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(54) **Title:** GRAPH-BASED KEY FRAME SELECTION FOR 3-D SCANNING

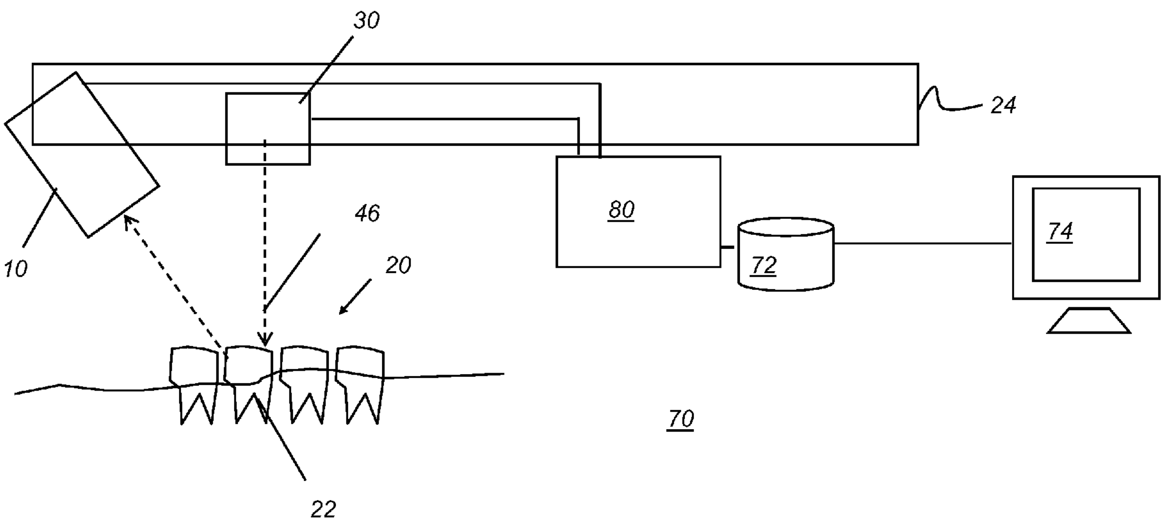

FIG. 1

(57) **Abstract:** A method for acquiring and updating a 3-D dentition surface acquires a succession of 3-D image frames of the dentition from different points of view using a 3-D scanning device. For each individual acquired 3-D image frame, one or more spatial relationships to other acquired 3-D image frames is identified according to relative distance and overlap between the individual and other acquired 3-D image frames. The 3-D surface of the dentition is formed and updated using a matching algorithm that aggregates image content from the 3-D image frames according to the one or more spatial relationships and according to overlap and distance of each 3-D image frame relative to the 3-D surface of the dentition. A subset of the succession of 3-D image frames having reduced data redundancy is selected, based on spatial relationships. A pose of the 3-D surface is rendered and displayed according to the selected subset.

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GRAPH-BASED KEY FRAME SELECTION FOR 3-D SCANNING

TECHNICAL FIELD

The disclosure relates generally to 3-D surface contour scanning and more particularly to methods and apparatus for improving pose acquisition, processing, and presentation by selecting a subset of the scanned image data.

BACKGROUND

Three-dimensional (3-D) imaging and 3-D image processing are of growing interest to dental practitioners for computer-aided diagnosis and overall improved patient care. In orthodontics and other areas, such as cephalometric analysis, 3-D imaging and 3-D image processing offer significant advantages over existing techniques in terms of flexibility, accuracy, and repeatability.

Optical intraoral scans, in general, produce contours of dentition objects and have been helpful in improving visualization of teeth, gums, and other intra-oral structures. Surface contour information can be particularly useful for assessment of tooth condition and has recognized value for various types of dental procedures, such as for restorative dentistry. This can provide a valuable tool to assist the dental practitioner in identifying various problems and in validating other measurements and observations related to the patient's teeth and supporting structures. Surface contour information can also be used to generate 3-D models of dentition components such as individual teeth; the position and orientation information related to individual teeth can then be used in assessing and planning restorative dental prostheses and for evaluating orthodontic treatment progress. With proper use of surface contour imaging, the need for multiple 2-D or 3-D X-ray acquisitions of a patient's dentition can be avoided.

A number of techniques have been developed for obtaining surface contour information from various types of objects in medical, industrial, and other applications. Optical 3-dimensional (3-D) measurement methods provide shape and depth information using light directed onto a surface in various ways. Among types of imaging methods used for contour imaging are structured light imaging devices. Structured light projection imaging uses patterned or structured light and camera/sensor triangulation to obtain surface contour information for structures of various types. Once the structured light projection images are processed, a point cloud can be generated. A 3-D mesh can then be formed from the point cloud, in order to reconstruct a close approximation to the surface.

Mesh representation can be particularly useful for showing surface structure of teeth and gums and can be obtained using a handheld camera and without requiring harmful radiation levels. Improved scanner acquisition speeds for 3-D frame captures make it possible to process the captured frames and generate highly detailed 3-D contour surfaces in mesh or point cloud form while the scan is being performed.

Rapid contour image acquisition using continuous 3-D scanning, however, can require storage and processing of a significant amount of redundant data from the scanner. For accuracy and to provide a useful range of pose positions, only a fraction of the generated 3-D frames is needed. There would be advantages to acquisition processing methods that can select the subset of image frames necessary for forming an individual pose, thus reducing response time without noticeable impact on image quality and surface contour accuracy.

SUMMARY

It is an object of the present disclosure to advance the art of surface contour characterization. For intraoral imaging applications, embodiments of the present disclosure address the need to reduce the data processing and storage burden for 3-D surface acquisition and representation by selecting a subset of key frames from the larger set of structured light images of the surface of interest.

These objects are given only by way of illustrative example, and such objects may be exemplary of one or more embodiments of the invention. Other desirable objectives and advantages inherently achieved may occur or become apparent to those skilled in the art. The invention is defined by the appended claims.

According to one aspect of the disclosure, there is provided a method for acquiring and updating a 3-D surface of a dentition, the method executed at least in part by a computer and comprising:

a) acquiring a succession of a plurality of 3-D image frames of the dentition from different points of view using a 3-D scanning device;

b) for each individual acquired 3-D image frame, identifying one or more spatial relationships to other acquired 3-D image frames according to relative distance and an overlap metric between the individual and other acquired 3-D image frames;

c) forming and updating the 3-D surface of the dentition using a matching algorithm that aggregates image content from the 3-D image frames according to the one or more spatial relationships and according to overlap and distance of each 3-D image frame relative to the 3-D surface of the dentition;

d) selecting a subset of the succession of 3-D image frames having reduced data redundancy, based on the spatial relationships; and

e) rendering a pose of the 3-D surface and displaying the rendered pose according to the selected subset.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features, and advantages of the invention will be apparent from the following more particular description of the embodiments of the invention, as illustrated in the accompanying drawings.

The elements of the drawings are not necessarily to scale relative to each other.

FIG. 1 is a schematic diagram that shows components of an imaging apparatus for surface contour imaging of a patient's teeth and related structures.

FIG. 2 shows schematically how patterned light is used for obtaining surface contour information using a handheld camera or other portable imaging device.

FIG. 3 shows an example of surface imaging using a pattern with multiple lines of light.

FIG. 4 shows a point cloud generated from structured light imaging, such as that shown in FIG. 3.

FIG. 5 shows a polygon mesh in the simple form of a triangular mesh.

FIG. 6 is a logic flow diagram that shows a sequence for 3-D intraoral surface acquisition, view positioning, and updating according to an embodiment of the present disclosure.

FIG. 7A shows relative scan positions for a full set of image frames acquired in an intraoral imaging session.

FIG. 7B shows a partial subset of image frames that can be used as key frames for pose setup and configuration.

FIG. 8 shows a simplified schematic representing a set of acquired images as vertices in a spanning tree.

FIG. 9 shows an exemplary connected dominating subset generated from the simplified spanning tree shown in FIG. 8.

DETAILED DESCRIPTION OF THE EMBODIMENTS

The following is a detailed description of the preferred embodiments, reference being made to the drawings in which the same reference numerals identify the same elements of structure in each of the several figures.

Where they are used, the terms “first”, “second”, and so on, do not necessarily denote any ordinal or priority relation, but may be used for more clearly distinguishing one element or time interval from another.

The term “exemplary” indicates that the description is used as an example, rather than implying that it is an ideal.

The term “in signal communication” as used in the application means that two or more devices and/or components are capable of communicating with each other via signals that travel over some type of signal path. Signal communication may be wired or wireless. The signals may be communication, power, data, or energy signals which may communicate information, power, and/or energy from a first device and/or component to a second device and/or component along a signal path between the first device and/or component and second device and/or component. The signal paths may include physical, electrical, magnetic, electromagnetic, optical, wired, and/or wireless connections between the first device and/or component and second device and/or component. The signal paths may also include additional devices and/or components between the first device and/or component and second device and/or component.

In the context of the present disclosure, the terms “pixel” and “voxel” may be used interchangeably to describe an individual digital image data element, that is, a single value representing a measured image signal intensity. Conventionally an individual digital image data element is referred to as a voxel for 3-dimensional or volume images and a pixel for 2-dimensional (2-D) images. For the purposes of the description herein, the terms voxel and pixel can generally be considered equivalent, describing an image elemental datum that is capable of having a range of numerical values. Voxels and pixels have attributes of both spatial location and image data code value.

The equivalent terminology "patterned light" or “structured light” is used to indicate light that has a predetermined spatial pattern, such that the light has one or more features such as one or more discernable parallel lines, curves, a grid or checkerboard pattern, or other features having areas of light separated by areas without illumination. In the context of the present disclosure, the phrases "patterned light" and "structured light" are considered to be equivalent, both used to identify the light that is projected onto the surface of interest, such as onto the surface of the patient's dentition, in order to derive contour image data.

In the context of the present disclosure, the terms "viewer", "operator", and "user" are considered to be equivalent and refer to the viewing practitioner, technician, or other person who views and manipulates a contour image that is formed from a combination of multiple structured light images on a display monitor.

A "viewer instruction", "operator instruction", or "operator command" can be obtained from explicit commands entered by the viewer or may be implicitly obtained or derived based on some other user action, such as making an equipment setting, for example. With respect to entries entered on an operator interface, such as an interface using a display monitor and keyboard, for example, the terms "command" and "instruction" may be used interchangeably to refer to an operator entry.

In the context of the present disclosure, a single projected line of light is considered a "one dimensional" pattern, since the line has an almost negligible width, such as when projected from a line laser, and has a length that is its predominant dimension. Two or more of such lines projected side by side, either simultaneously or in a scanned arrangement, provide a two-dimensional pattern.

The terms "3-D model", "3-D mesh", and "point cloud" may be used synonymously to describe a surface contour image in the context of the present disclosure. The dense point cloud is formed using techniques familiar to those skilled in the volume imaging arts for forming a point cloud and relates generally to methods that identify, from the point cloud, vertex points corresponding to surface features. The dense point cloud is thus generated using the reconstructed contour data from one or more reflectance images, such as those described subsequently herein. Dense point cloud information serves as the basis for a polygon model at high density for the teeth and gum surface.

The term "set", as used herein, refers to a non-empty set or subset, as the concept of a collection of elements or members of a set is widely understood in elementary mathematics. The term "subset", unless otherwise explicitly stated, is used herein to refer to a non-empty proper subset, that is, to a subset of the larger set, having one or more members, but having at least one fewer member than the larger set. A "proper subset" of set S is strictly contained in set S, is non-empty, and excludes at least one member of set S. Cardinality refers to the number of members in a set.

Embodiments of the present disclosure provide methods that help to reduce the processing burden, both in terms of processing time and storage requirements, where the full set of acquired 3-D image frames for the surface of interest has substantial redundant information. The methods described herein provide the logic for selection of a subset of key frames for processing and 3-D contour generation, wherein the subset is significantly reduced in size (cardinality) from the full set of acquired contour images.

Various types of 3-D acquisition devices can be used for scanning the tooth surface and forming 3-D images from the series of images obtained.

Reference is hereby made to an article by A. Melbourne, G. Ridgway, D. J. Hawkes, entitled "Image Similarity Metrics in Image Registration" in *Medical Imaging 2010, Proceedings SPIE* Volume 7623, 762335 (2010); doi: 10.1117/12.840389. Further reference is made to an article by Li, P.C. & Toulouse, Michel, entitled. "Maximum leaf spanning tree problem for grid graphs" *JCMCC. The Journal of Combinatorial Mathematics and Combinatorial Computing.* 73, May 2010.

FIG. 1 is a schematic diagram showing a type of imaging apparatus 70 that serves as a scanning device for generating 3-D images. Imaging apparatus 70 can be used for projecting and imaging using structured light patterns 46. Imaging apparatus 70 uses a handheld camera 24 for image frame acquisition according to an embodiment of the present disclosure. A control logic processor 80, or other type of computer that may be part of camera 24 controls the operation of an illumination array 10, such as an array having one or more light emitting diodes (LEDs), or other suitable light source, that generates the structured light and controls operation of an imaging sensor array 30. Image data from surface 20, such as from a tooth 22, is obtained, as a series of one or more image frames, from imaging sensor array 30 and stored in a memory 72. Control logic processor 80, in signal communication with camera 24 components that acquire the image, processes the received image data, generates a mapping of the surface contour by stitching together content from adjacent image frames, and stores the mapping in memory 72. The resulting 3-D contour image from memory 72 is then optionally rendered and displayed on a display 74. Memory 72 may also include a display buffer for temporarily storing display 74 image content.

In structured light projection imaging of a surface, a pattern of lines or other features is projected from illumination array 10 toward the surface of an object from a given angle. The projected pattern from the surface is then viewed from another angle as a contour image, taking advantage of triangulation in order to analyze surface information based on the appearance of contour lines. Phase shifting, in which the projected pattern is incrementally shifted spatially for obtaining additional measurements at the new locations, is typically applied as part of structured light projection imaging, used in order to complete the contour mapping of the surface and to increase overall resolution in the contour image.

The schematic diagram of FIG. 2 shows, with the example of a single line of light L, how patterned light is used for obtaining surface contour information using a handheld camera or other portable imaging device. A mapping is obtained as an illumination array 10 directs a pattern of light onto a surface 20 and a corresponding image of a line L' is formed on imaging sensor array 30. Each pixel 32 on imaging sensor array 30 maps to a corresponding pixel 12 on illumination array 10 according to modulation by surface 20. Shifts in pixel position, as represented in FIG. 2, yield useful information about the contour of surface 20. It can be appreciated that the basic pattern shown in FIG. 2 can be implemented in a number of ways, using a variety of illumination sources and sequences and using one or more different types of sensor arrays 30. Illumination array 10 can utilize any of a number of types of arrays used for light modulation, such as a liquid crystal array or digital micromirror array, such as that provided using the Digital Light Processor or DLP device from Texas Instruments, Dallas, TX. This type of spatial light modulator is used in the illumination path to change the light pattern as needed for the mapping sequence.

By projecting and capturing images that show structured light patterns that duplicate the arrangement shown in FIGs. 1 and 2 multiple times, the image of the contour line on the camera simultaneously locates a number of surface points of the imaged object. This speeds the process of gathering many sample points, while the plane of light (and usually also the receiving camera) is laterally moved in order to "paint" some or all of the exterior surface of the object with the plane of light.

FIG. 3 shows surface imaging using a pattern with multiple lines of light. Incremental shifting of the line pattern and other techniques help to compensate for inaccuracies and confusion that can result from abrupt transitions along the surface, whereby it can be difficult to positively identify the segments that correspond to each projected line. In FIG. 3, for example, it can be difficult to determine whether line segment 16 is from the same line of illumination as line segment 18 or adjacent line segment 19.

By knowing the instantaneous position of the camera and the instantaneous position of the line of light within an object-relative coordinate system when the image was acquired, a computer and appropriate software logic can use triangulation methods to compute the coordinates of numerous illuminated surface points. As the plane is moved to intersect eventually with some or all of the surfaces of the object, the coordinates of an increasing number of points are accumulated. As a result of this image acquisition, a point cloud of vertex points or vertices can be identified and used to represent the extent of a surface within a volume.

Another type of 3-D acquisition device that can be used for scanning the tooth surface captures a series of 3-D images that can be stitched together in order to form a surface contour image of larger scale, such as an image of dentition for an upper or lower jaw, for example.

By way of example, FIG. 4 shows a dense 3-D point cloud 50 generated from a structured light imaging apparatus, CS 3500 3-D camera made by Carestream Inc., Rochester NY, USA, using results from patterned illumination such as that shown in FIG. 3. The point cloud 50 models physical location of sampled points on tooth surfaces and other intraoral surfaces or, more generally, of surfaces of a real-world object. Variable resolution can be obtained. The example of FIG. 4 shows an exemplary 100 micron resolution. The points in the point cloud represent actual, measured points on the three dimensional surface of an object.

The surface structure can be approximated from the point cloud representation by forming a polygon mesh, in which adjacent vertices are connected by line segments. For a particular vertex, its adjacent vertices are those vertices closest to the vertex in terms of Euclidean distance.

By way of example, FIG. 5 shows a 3-D polygon mesh model 60 in the simple form of a triangular mesh. A triangular mesh forms a basic mesh structure that can be generated from a point cloud and used as a digital model to represent a 3-D object by its approximate surface shape, in the form of triangular plane segments sharing adjacent boundaries. Methods for forming a polygon mesh model, such as a triangular mesh or more complex mesh structure, are well known to those skilled in the contour imaging arts. The polygon unit of the mesh model, and relationships between neighboring polygons, can be used in embodiments of the present disclosure to extract features such as minimum curvatures at the teeth boundaries.

It should be noted that structured light imaging, widely used for surface contour acquisition and modeling, is one among a number of imaging methods that can be used for generating a 3-D mesh model or a point cloud. Other types of imaging that can be used for surface contour characterization can include reflectance imaging used with structure from motion techniques, for example. Still other types of depth imaging have been implemented for various types of surface structure, including video speed 3-D imagers that obtain a succession of smaller 3-D images that can be stitched together. The graph-based selection method described herein can be applied to other types of contour and depth imaging that are stitched together in order to generate a 3-D surface contour for dentition or other type of surface.

In practice, reflectance images and associated depth information can be acquired as quickly as possible in order to minimize scanner displacement during the sequence of camera exposures during the generation of image data.

Point cloud or mesh data structures can be used equivalently to represent 3-D surface growth during and following image capture from the scanner. A point cloud with normals and colors can be extracted from a colored/texture mesh, such as using vertices from the mesh and their average triangle normal and vertex color, discarding the triangle data. A mesh with colors can be readily generated from a point cloud using methods well known to those skilled in the volume imaging arts.

A number of methods familiar to those skilled in the volume imaging arts can be used for stitching together the successive frames generated in continuous 3-D scanning in order to form a surface contour, including use of feature matching, iterative closest point calculations, refinement, and distance measurement and scoring, for example. Feature matching, for example, employs correspondences between feature descriptors in different views, selecting from a group of correspondences according to various metrics.

Numerous image frames are acquired by a scanning apparatus such as imaging apparatus 70 described with reference to FIG. 1, at rates that can be 8 frames per second or higher. As the scanner is moved along the tooth surface, processing software generates the 3-D surface contour in a continuous manner, growing the surface by matching and stitching together adjacent frames.

An embodiment of the present disclosure provides improved efficiency and reduced processing burden for generating a 3-D mesh from numerous individual scanned frames by reducing the number of frames needed to generate a 3-D pose.

The logic flow diagram of FIG. 6 shows a sequence for 3-D intraoral surface acquisition and updating according to an embodiment of the present disclosure. In an acquisition step S600, scanning of the mouth is executed, acquiring numerous 3-D image frames of patient dentition from different angles using an intraoral scanning camera, as described previously with reference to FIG. 1. A reconstruction step S610 obtains the image input from the scanner continuously during the scan and constructs and updates a model of the 3-D surface contour accordingly. Reconstruction step S610 employs various types of matching algorithm, aggregating and correlating the acquired image frames based on an overlap metric and factors such as relative distance of the acquired frame content from the 3-D surface. An overlap metric can be calculated, indicative of the amount of overlap between adjacent images, using a measurement of relative image correlation and a threshold for the correlation value, following procedures familiar to those skilled in the imaging arts. Overlap calculation characterizes the relative similarity or redundancy between peripheral image data for two adjacent images. A variable measure of relative redundancy can be calculated based in the similarity between adjacent images, using metrics known to those skilled in the imaging arts. A reduced level of data redundancy indicates that two adjacent images share some percentage of the same image content, but do not have extensive overlap.

A relational step S620 identifies the spatial relationships between neighboring or adjacent 3-D image content relative to the 3-D surface that is being formed. A subset selection step S630 then identifies a subset of the scanned image frames according to the spatial relationship data. A pose optimization step S640 uses the constructed subset of image frames for efficiently calculating and constructing a needed pose for display. A refinement step S650 then generates a complete view of the 3-D mesh by adding 3-D image input from frames outside the identified subset. A display step S660 then displays the identified surface contour

For improved speed and overall performance in pose construction using the acquired scanned image frames, an embodiment of the present disclosure selects only a partial subset of the acquired frames. By reducing the size of the data set that is manipulated in order to set up and render a particular pose, the methods of the present disclosure help to speed image construction and rendering without requiring the entire set of captured image frames. In particular, the subset of acquired frames that are used as "key frames" for pose rendering are selected according to their relative significance in defining the overall 3-D structure of the upper or lower dental arch.

By way of example, FIG. 7A visually represents the full set of image frames 90 generated in manually scanning a patient's mouth for an upper or lower arch. FIG. 7B then shows a partial subset of image frames 90 that are identified as key frames for pose setup and manipulation.

As is well known to those skilled in the computer processing art, spanning tree representation provides a visual analogue that facilitates data relations and is useful for visualizing sorting operations used to process various points of data.

An embodiment of the present disclosure employs spanning tree representation to relate multiple scans of the intraoral surface to each other and to help streamline the processing needed for image rendering for a desired image pose.

By way of simplified example, FIG. 8 shows a spanning tree having vertices V1, V2, V3, V4, V5, V6, V7, V8, and V9. Each vertex V*n* represents a 3-D image frame obtained during scanning. Edges E constructed between vertices V*n* indicate that there is some relationship between the connected vertices. In the context of the present disclosure, each edge E connection indicates that the corresponding connected vertices have some amount of shared image content. Thus, for example, in the spanning tree graph shown in FIG. 8, vertices V5 and V6 share some common image content, measurable in terms of overlay and a distance metric, such as a Euclidean distance, familiar to those skilled in the imaging and data processing art, indicating that the vertices have a given relationship that can be spatial (distance) as well as providing a metric indicative of overlap.

As can be appreciated from the simplified spanning tree graph shown in FIG. 8, there are a number of relationships that can be measured between the various vertices V1-V9, including a number of redundant relationships, wherein a single vertex has shared content with multiple nearby vertices. Thus, for example, vertex V7 shares some image content and is within a defined distance of vertices V4, V5, V8, and V9.

Spanning tree manipulation techniques are used to facilitate rendering of an image wherein multiple different image frames share the same content and wherein there is considerable redundancy of data, such as in the example of vertex V7 just described. For the purpose of pose rendering, in which a 3-D image is rendered at a particular perspective angle, it can be cumbersome to process all of the vertices having the relational arrangement shown in FIG. 8, particularly since there can be numerous scans having shared content.

An embodiment of the present disclosure simplifies pose rendering by forming a subset of the vertices, termed a connected dominating subset in spanning tree processing parlance, and using this subset as a type of initial “skeleton” representative of the full set of image frames. For the example relational mapping of the spanning tree of FIG. 8, one skeletal, connected dominating subset is shown in the example of FIG. 9. Here, vertices V2, V4, V5, and V7 constitute a connected dominating subset in an arrangement termed a “maximum leaf spanning tree”. Vertices V1, V3, V6, V8, and V9 form “leaves” of the spanning tree. The maximum leaf spanning tree is a data construct that reorganizes the relational matrix of the spanning tree to identify key vertices whose configuration connects the full set of vertices. The key vertices can be manipulated to provide a skeletal basis for rendering an image obtained by the full set of scans for a particular pose. In set terminology, these key vertices form a connected dominating subset.

A number of well-established algorithms can be used to derive, from a spanning tree having the full set of vertices, a connected dominating subset. By first manipulating the connected dominating subset for rendering a desired image pose, embodiments of the present disclosure both speed and simplify rendering processing. Once the skeletal subset is rendered, subsequent processing can then supplement the skeletal rendering with full image frame data from the leaf vertices.

It is significant to note that the leaf vertices, correspondingly, the image frames that are not part of the connected dominating subset, are not discarded for rendering. Instead, image processing using this construction helps to determine which image data are relevant for a particular rendered pose and which can be ignored.

There are no rigorous criteria for determining the size of the connected dominating subset relative to the size of the full set of acquired 3-D image frames. However, the Applicants have found that by arranging multiple image frames as a spanning tree, then generating a connected dominating subset, the number of frames needed for initial generation of an image pose can be greatly reduced, such as by requiring only 30% or less of the full subset of acquired images. FIGs. 7A and 7B show one example in which the connected dominating subset, represented in FIG. 7B only requires a small number of the full scan set represented in FIG. 7A.

Consistent with one embodiment, the present invention utilizes a computer program with stored instructions that control system functions for image acquisition and image data processing for image data that is stored and accessed from an electronic memory. As can be appreciated by those skilled in the image processing arts, a computer program of an embodiment of the present invention can be utilized by a suitable, general-purpose computer system, such as a personal computer or workstation that acts as an image processor, when provided with a suitable software program so that the processor operates to acquire, process, transmit, store, and display data as described herein. Many other types of computer systems architectures can be used to execute the computer program of the present invention, including an arrangement of networked processors, for example.

The computer program for performing the method of the present invention may be stored in a computer readable storage medium. This medium may comprise, for example; magnetic storage media such as a magnetic disk such as a hard drive or removable device or magnetic tape; optical storage media such as an optical disc, optical tape, or machine readable optical encoding; solid state electronic storage devices such as random access memory (RAM), or read only memory (ROM); or any other physical device or medium employed to store a computer program. The computer program for performing the method of the present invention may also be stored on computer readable storage medium that is connected to the image processor by way of the internet or other network or communication medium. Those skilled in the image data processing arts will further readily recognize that the equivalent of such a computer program product may also be constructed in hardware.

It is noted that the term “memory”, equivalent to “computer-accessible memory” in the context of the present disclosure, can refer to any type of temporary or more enduring data storage workspace used for storing and operating upon image data and accessible to a computer system, including a database. The memory could be non-volatile, using, for example, a long-term storage medium such as magnetic or optical storage. Alternately, the memory could be of a more volatile nature, using an electronic circuit, such as random-access memory (RAM) that is used as a temporary buffer or workspace by a microprocessor or other control logic processor device. Display data, for example, is typically stored in a temporary storage buffer that is directly associated with a display device and is periodically refreshed as needed in order to provide displayed data. This temporary storage buffer can also be considered to be a memory, as the term is used in the present disclosure. Memory is also used as the data workspace for executing and storing intermediate and final results of calculations and other processing. Computer-accessible memory can be volatile, non-volatile, or a hybrid combination of volatile and non-volatile types.

It is understood that the computer program product of the present invention may make use of various image manipulation algorithms and processes that are well known. It will be further understood that the computer program product embodiment of the present invention may embody algorithms and processes not specifically shown or described herein that are useful for implementation. Such algorithms and processes may include conventional utilities that are within the ordinary skill of the image processing arts. Additional aspects of such algorithms and systems, and hardware and/or software for producing and otherwise processing the images or co-operating with the computer program product of the present invention, are not specifically shown or described herein and may be selected from such algorithms, systems, hardware, components and elements known in the art.

The invention has been described in detail, and may have been described with particular reference to a suitable or presently preferred embodiment, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention. The presently disclosed embodiments are therefore considered in all respects to be illustrative and not restrictive. The scope of the invention is indicated by the appended claims, and all changes that come within the meaning and range of equivalents thereof are intended to be embraced therein.

PartsList_100512

10. Illumination array
12. Pixel
16, 18, 19. Line segment
20. Surface
22. Tooth
24. Camera
30. Imaging sensor array
32. Pixel
46. Structured light pattern
50. Point cloud
60. Polygon mesh model
70. Imaging apparatus
72. Memory
74. Display
80. Control logic processor
90. Frame

L, L'. Line

S600. Image acquisition step
S610. Reconstruction step
S620. Relational step
S630. Subset selection step
S640. Pose optimization step
S650. Refinement step
S660. Display step

E. Edge
V1, V2, V3, V4, V5, V6, V7, V8, and V9. Vertex

WHAT IS CLAIMED IS:

1. A method for acquiring and updating a 3-D surface of a dentition, the method executed at least in part by a computer and comprising:
   a) acquiring a succession of a plurality of 3-D image frames of the dentition from different points of view using a 3-D scanning device;
   b) for each individual acquired 3-D image frame, identifying one or more spatial relationships to other acquired 3-D image frames according to relative distance and an overlap metric between the individual and other acquired 3-D image frames;
   c) forming and updating the 3-D surface of the dentition using a matching algorithm that aggregates image content from the 3-D image frames according to the one or more spatial relationships and according to overlap and distance of each 3-D image frame relative to the 3-D surface of the dentition;
   d) selecting a subset of the succession of 3-D image frames having reduced data redundancy, based on the spatial relationships; and
   e) rendering a pose of the 3-D surface and displaying the rendered pose according to the selected subset.

2. The method of claim 1 wherein rendering the pose further comprises:
   (i) forming an initial 3-D mesh using the subset of 3-D image frames; and
   (ii) forming a refined 3-D mesh by supplementing the initial 3-D mesh with image content from the succession of acquired 3-D images.

3. The method of claim 1 further comprising relating the acquired plurality of 3-D image frames to each other according to a spanning tree connection model.

4. The method of claim 3 wherein the spanning tree connection model relates acquired 3-D image frames according to spatial relationship.

5. The method of claim 4 further comprising configuring the spanning tree connection model to form a maximum leaf spanning tree model.

6. The method of claim 5 further comprising adding one or more leaves into the maximum leaf spanning tree according to a metric indicating the relative overlap of 3-D frames.

7. The method of claim 1 where the 3-D scanning device is an intraoral scanner.

8. The method of claim 1 further comprising storing or transmitting the rendered pose.

9. An apparatus for processing 3-D contour images comprising:

a 3-D scanner that generates a collection of 3-D contour images of a dentition from a different points of view;

a computer that is in signal communication with the 3-D scanner and is programmed with instructions for a process comprising a sequence of:

(i) acquiring a succession of a plurality of 3-D image frames of the dentition from different points of view using a 3-D scanning device;

(ii) for each individual acquired 3-D image frame, identifying one or more spatial relationships to other acquired 3-D image frames according to relative distance and an overlap metric between the individual and other acquired 3-D image frames;

(iii) forming and updating the 3-D surface of the dentition using a matching algorithm that aggregates image content from the 3-D image frames according to the one or more spatial relationships and according to overlap and distance of each 3-D image frame relative to the 3-D surface of the dentition;

(iv) selecting a subset of the succession of 3-D image frames having reduced data redundancy, based on the spatial relationships; and

(v) rendering a pose of the 3-D surface and displaying the rendered pose according to the selected subset.

10. The apparatus of claim 9, where the 3-D scanner comprises a video camera that continuously generates the collection of 3-D image frames, and where members of the subset of 3-D contour image frames have one or more connections with non-member 3-D image frames.

11. A method for acquiring and updating a 3-D surface of a dentition, the method executed at least in part by a computer and comprising:

a) acquiring a succession of a plurality of 3-D image frames of the dentition from different points of view using a 3-D scanning device that forms a complete 3-D image frame using structured light;

b) for each individual acquired 3-D image frame, identifying one or more spatial relationships with other acquired 3-D image frames according to relative distance and an overlap metric between the individual frame and other acquired 3-D image frames;

c) forming and updating the 3-D surface of the dentition using feature matching that aggregates image content from adjacent 3-D image frames according to the one or more spatial relationships and according to overlap and distance of each 3-D image frame relative to the 3-D surface of the dentition;

d) selecting a subset of the succession of 3-D image frames having a reduced data redundancy, based on the spatial relationships; and

e) rendering and displaying a pose of the 3-D surface according to the selected subset.

12. The method of claim 11 wherein the structured light comprises lines of projected light.

13. The method of claim 11 wherein selecting the subset employs logic that identifies key frames by forming a maximum leaf spanning tree of the 3-D image frames and identifying a connected dominating subset of the 3-D image frames.

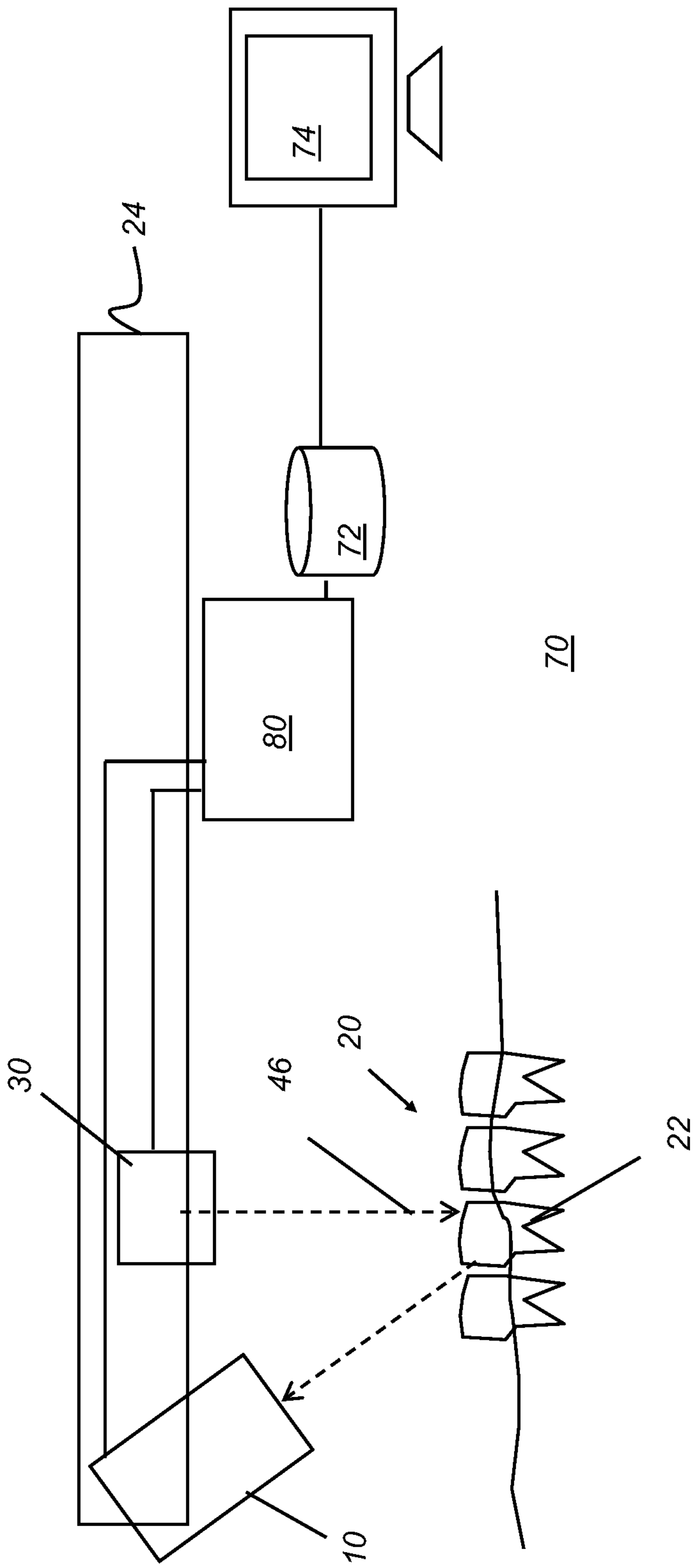

FIG. 1

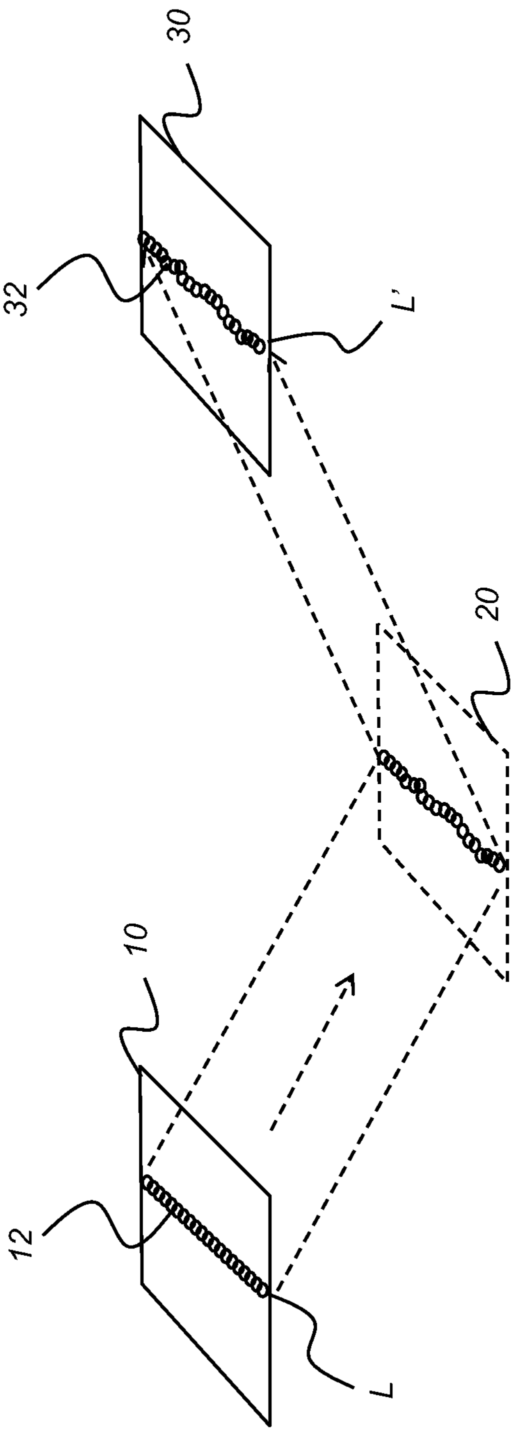

FIG. 2

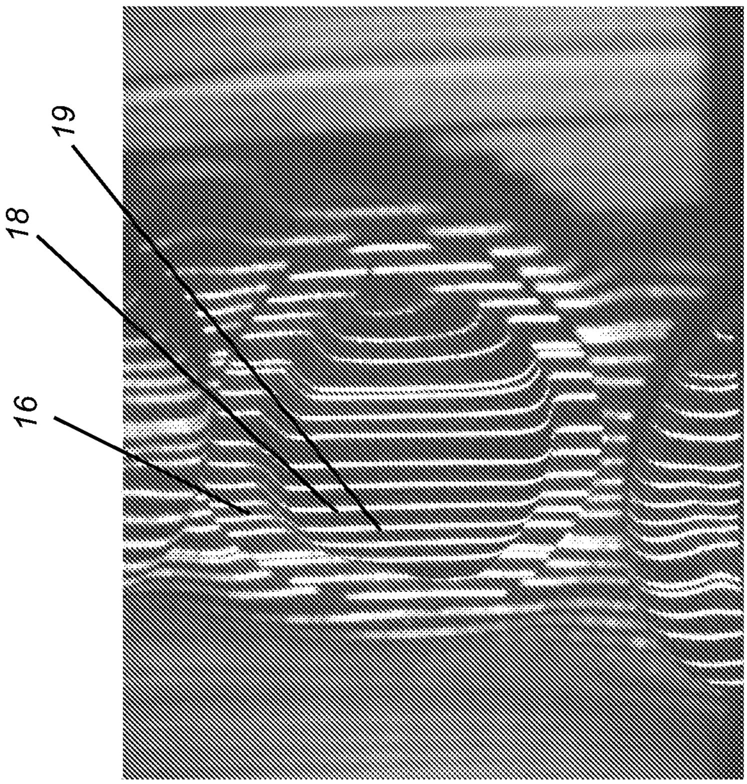

FIG. 3

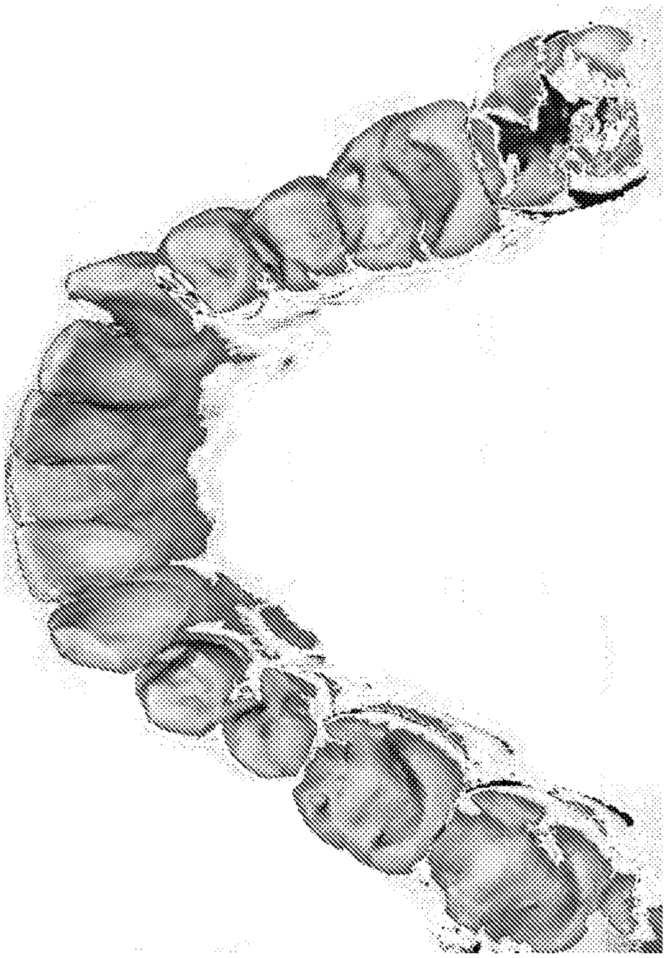

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FIG. 4

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FIG. 5

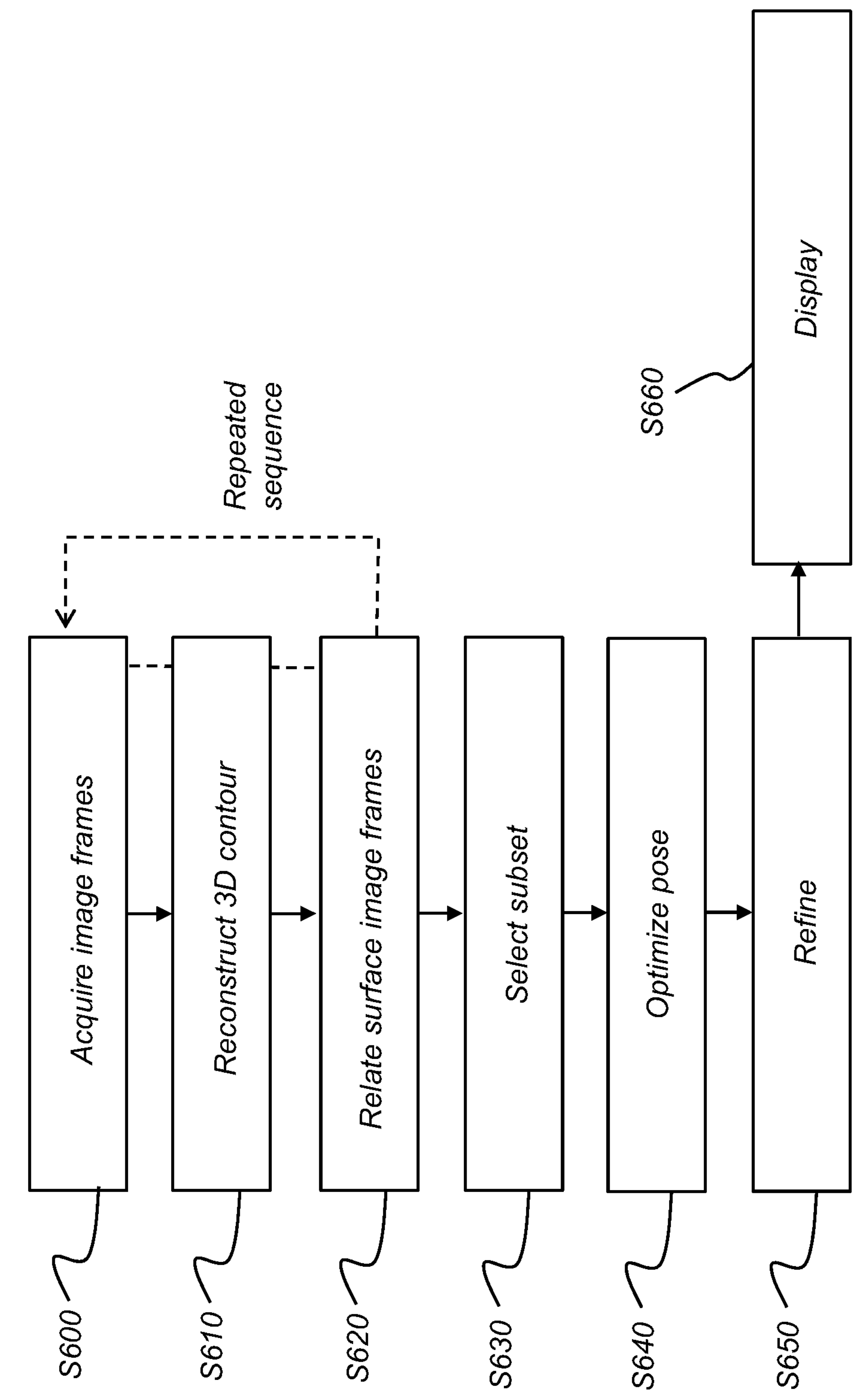
Repeated sequence
S600
Acquire image frames
S610
Reconstruct 3D contour
S620
Relate surface image frames
S630
Select subset
S640
Optimize pose
S650
Refine
S660
Display

FIG. 6

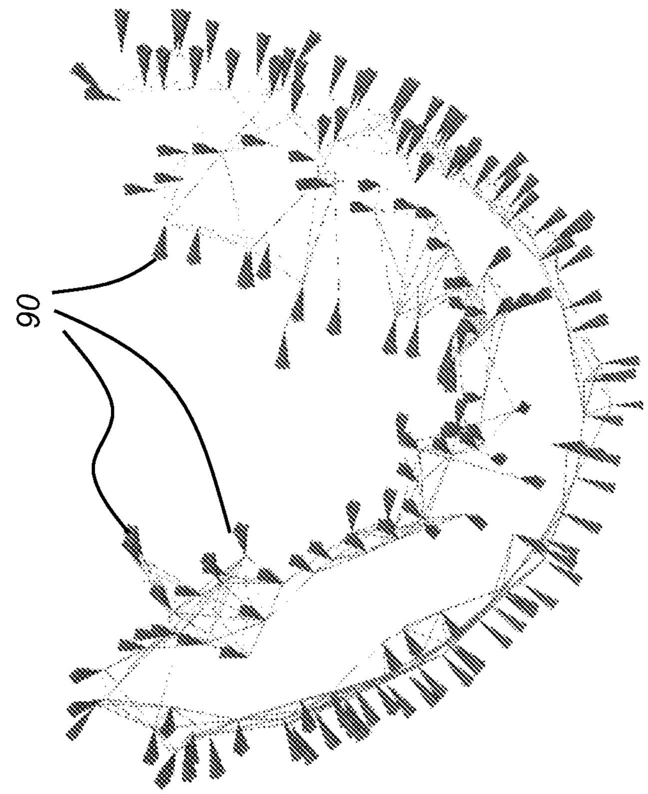

FIG. 7B

FIG. 7A

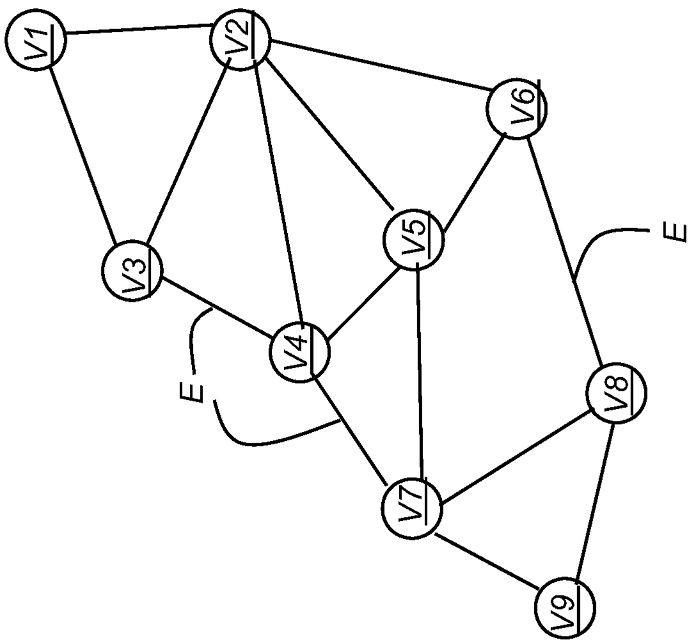

FIG. 8

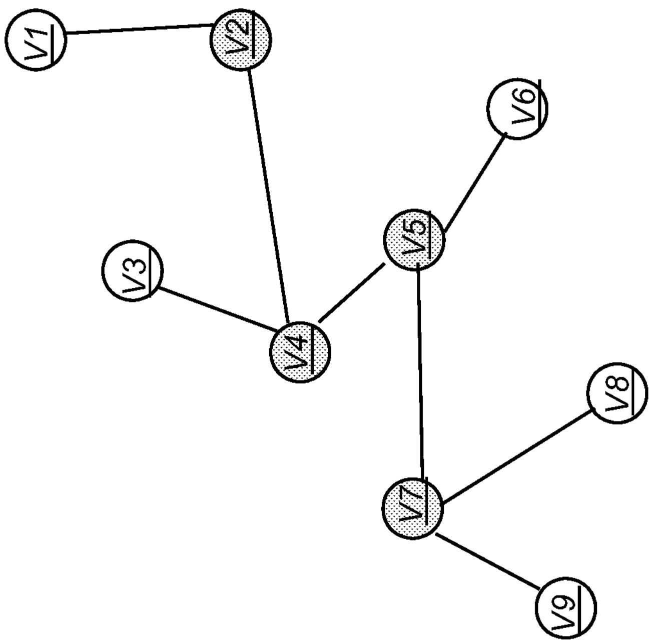

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2018/101870

A. CLASSIFICATION OF SUBJECT MATTER

G01B 11/25(2006.01)i; G06T 15/04(2011.01)i; G06T 17/20(2006.01)i; A61B 5/00(2006.01)n

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01B,G06T,A61B

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

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

CNTXT;CNABS;CNKI;VEN: 牙，齿，口，三维，图像，表面，帧，空间，关系，距离，度量，交叠，聚集，收集，冗余，渲染，姿态，姿势，生成，网格，网眼，最大，叶，生成树，dentition, tooth, teeth, dental, three?dimension+, 3D, image, picture, surface, frame, spatial ,relationship, aggregate+, collect+, pose, redundan+, mesh, spanning tree, maximum, leaf

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2018025529 A1 (CARESTREAM HEALTH INC) 25 January 2018 (2018-01-25) paragraphs [0008-0148];figs.1-13	1-2,8-12
Y	US 2018025529 A1 (CARESTREAM HEALTH INC) 25 January 2018 (2018-01-25) paragraphs [0008-0148];figs.1-13	3-7,13
Y	Fernau, H et al. "An exact algorithm for the Maximum Leaf Spanning Tree problem" *THEORETICAL COMPUTER SCIENCE,* Vol. 412, No. 45, 21 October 2011 (2011-10-21), pags 6290-6302	3-7,13
A	US 2015017598 A1 (CARESTREAM HEALTH INC) 15 January 2015 (2015-01-15) all document	1-13
A	US 2009087050 A1 (GANDYRA MICHAEL) 02 April 2009 (2009-04-02) all document	1-13
A	US 2008131837 A1 (KORDASS BERND ET AL.) 05 June 2008 (2008-06-05) all document	1-13
A	US 2009061381 A1 (DURBIN DUANE MILFORD ET AL.) 05 March 2009 (2009-03-05) all document	1-13

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

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

Date of the actual completion of the international search	Date of mailing of the international search report
21 May 2019	**30 May 2019**

Name and mailing address of the ISA/CN	Authorized officer
National Intellectual Property Administration, PRC **6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing 100088** **China**	**PAN,Jingliang**
Facsimile No. **(86-10)62019451**	Telephone No. **8601062089969**

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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A	US 2010303341 A1 (HAEUSLER GERD) 02 December 2010 (2010-12-02) all document	1-13
A	CN 101661631 A (DALIAN NATIONALITIES UNIVERSITY) 03 March 2010 (2010-03-03) all document	1-13

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2018/101870

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				EP	2185891	A1	19 May 2010
				CA	2698525	C	21 March 2017
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				CN	101904773	A	08 December 2010
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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2018/101870

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				DK	3025122	T3	28 May 2018
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				US	9860520	B2	02 January 2018
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				JP	5583761	B2	03 September 2014
				US	9091536	B2	28 July 2015
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