suitable vacuum molding machines are available from Raintree Essix, Inc.

After production, the plurality of appliances which comprise the system of the present invention are preferably supplied to the treating professional all at one time. The appliances will be marked in some manner, typically by sequential numbering directly on the appliances or on tags, pouches, or other items which are affixed to or which enclose each appliance, to indicate their order of use. Optionally, written instructions may accompany the system which set forth that the patient is to wear the individual appliances in the order marked on the appliances or elsewhere in the packaging. Use of the appliances in such a manner will reposition the patient's teeth progressively toward the final tooth arrangement.

Fig. **11** is a simplified block diagram of a data processing system **300** embodying the present invention. Data processing system **300** typically includes at least one processor **302** which communicates with a number of peripheral devices via bus subsystem **304**. These peripheral devices typically include a storage subsystem **306** (memory subsystem **308** and file storage subsystem **314**), a set of user interface input and output devices **318**, and an interface to outside networks **316**, including the public switched telephone network. This interface is shown schematically as "Modems and Network Interface" block **316**, and is coupled to corresponding interface devices in other data processing systems via communication network interface **324**. Data processing system **300** could be a terminal or a low-end personal computer or a high-end personal computer, workstation or mainframe.

The user interface input devices typically include a keyboard and may further include a pointing device and a scanner. The pointing device may be an indirect pointing device such as a mouse, trackball, touchpad, or graphics tablet, or a direct pointing device such as a touchscreen incorporated into the display. Other types of user interface input devices, such as voice recognition systems, are also possible.

User interface output devices typically include a printer and a display subsystem, which includes a display controller and a display device coupled to the controller. The display device may be a cathode ray tube (CRT), a flat-panel device such as a liquid crystal display (LCD), or a projection device. The display subsystem may also provide non-visual display such as audio output.

Storage subsystem **306** maintains the basic programming and data constructs that provide the functionality of the present invention. The software modules discussed above are typically stored in storage subsystem **306**. Storage subsystem **306** typically comprises memory subsystem **308** and file storage subsystem **314**.

Memory subsystem **308** typically includes a number of memories including a main random access memory (RAM) **310** for storage of instructions and data during program execution and a read only memory (ROM) **312** in which fixed instructions are stored. In the case of Macintosh-compatible personal computers the ROM would include portions of the operating system; in the case of IBM-compatible personal computers, this would include the BIOS (basic input/output system).

File storage subsystem **314** provides persistent (non-volatile) storage for program and data files, and typically includes at least one hard disk drive and at least one floppy disk drive (with associated removable media). There may also be other devices such as a CD-ROM drive and optical drives (all with their associated removable media).

Additionally, the system may include drives of the type with removable media cartridges. The removable media cartridges may, for example be hard disk cartridges, such as those marketed by Syquest and others, and flexible disk cartridges, such as those marketed by Iomega. One or more of the drives may be located at a remote location, such as in a
5 server on a local area network or at a site on the Internet's World Wide Web.

In this context, the term "bus subsystem" is used generically so as to include any mechanism for letting the various components and subsystems communicate with each other as intended. with the exception of the input devices and the display, the other
10 components need not be at the same physical location. Thus, for example, portions of the file storage system could be connected via various local-area or wide-area network media, including telephone lines. Similarly, the input devices and display need not be at the same location as the processor, although it is display need not be at the same location as the processor, although it is anticipated that the present invention will most often be
15 implemented in the context of PCs and workstations.

Bus subsystem **304** is shown schematically as a single bus, but a typical system has a number of buses such as a local bus and one or more expansion buses (e. g., ADB, SCSI, ISA, EISA, MCA, NuBus, or PCI), as well as serial and parallel ports. Network
20 connections are usually established through a device such as a network adapter on one of these expansion buses or a modem on a serial port. The client computer may be a desktop system or a portable system.

Scanner **320** is responsible for scanning casts of the patient's teeth obtained either from
25 the patient or from an orthodontist and providing the scanned digital data set information to data processing system **300** for further processing. In a distributed environment, scanner **320** may be located at a remote location and communicate scanned digital data set information to data processing system **300** via network interface **324**.

Fabrication machine **322** fabricates dental appliances based on intermediate and final data set information received from data processing system **300**. In a distributed environment, fabrication machine **322** may be located at a remote location and receive data set information from data processing system **300** via network interface **324**.

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While the above is a complete description of the preferred embodiments of the invention, various alternatives, modifications, and equivalents may be used. Therefore, the above description should not be taken as limiting the scope of the invention which is defined by the appended claims.

**THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE
PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:**

1. A method for producing a data set representing a desired tooth arrangement, said method comprising:

5 receiving at a computer, a first data set representing an initial tooth arrangement;

presenting an image representing the initial tooth arrangement based on the first data set;

10 causing the computer to manipulate the image of the initial tooth arrangement to reposition individual teeth in the image to produce an image representing the desired tooth arrangement; and

causing the computer to produce a second data set representing the desired tooth arrangement with repositioned teeth as observed in the image.

2. The method as in claim 1, further comprising:

15 producing a plurality of intermediate data sets representing a series of successive tooth arrangements progressing from the initial tooth arrangement toward the desired tooth arrangement.

3. The method as in claim 2, further comprising:

20 fabricating a plurality of successive tooth repositioning appliances, at least some of which are related to at least some of the produced data sets.

4. The method as in any one of claims 1 to 3, wherein receiving the first data set representing the initial tooth arrangement comprises scanning a three-dimensional model of a patient's teeth.

5. The method as in any one of claims 1 to 4, wherein causing the computer to manipulate the image comprises:
- defining tooth boundaries about at least some of the individual teeth; and
- moving at least some of the tooth boundaries relative to the other teeth in the image.
6. The method as in any one of claims 1 to 5, wherein fabricating the plurality of successive tooth repositioning appliances comprises fabricating a plurality of polymeric shell appliances.
7. The method as in claim 1, further comprising:
- producing a plurality of intermediate data sets representing a series of successive tooth arrangements progressing from the initial tooth arrangement to the desired tooth arrangement; and
- providing a plurality of the intermediate data sets to a fabrication operation for fabricating a series of successive tooth repositioning appliances to facilitate repositioning teeth.
8. The method as in claim 7, wherein the intermediate and second data sets represent substantially accurate shapes of a patient's actual teeth.
9. The method as in any one of claims 7 to 8, further comprising fabricating a plurality of successive tooth repositioning appliances based on at least a plurality of said intermediate data sets provided to the fabrication operation.
10. The method as in any one of claims 7 to 9, wherein fabricating the plurality of successive tooth repositioning appliances comprises fabricating polymeric shell appliances.

11. The method as in any one of claims 1 to 10 wherein the desired tooth arrangement comprises a first desired tooth arrangement and further comprising:

5 causing the computer to manipulate the image representing the first desired tooth arrangement to produce an image representing a second desired tooth arrangement; and

causing the computer to produce a third data set representing the second desired tooth arrangement with repositioned teeth as observed in the image representing a second desired tooth arrangement.

12. The method of claim 11 wherein the second data set and the third data set are produced at different times.

13. A method for producing a plurality of data sets representing a series of discrete tooth arrangements progressing from an initial tooth arrangement toward a desired tooth arrangement, said method comprising:

15 receiving at a computer, a first data set representing the initial tooth arrangement;

causing the computer to produce a second data set representing the desired tooth arrangement; and

20 causing the computer to produce a plurality of successive data sets based on said first and second data sets, wherein said plurality of successive data sets represent a series of successive tooth arrangements progressing from the initial tooth arrangement toward the desired tooth arrangement.

14. The method as in claim **13**, further comprising:

fabricating a plurality of dental incremental adjustment appliances based on at least some of the plurality of successive data sets.

15. The method as in any one of claims **13** to **14**, wherein receiving the first data set representing the initial tooth arrangement comprises scanning a three-dimensional model of a patient's teeth.

16. The method as in any one of claims **13** to **15**, wherein causing the computer to produce the second data set representing the desired tooth arrangement comprises:

defining tooth boundaries about at least some of the individual teeth; and

moving at least some of the tooth boundaries relative to the other teeth in an image based on the first data set to produce the second data set.

17. The method as in any one of claims **13** to **16**, wherein causing the computer to produce the plurality of successive data sets comprises determining positional differences between the first data set and the second data set and interpolating said positional differences.

18. The method as in claim **17**, wherein the interpolating step comprises linear interpolation.

19. The method as in claim **17**, wherein the interpolating step comprises non-linear interpolation.

20. The method as in any one of claims **17** to **19**, further comprising defining one or more key frames between the initial tooth arrangement and desired tooth arrangement and interpolating between the key frames.

21. The method as in any one of claims **14** to **20**, wherein fabricating comprises:

controlling a fabrication machine based on the successive data sets to produce successive positive models of the successive tooth arrangements; and

5 producing the dental appliances as negatives of the positive models.

22. The method as in claim **21**, wherein controlling the fabrication machine comprises, for each of the successive positive models:

providing a volume of non-hardened polymeric resin; and

10 scanning a laser to selectively harden the resin in a shape based on the respective successive data set to produce the respective successive positive model.

23. The method as in any one of claims **21** to **22**, wherein producing the dental appliances comprises modeling the dental appliances over the positive models.

15 **24.** The method as in any one of claims **14** to **23**, wherein fabricating the dental appliances comprises fabricating a series of successive appliances.

25. The method as in any one of claims **14** to **24**, wherein fabricating the dental appliances comprises fabricating polymeric shell appliances.

26. The method as in any one of claims **14** to **25** wherein causing the computer to produce the plurality of successive data sets comprises:

20 causing the computer to produce a plurality of successive data sets based on both of the first and second data sets, wherein said plurality of successive data sets represents substantially accurate shapes of a patient's

actual teeth in a series of successive tooth arrangements progressing from the initial tooth arrangement toward the desired tooth arrangement.

27. The method as in claim **26**, wherein the dental appliances are fabricated based on corresponding individual ones of the plurality of successive data sets.

5 **28.** The method as in any one of claims **13** to **27**, further comprising annotating the successive data sets to add text or numbering.

29. The method as in claim **28** wherein fabricating appliances based on at least some of the produced data sets comprises fabricating dental appliances having the text or numbering appearing on the dental appliances.

10 **30.** The method as in claim **29**, wherein the numbering appearing on the dental appliances indicates the order of use of each of the dental appliances.

31. The method as in any one of claims **13** to **30** wherein the desired tooth arrangement comprises a first desired tooth arrangement and further comprising:

15 causing the computer to produce a third data set representing a second desired tooth arrangement; and

 causing the computer to produce a further plurality of successive data sets based on said second and third data sets, wherein said further plurality of successive data sets represent a further series of successive tooth arrangements progressing from the first desired tooth arrangement toward
20 the second desired tooth arrangement.

32. The method of claim **31** wherein the second data set and the third data set are produced at different times.

33. A dental appliance fabricated in accordance with any one of methods of claims **1** to **32** for use in repositioning at least some of a patient's teeth.

34. A computer readable medium encoded with codes for directing a processor to execute the method of any one of claims **1** to **32**.

35. An apparatus for producing a data set representing a desired tooth arrangement, the apparatus comprising a processor circuit operably configured to:

5 in response to receiving a first data set representing an initial tooth arrangement:

 present an image representing the initial tooth arrangement based on the first data set;

10 manipulate the image of the initial tooth arrangement to reposition individual teeth in the image to produce an image representing the desired tooth arrangement; and

 produce a second data set representing the desired tooth arrangement with repositioned teeth as observed in the image.

15 **36.** The apparatus as in claim **35**, wherein the first data set comprises a scanned three-dimensional model of a patient's teeth.

37. The apparatus as in any one of claims **35** to **36**, wherein the processor is operably configured to:

 define tooth boundaries about at least some of the individual teeth; and

20 move at least some of the tooth boundaries relative to the other teeth in the image.

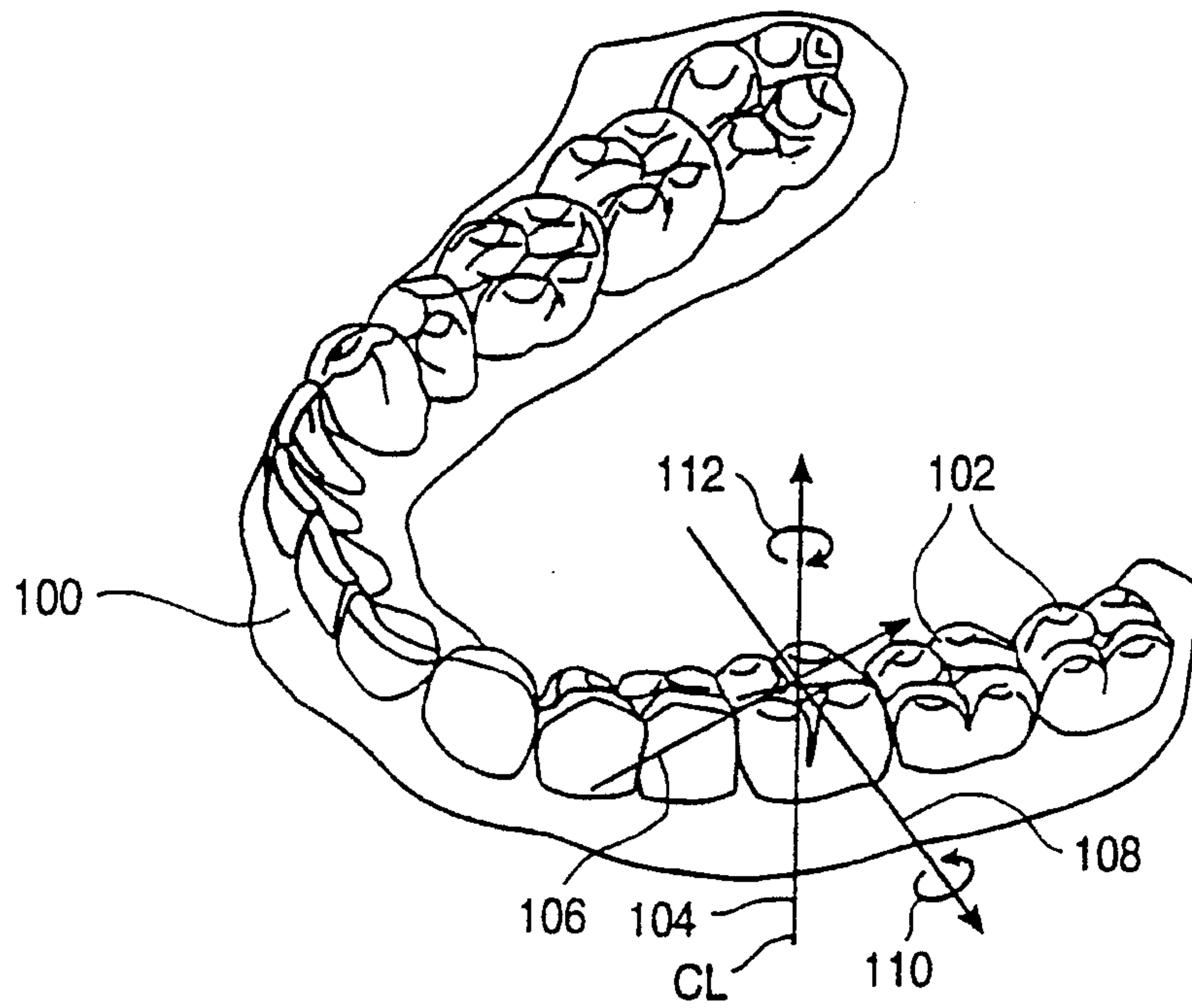


FIG. 1A

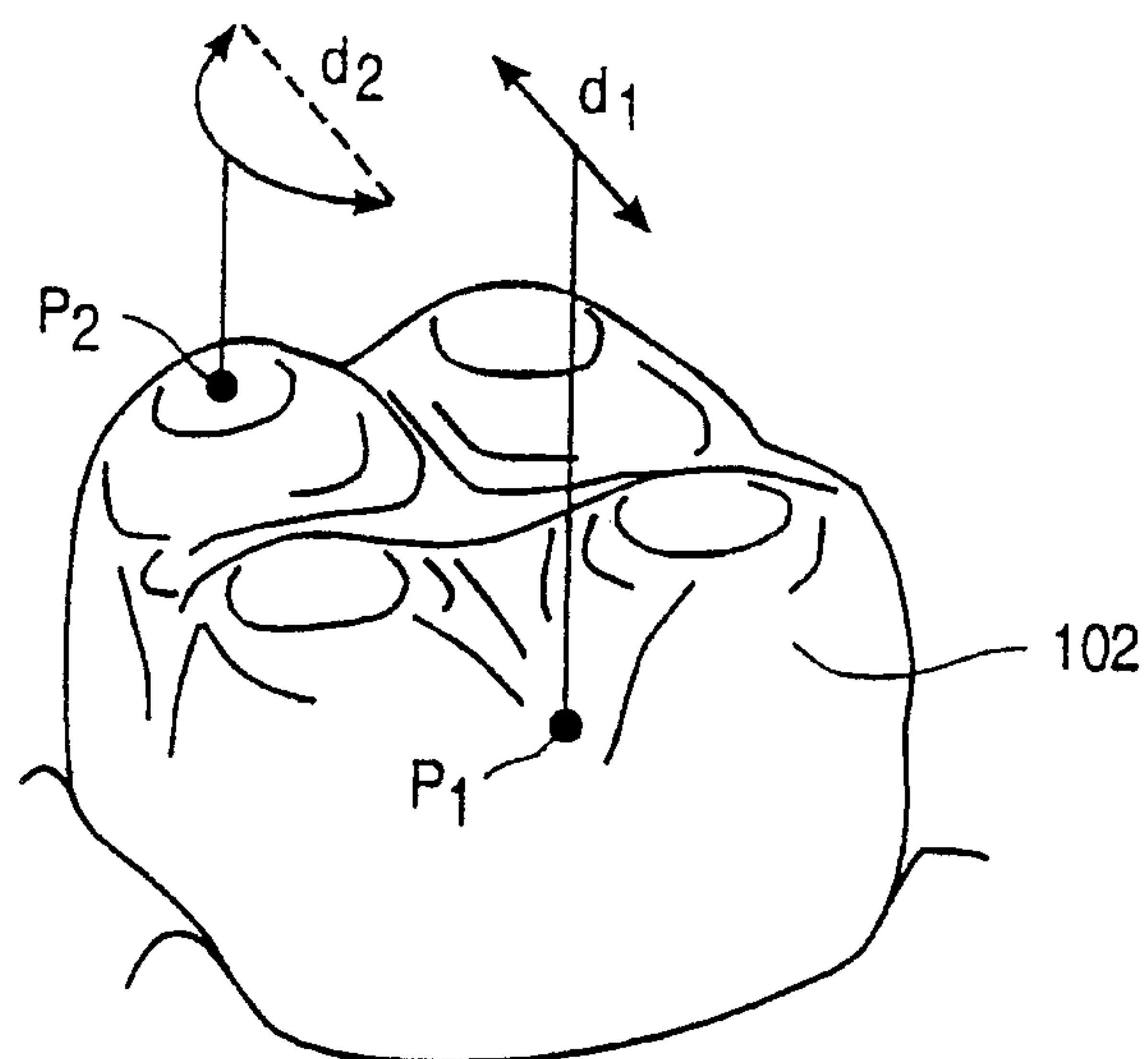


FIG. 1B

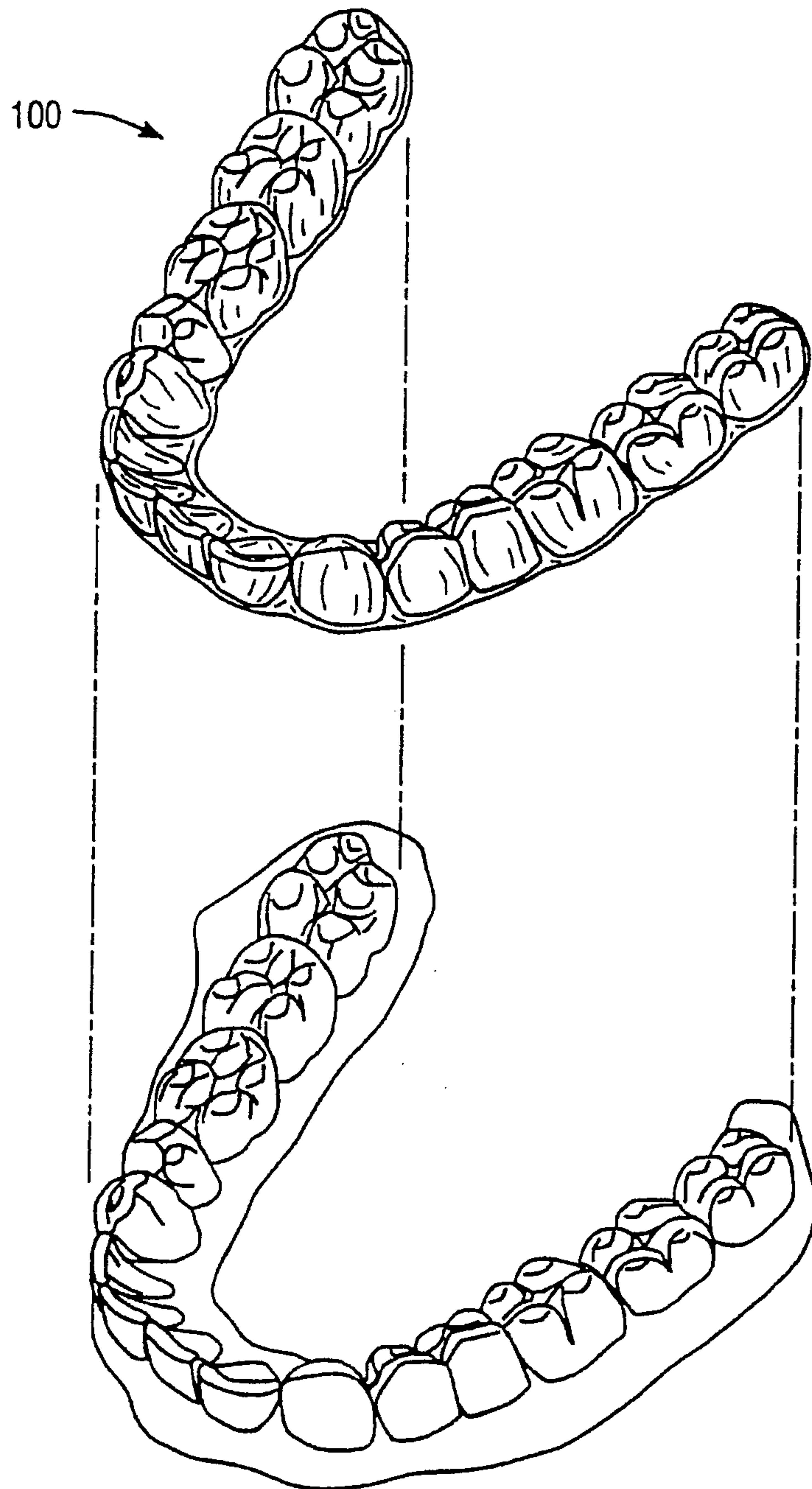


FIG. 1C

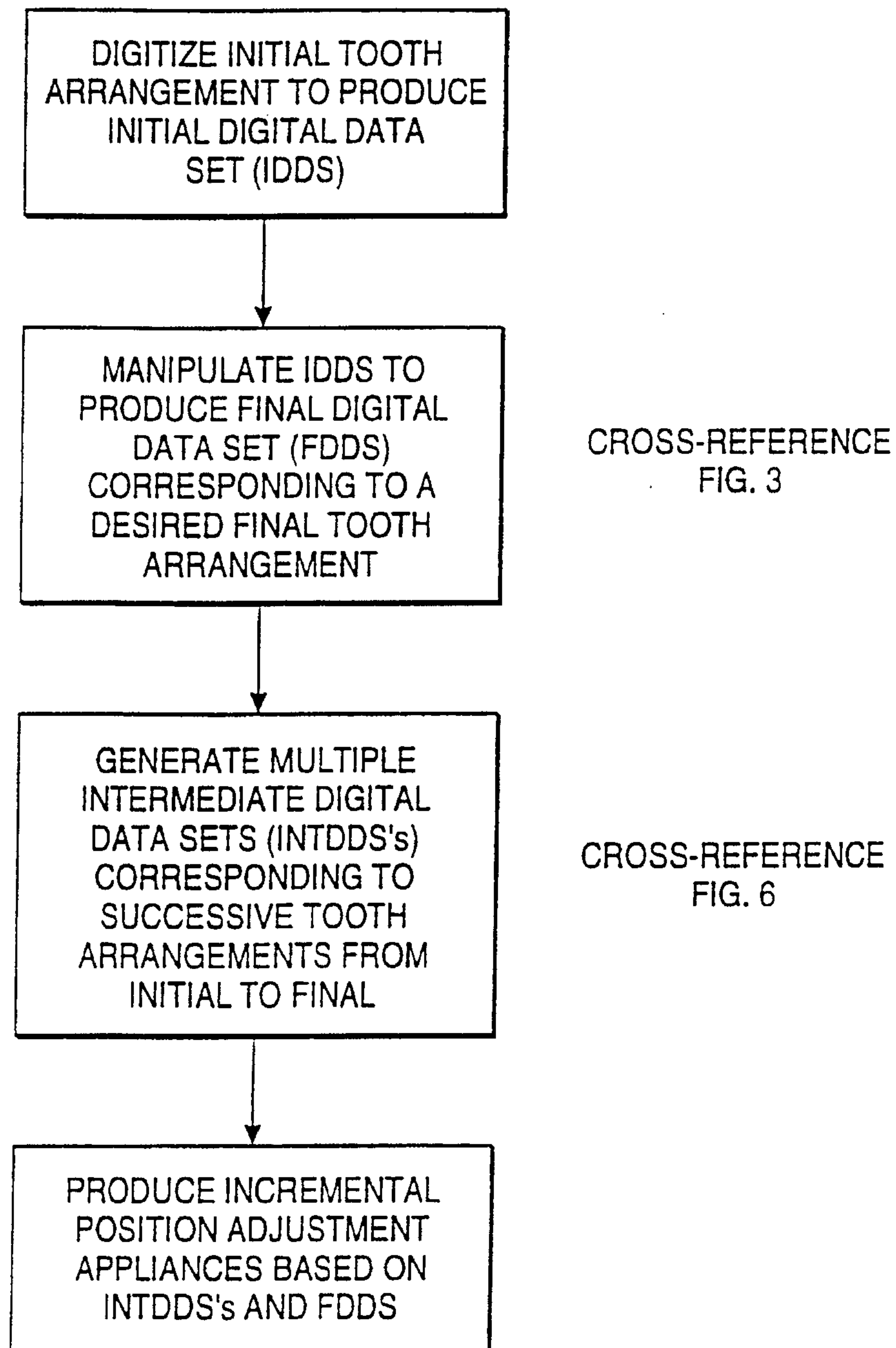


FIG. 2

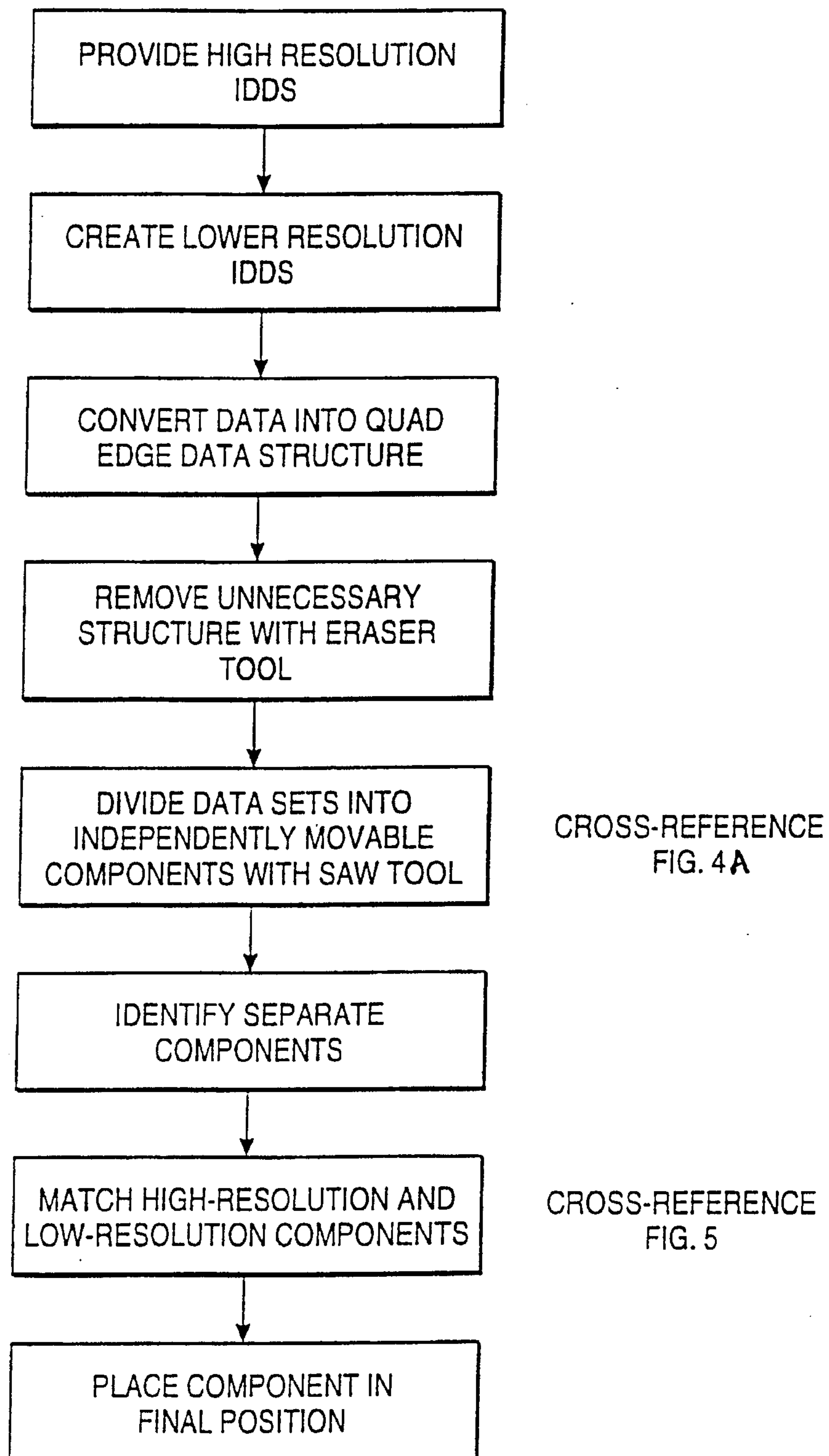
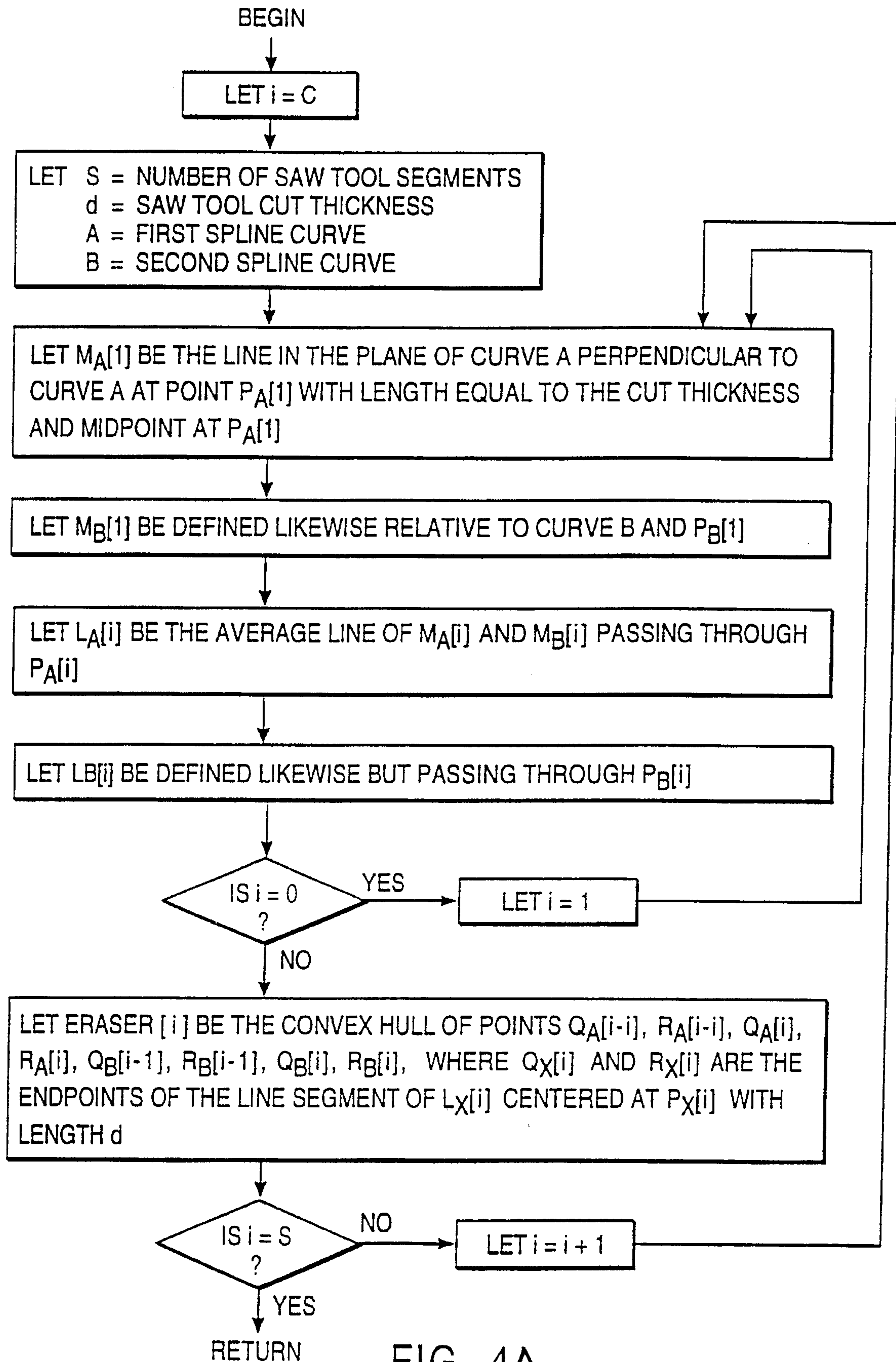


FIG. 3

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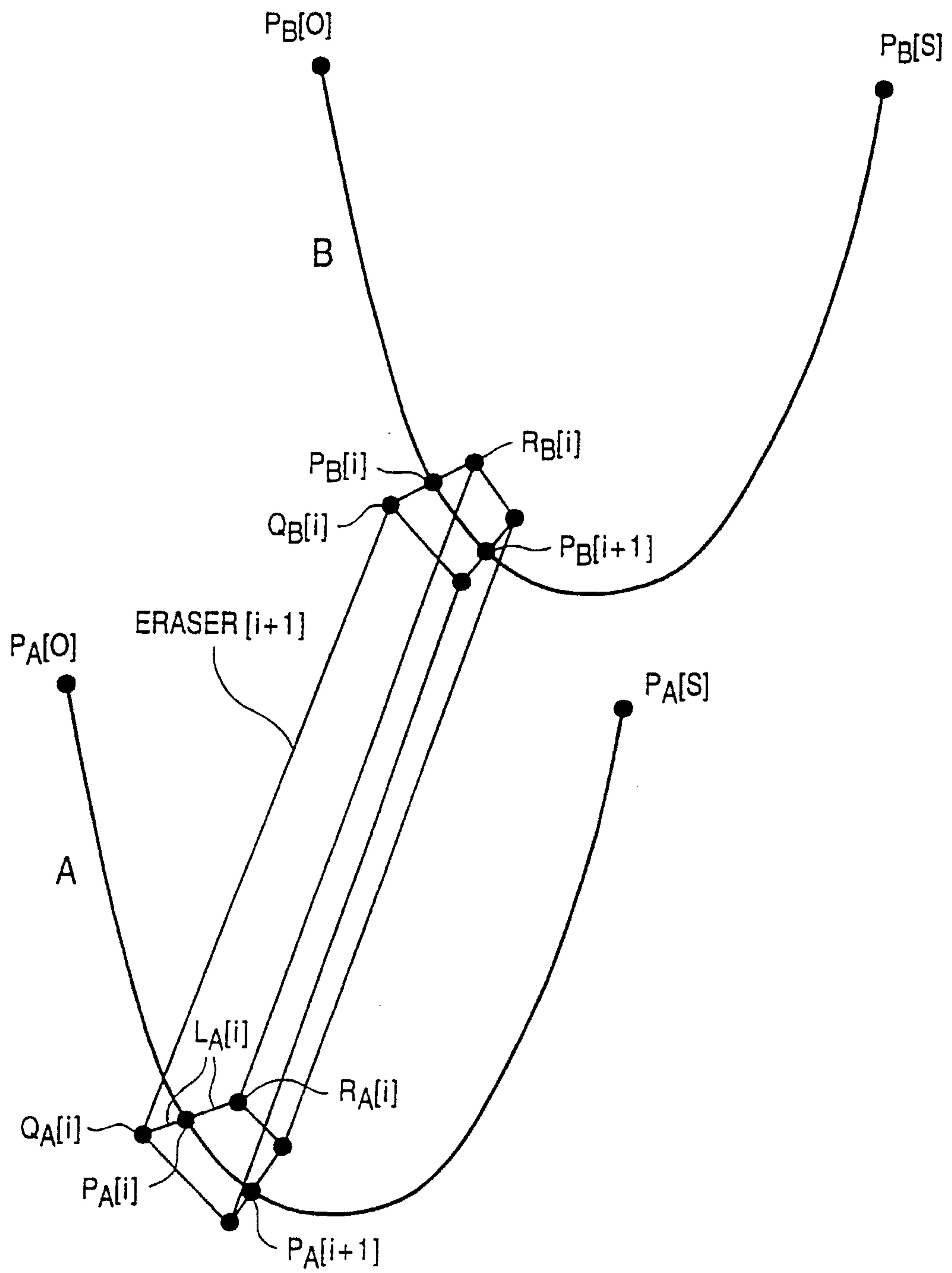


FIG. 4 B

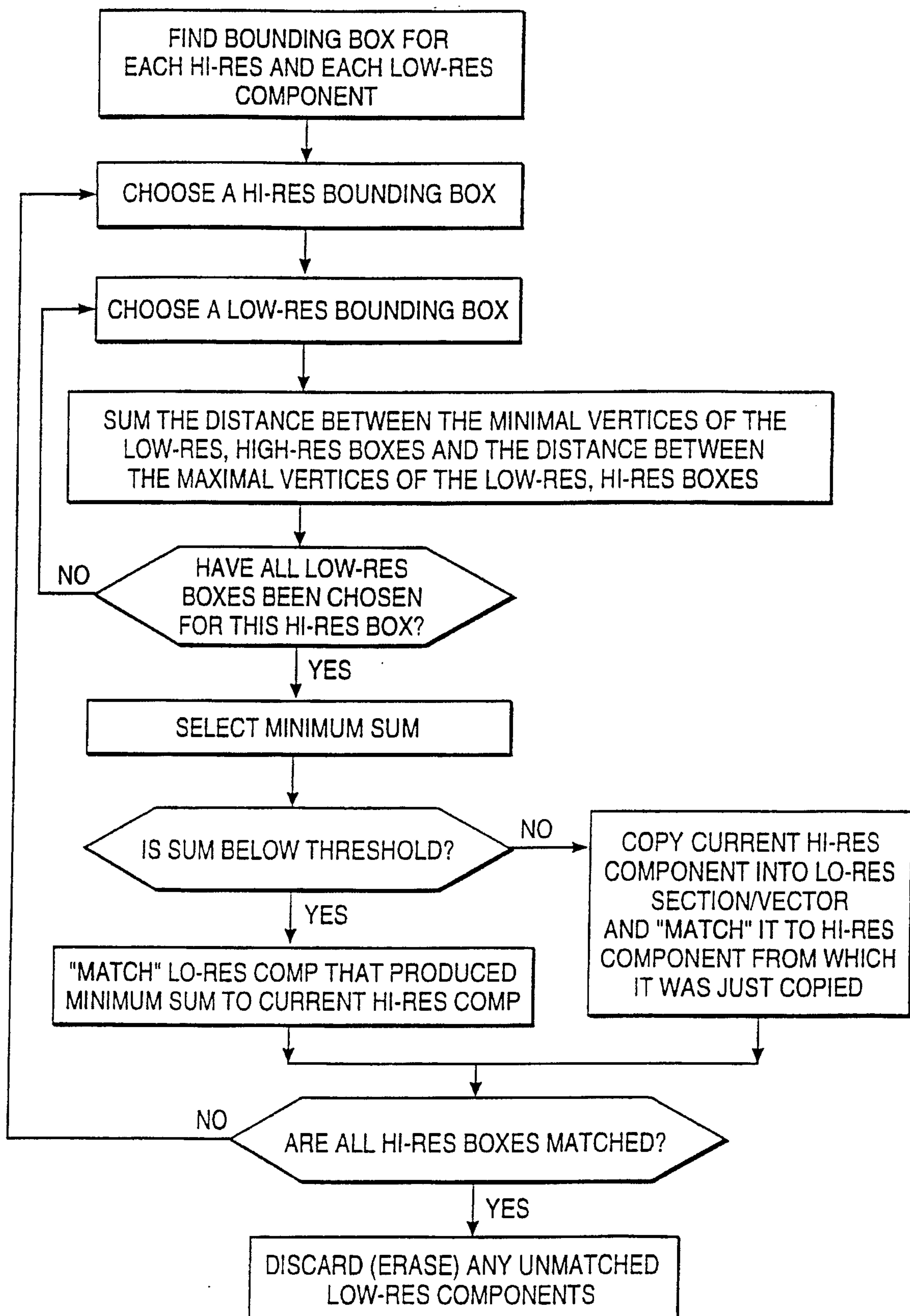


FIG. 5

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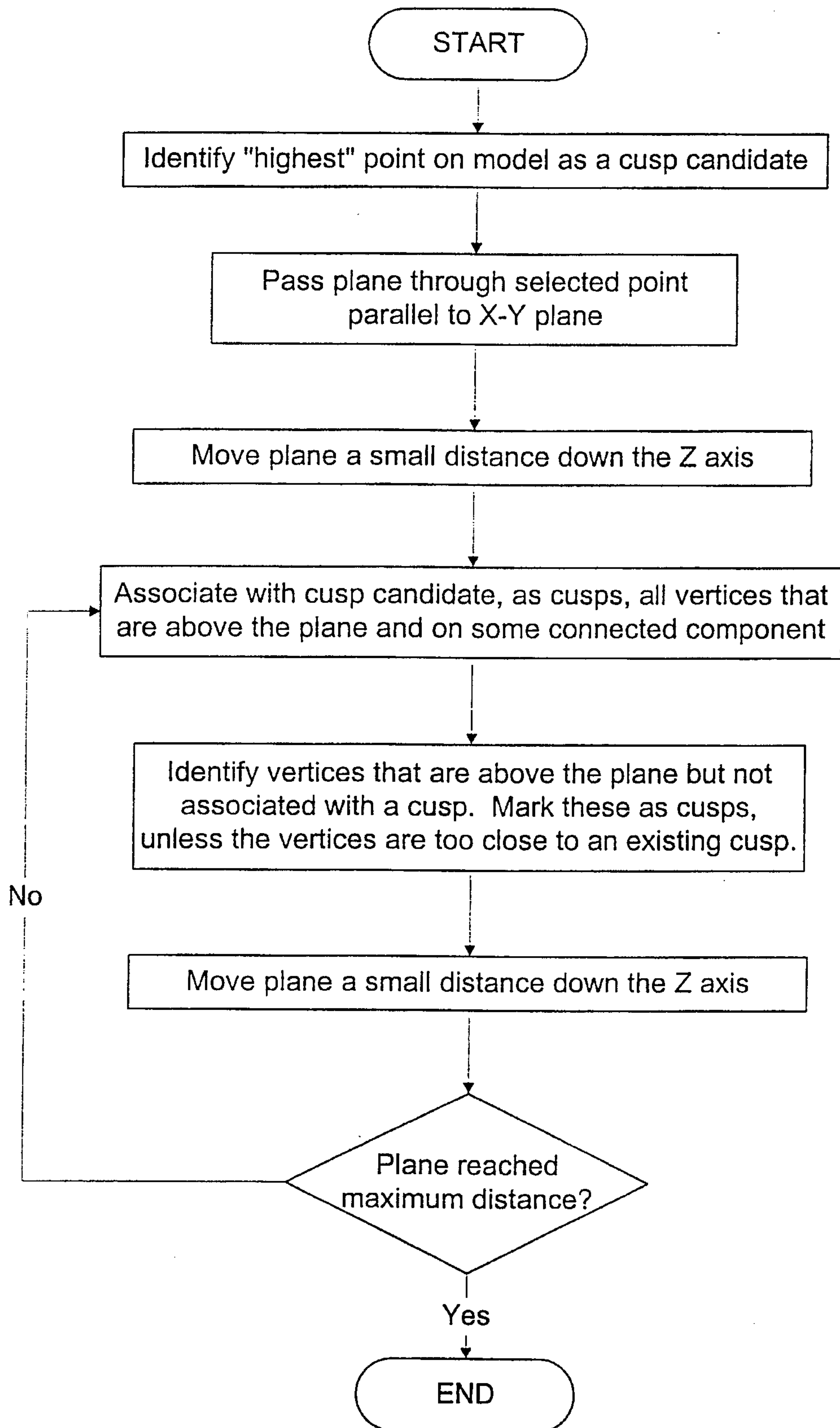


FIG. 6A

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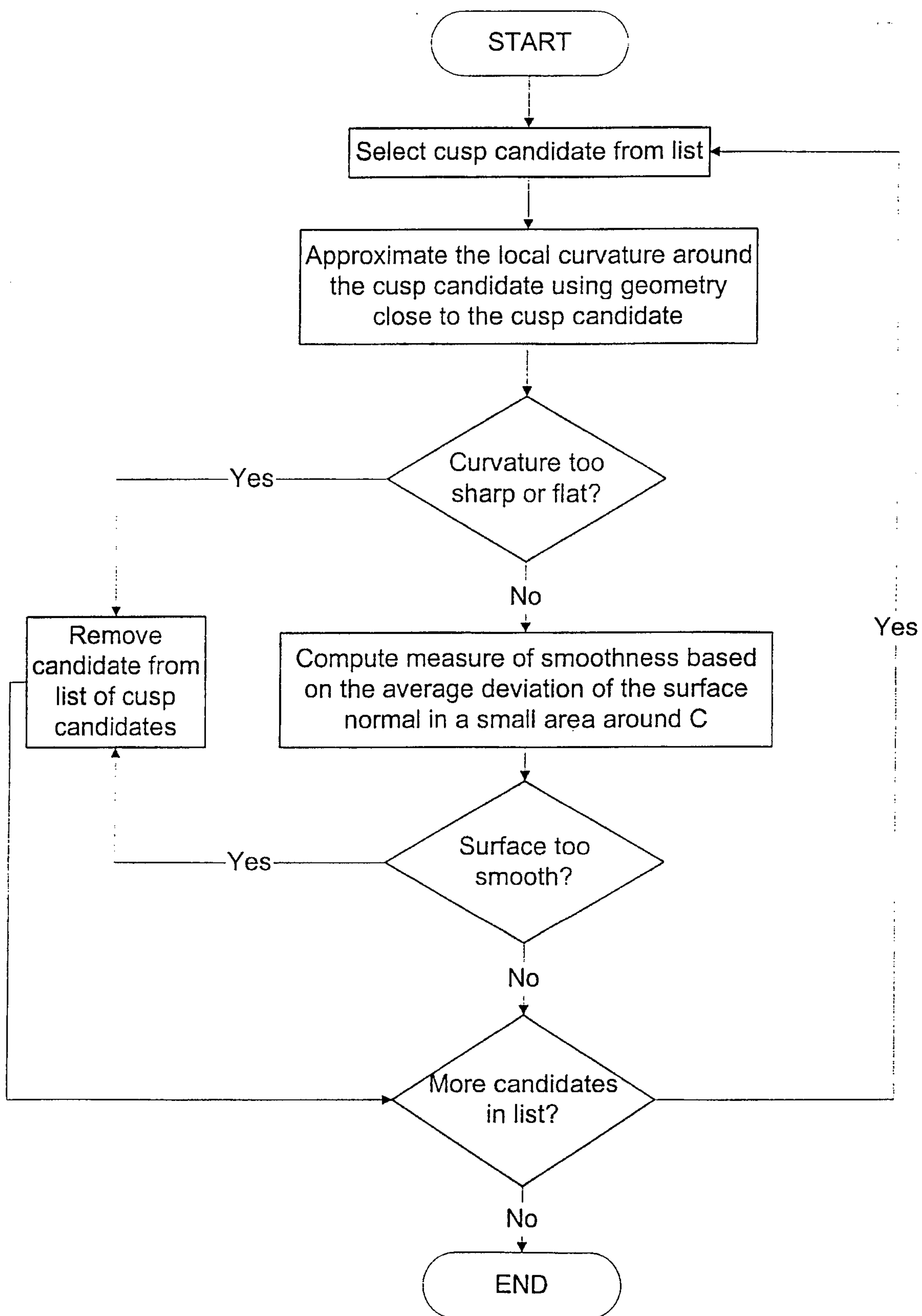


FIG. 6B

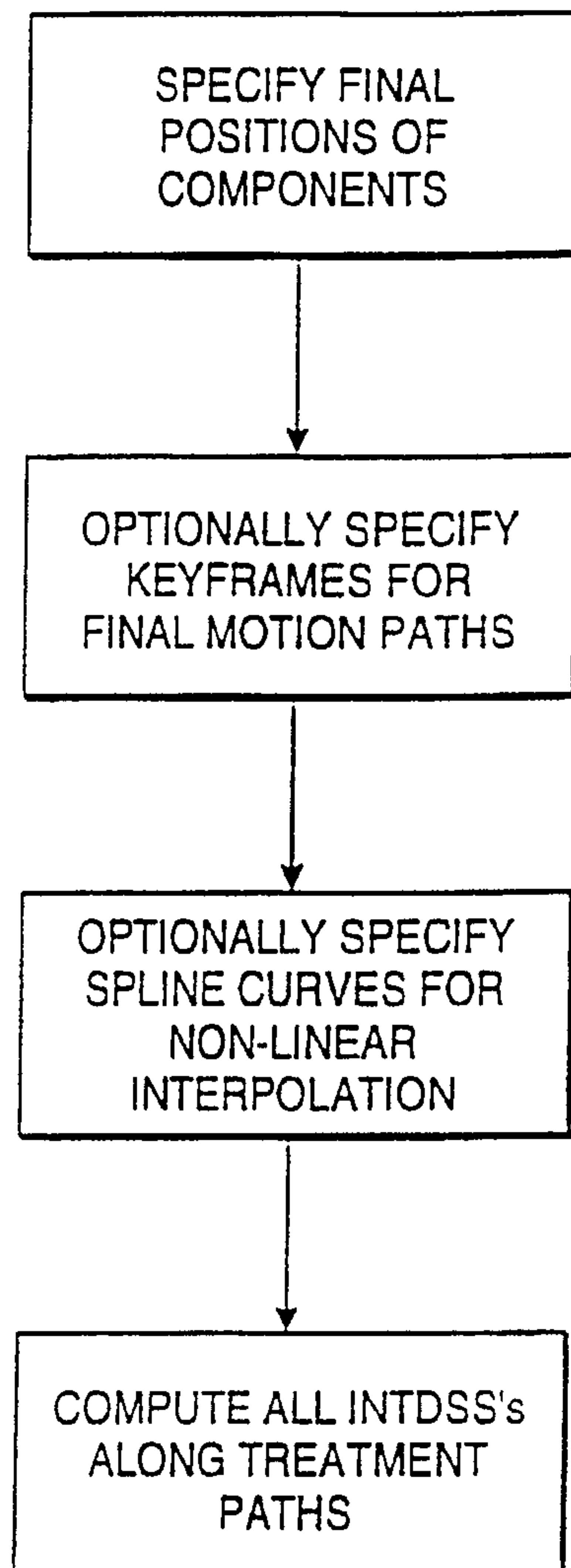


FIG. 7

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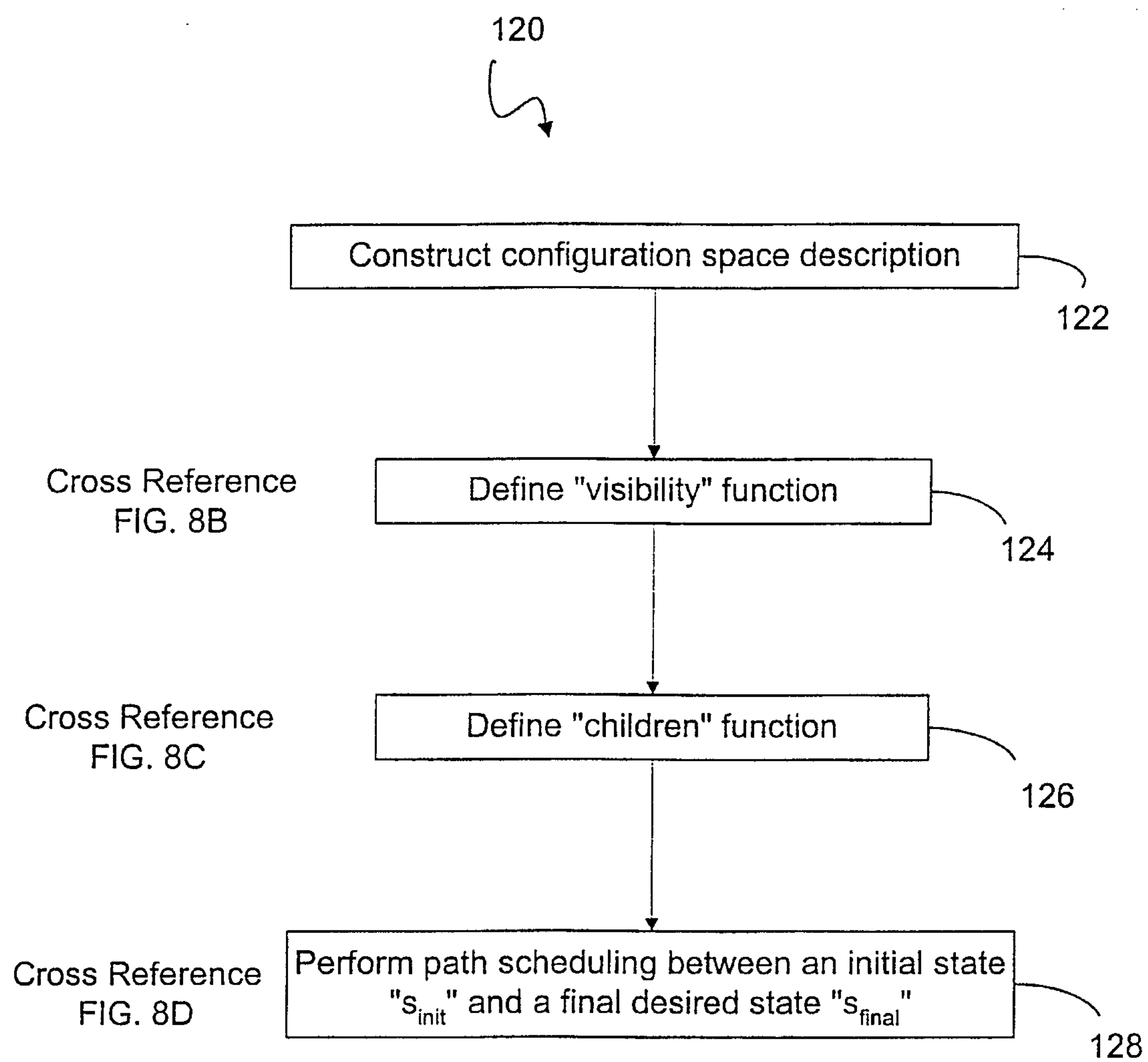


FIG. 8A

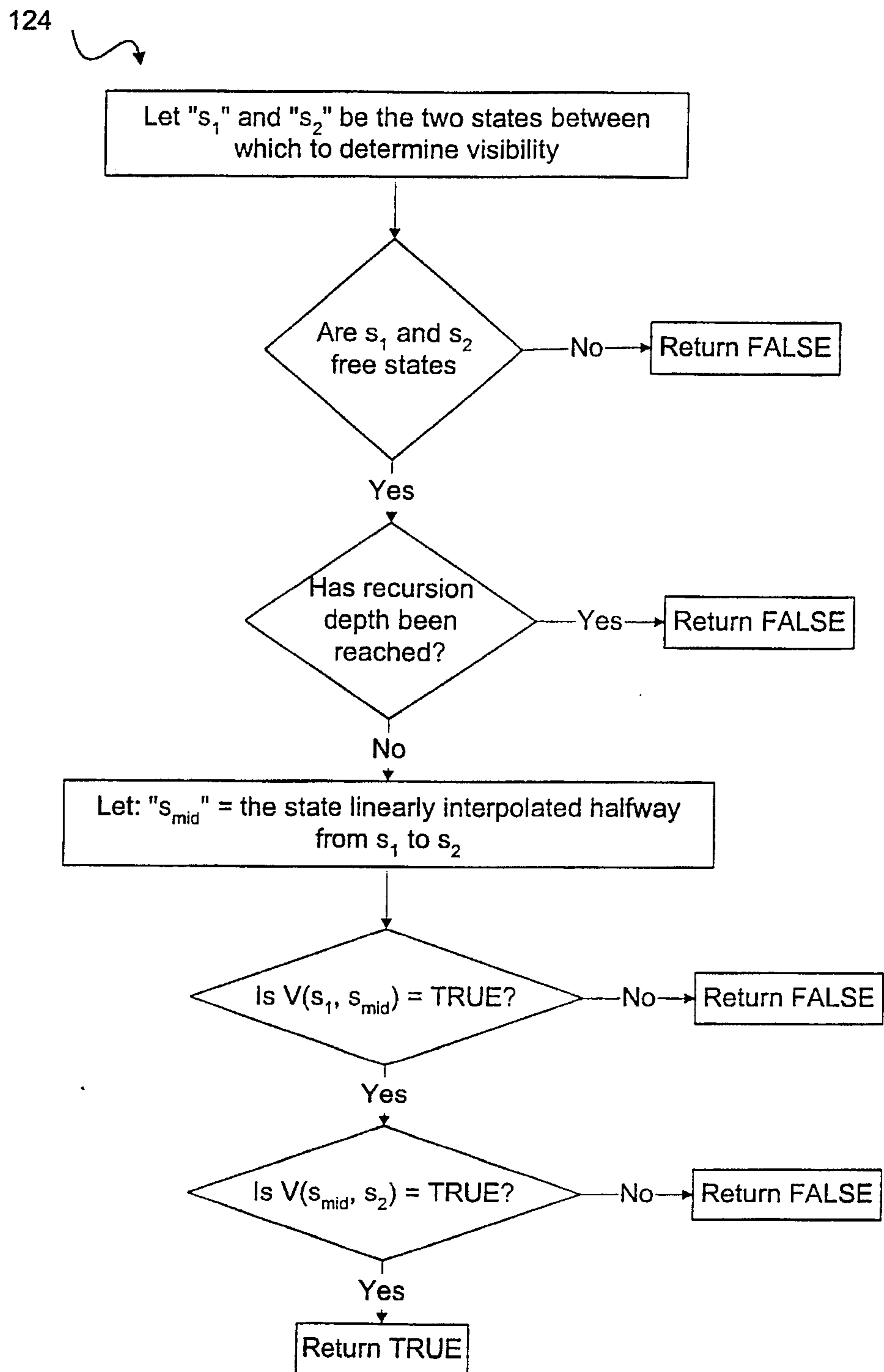


FIG. 8B

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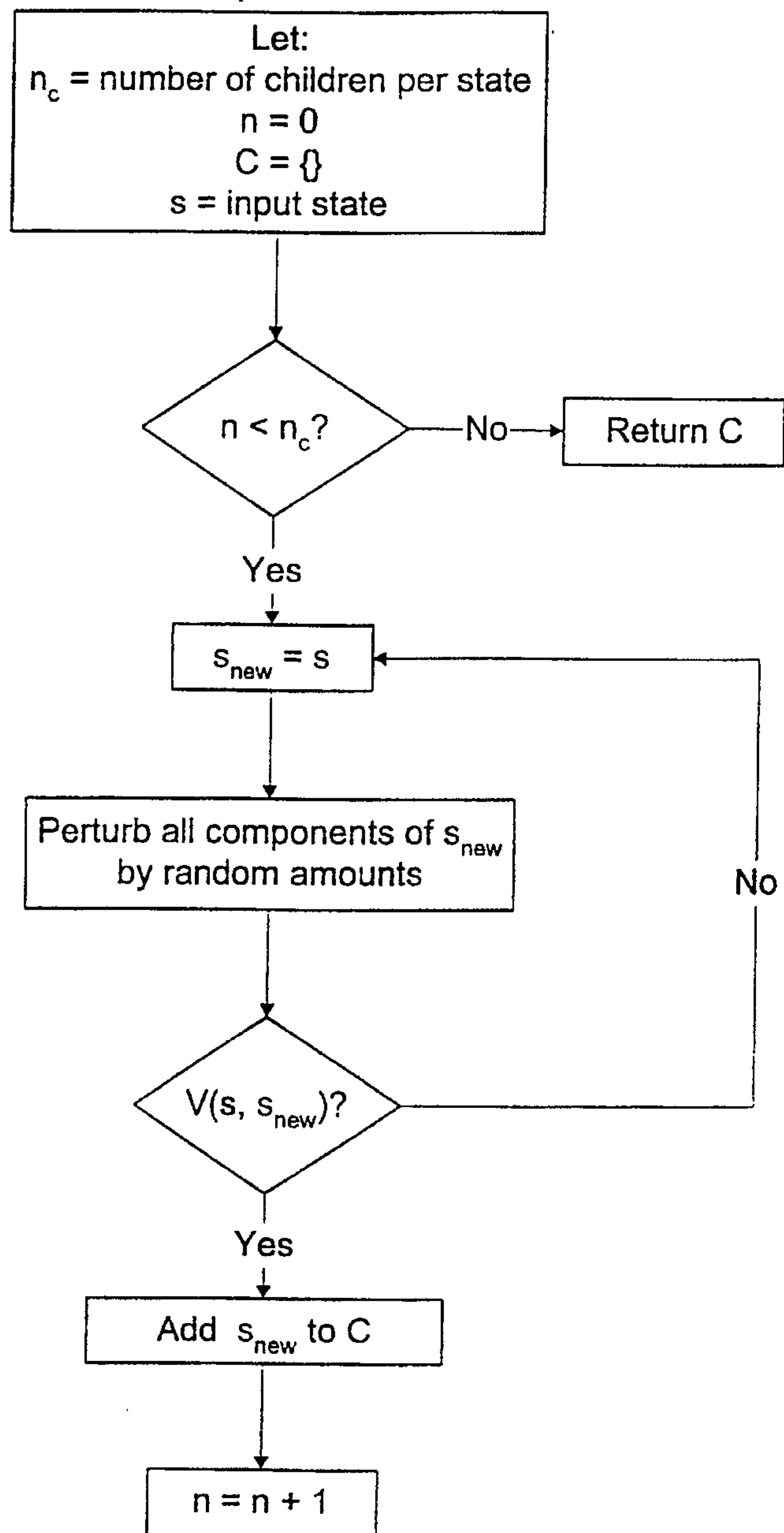


FIG. 8C

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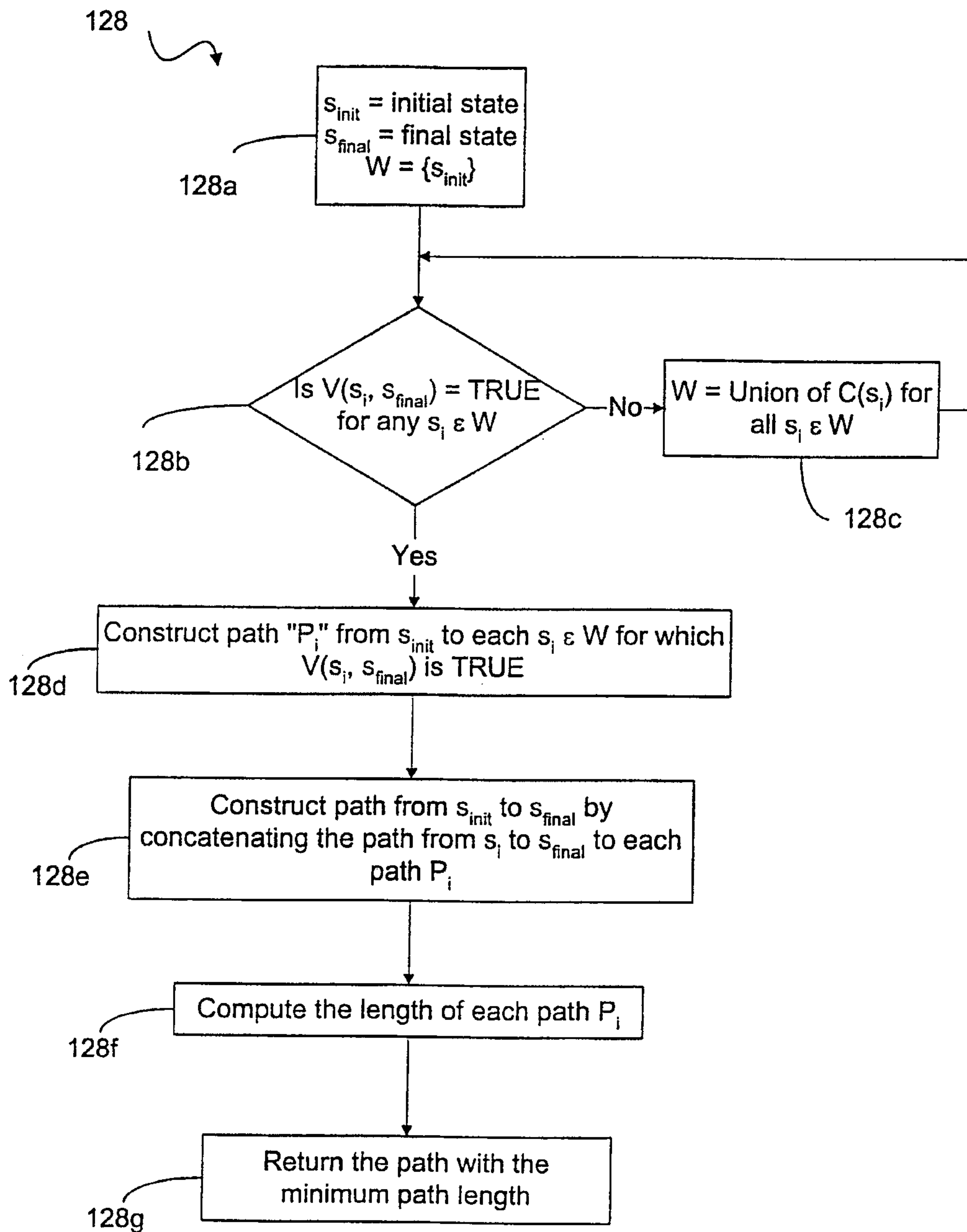


FIG. 8D

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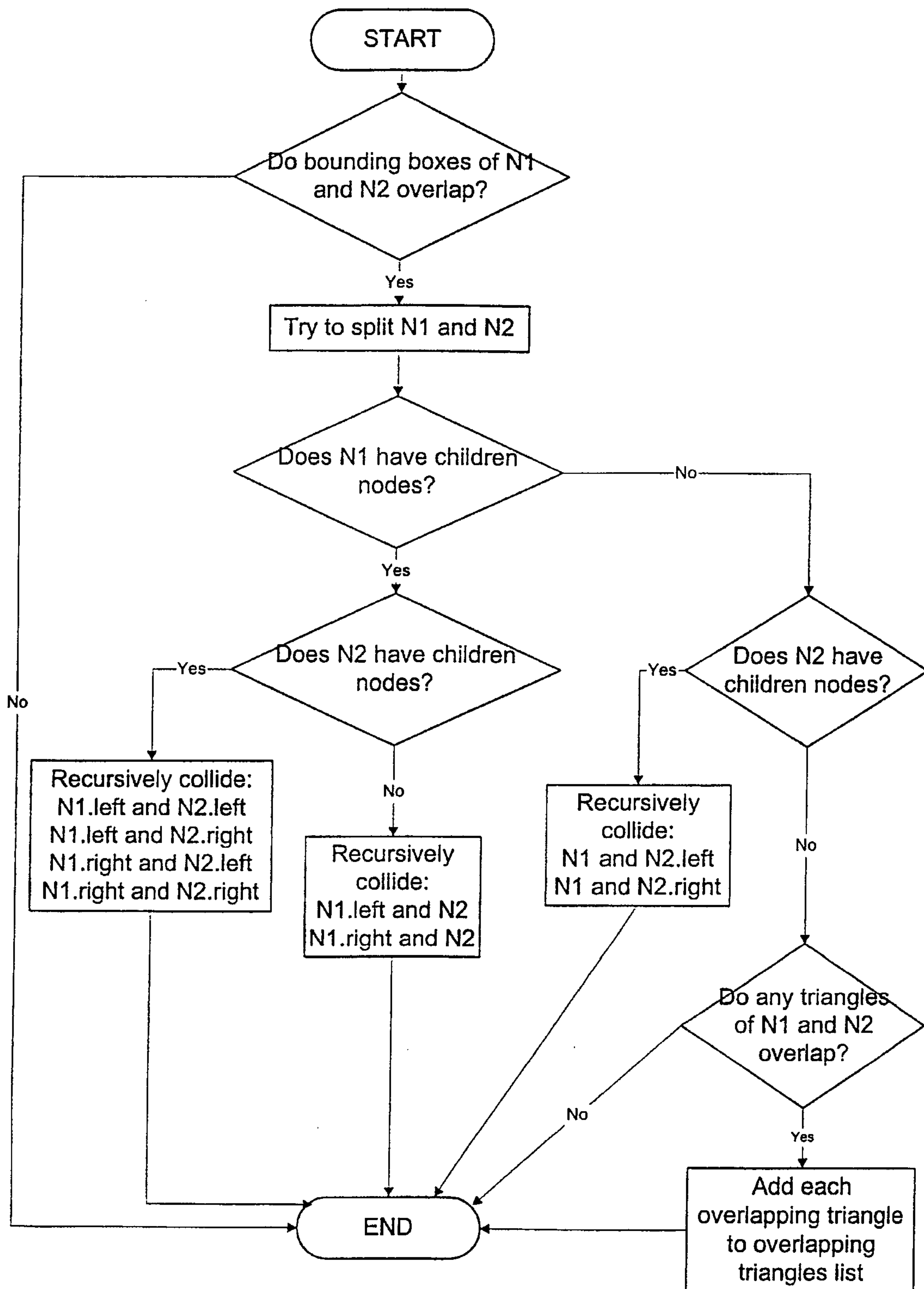


FIG. 9A

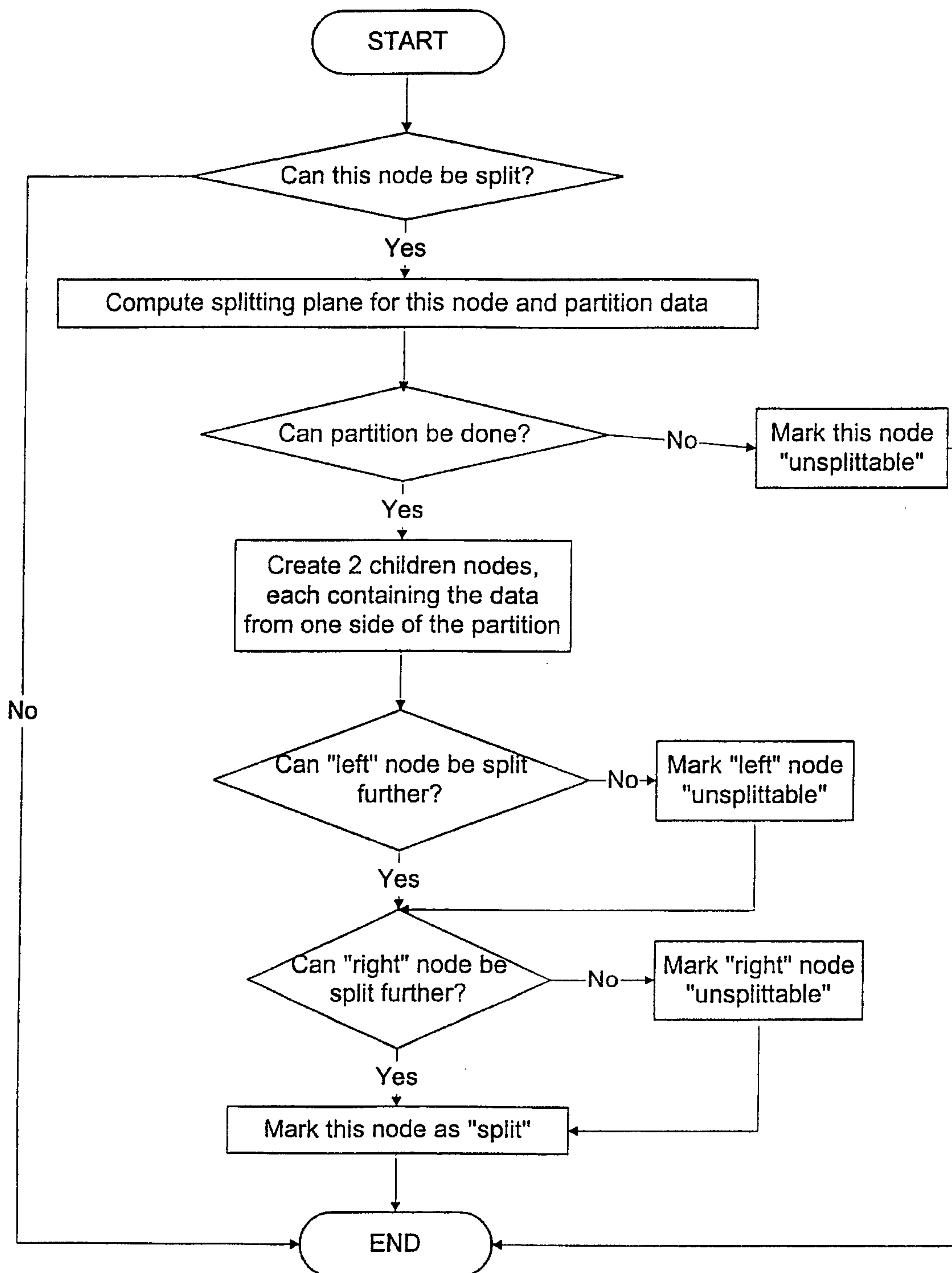


FIG. 9B

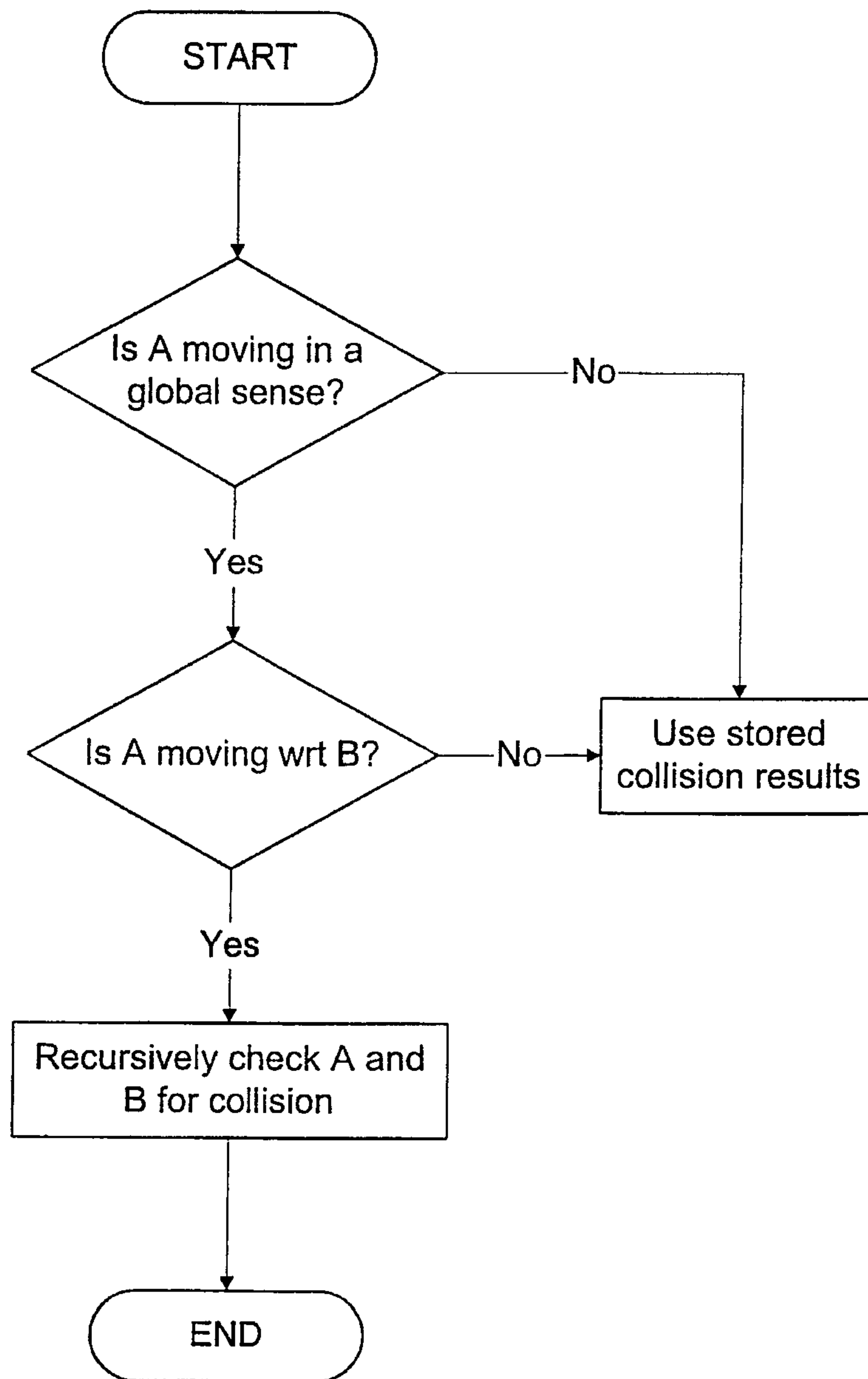


FIG. 9C

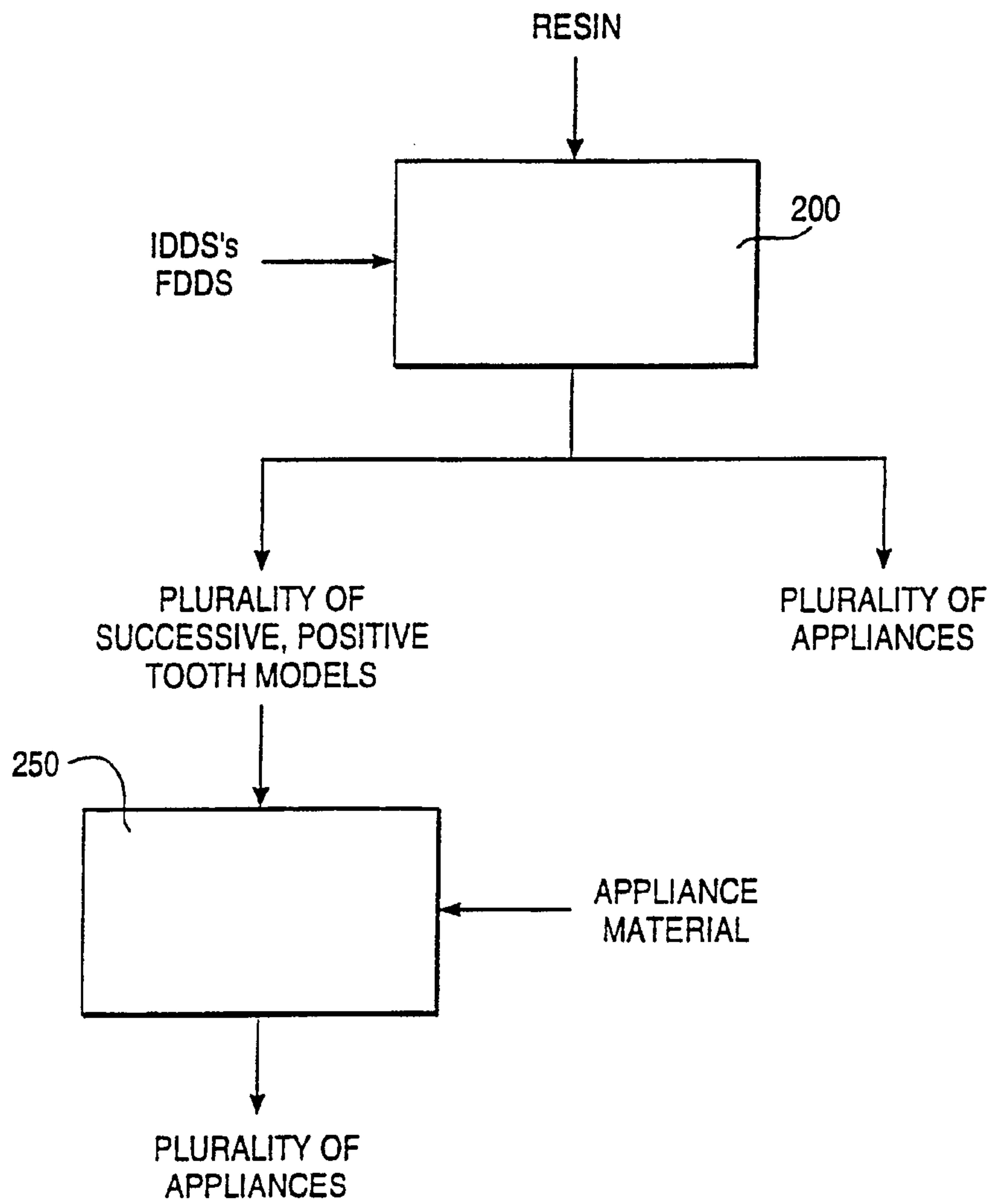


FIG. 10

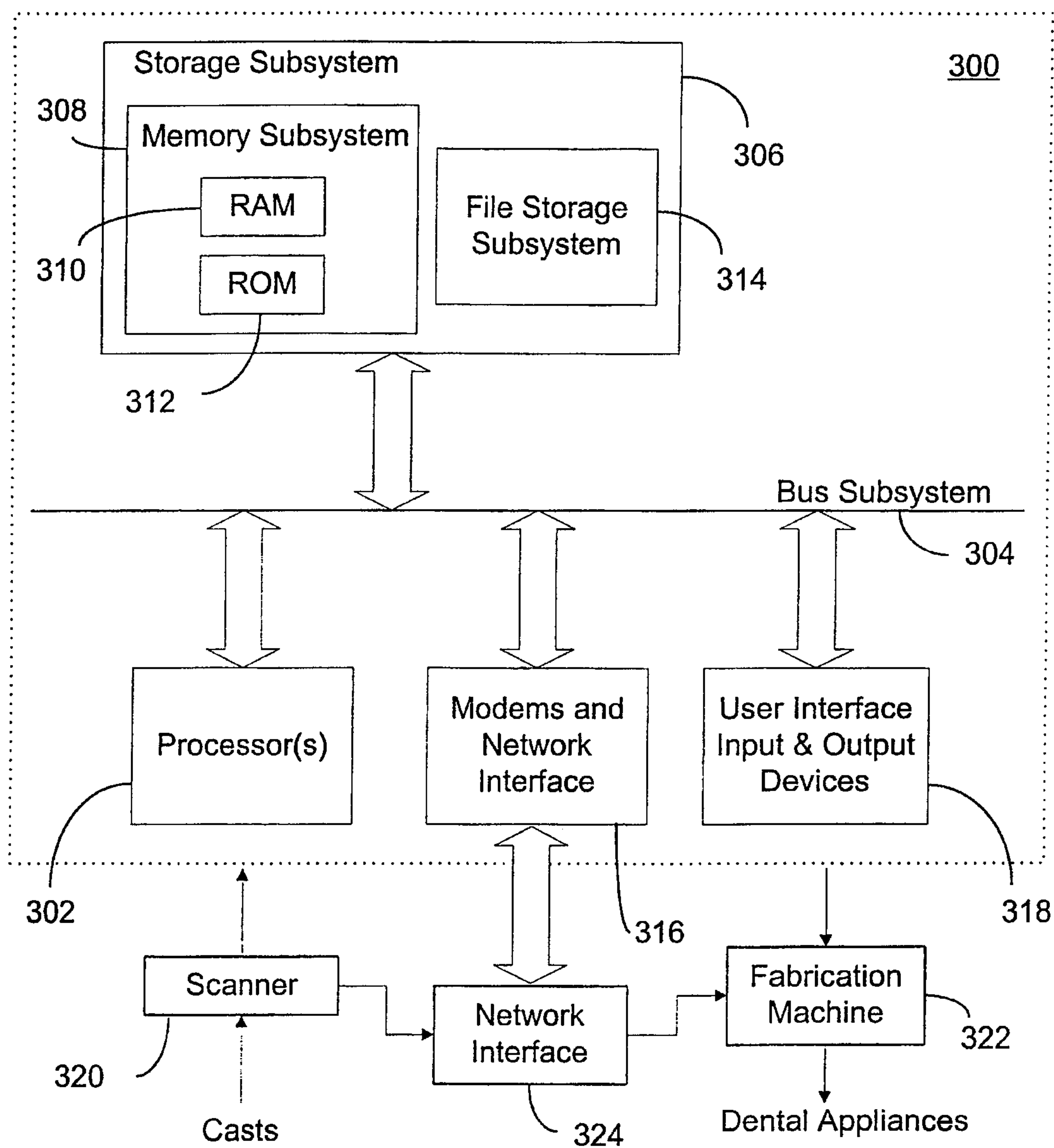


FIG. 11

DIGITIZE INITIAL TOOTH
ARRANGEMENT TO PRODUCE
INITIAL DIGITAL DATA
SET (IDDS)



MANIPULATE IDDS TO
PRODUCE FINAL DIGITAL
DATA SET (FDDS)
CORRESPONDING TO A
DESIRED FINAL TOOTH
ARRANGEMENT

CROSS-REFERENCE
FIG. 3



GENERATE MULTIPLE
INTERMEDIATE DIGITAL
DATA SETS (INTDDS's)
CORRESPONDING TO
SUCCESSIVE TOOTH
ARRANGEMENTS FROM
INITIAL TO FINAL

CROSS-REFERENCE
FIG. 6



PRODUCE INCREMENTAL
POSITION ADJUSTMENT
APPLIANCES BASED ON
INTDDS's AND FDDS