



US008452052B2

(12) **United States Patent**  
**Erignac**

(10) **Patent No.:** **US 8,452,052 B2**

(45) **Date of Patent:** **May 28, 2013**

(54) **MODELING MOTION CAPTURE VOLUMES WITH DISTANCE FIELDS**

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(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1359 days.

(21) Appl. No.: **12/017,111**

(22) Filed: **Jan. 21, 2008**

(65) **Prior Publication Data**

US 2009/0185719 A1 Jul. 23, 2009

(51) **Int. Cl.**  
**G06K 9/00** (2006.01)

(52) **U.S. Cl.**  
USPC ..... **382/104**; 382/107; 382/154; 345/419; 356/12; 348/42; 348/143

(58) **Field of Classification Search**  
USPC ..... 382/100, 104, 154, 285, 107, 103; 345/419-427; 356/12-14; 348/42-60, 143-160  
See application file for complete search history.

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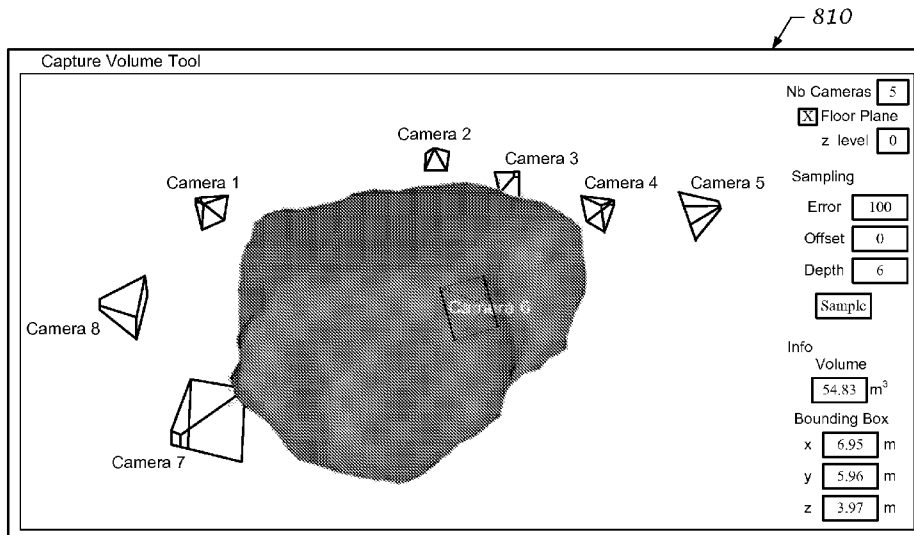
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(57) **ABSTRACT**

A k-covered motion capture volume is modeled. The modeling includes representing the k-covered motion capture volume with a distance field.

**32 Claims, 6 Drawing Sheets**



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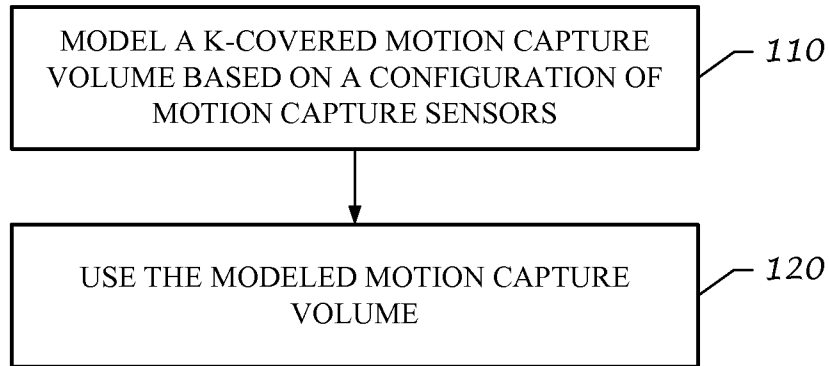
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*FIG. 1*



*FIG. 2*

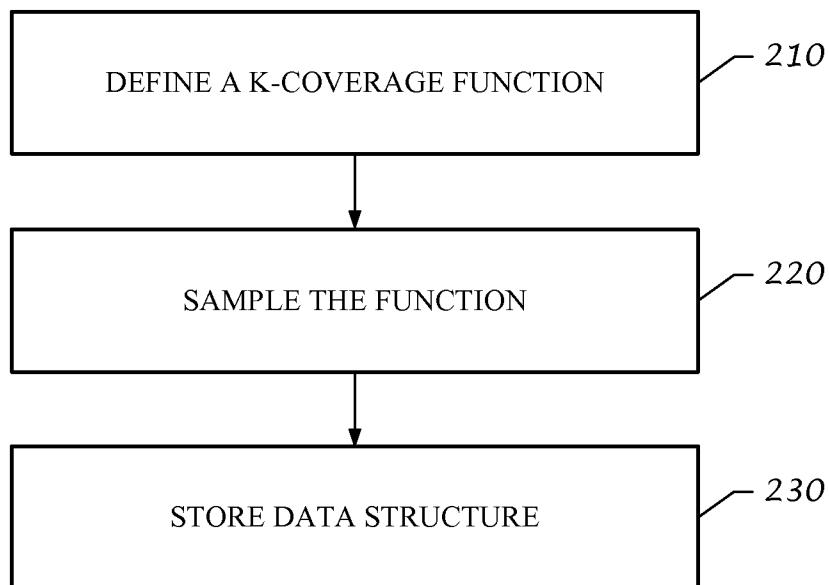


FIG. 3

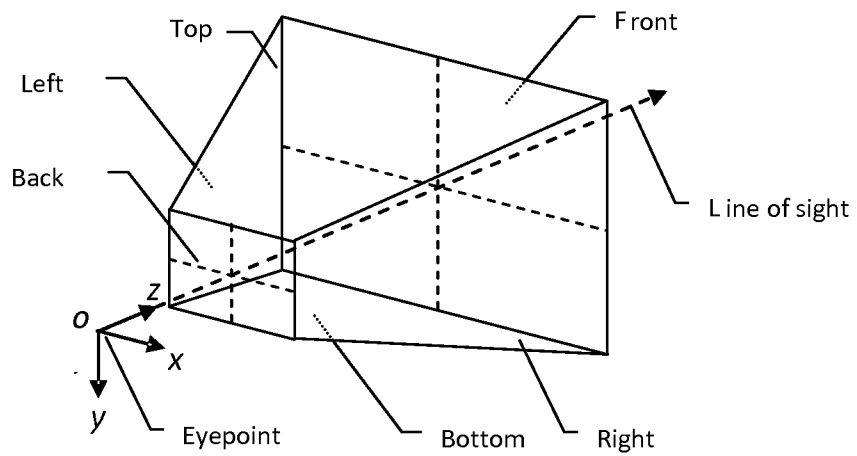
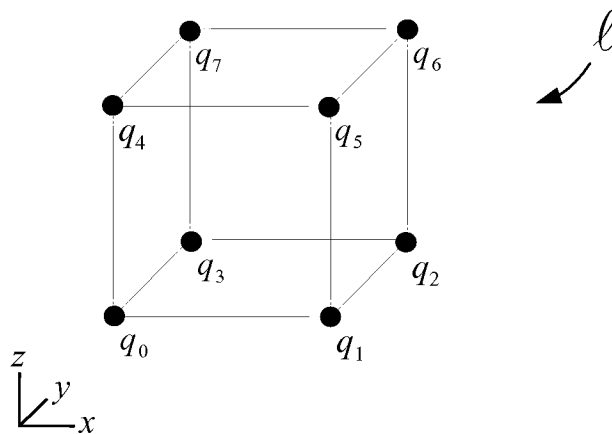


FIG. 11



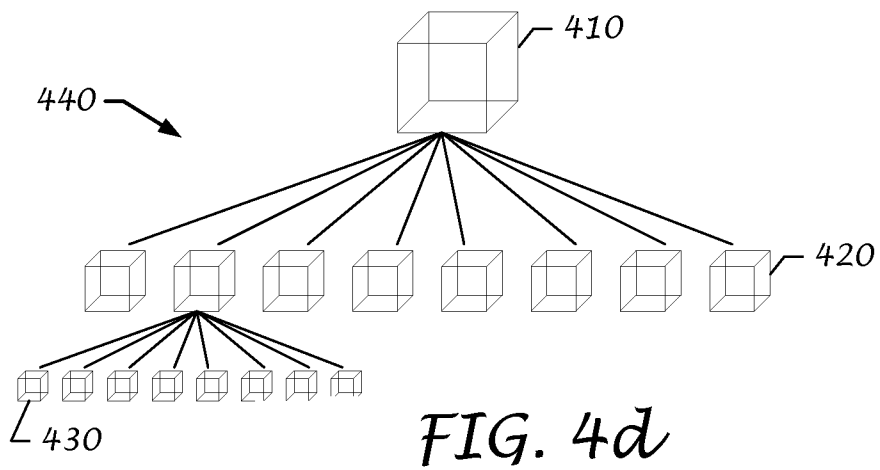
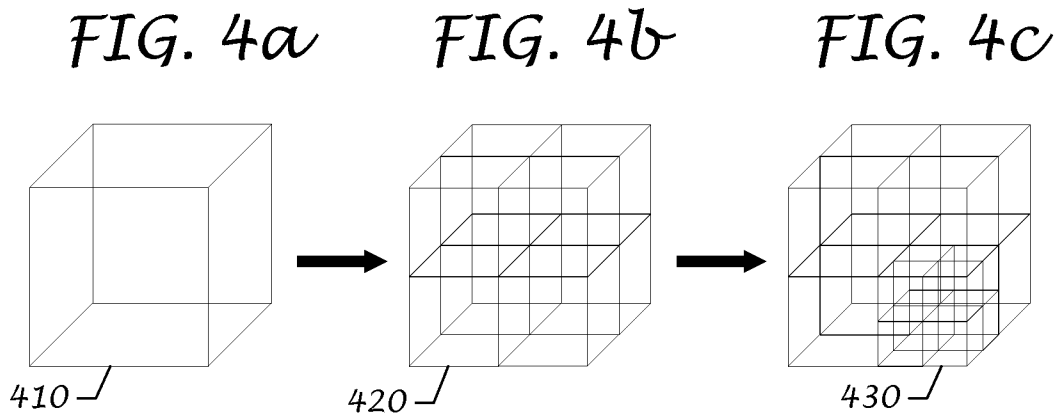


FIG. 5

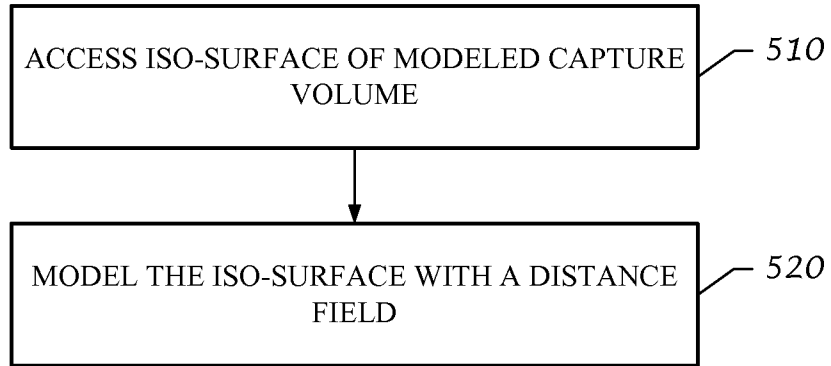


FIG. 6

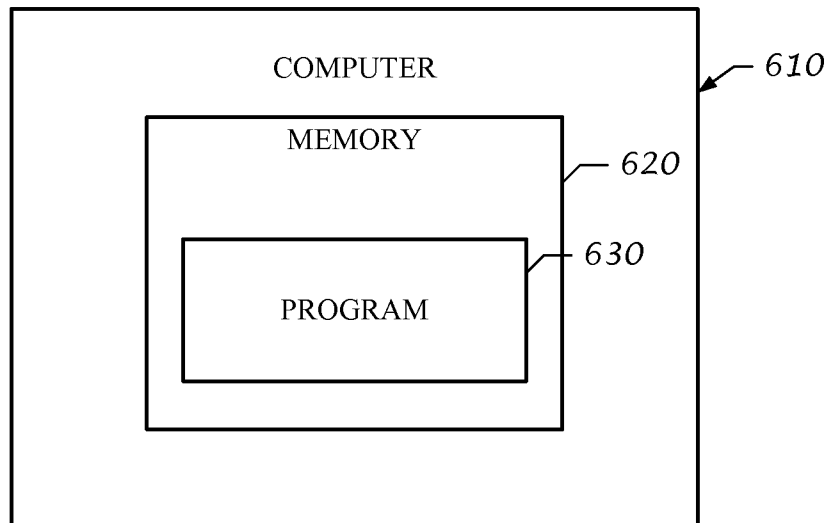


FIG. 7

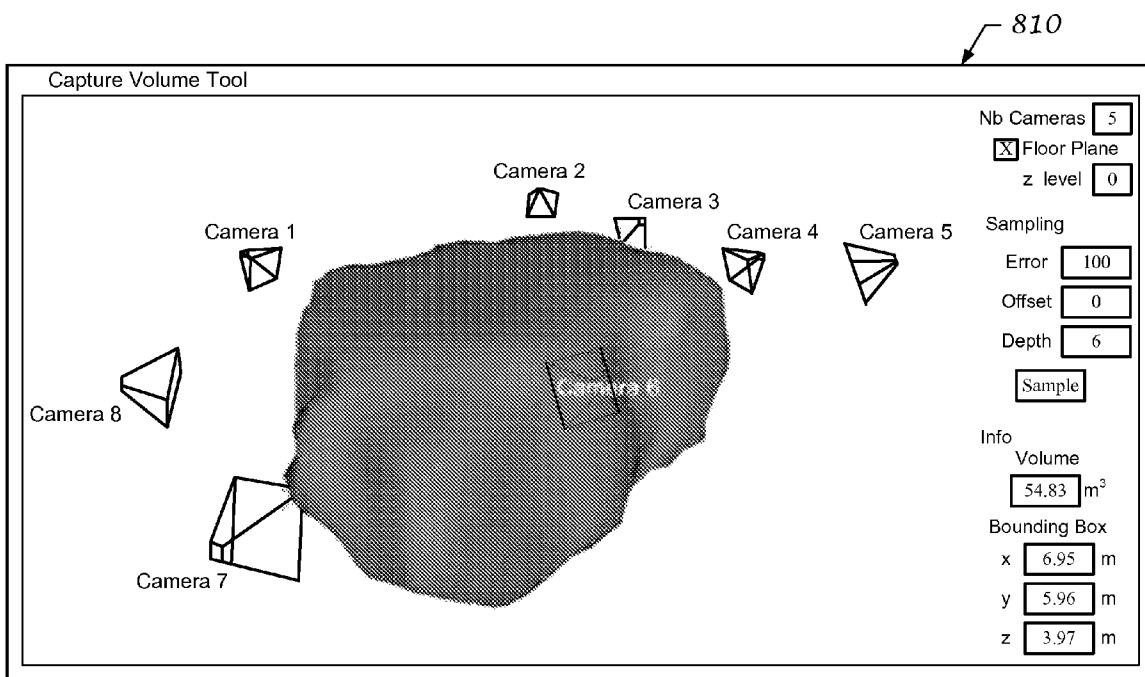
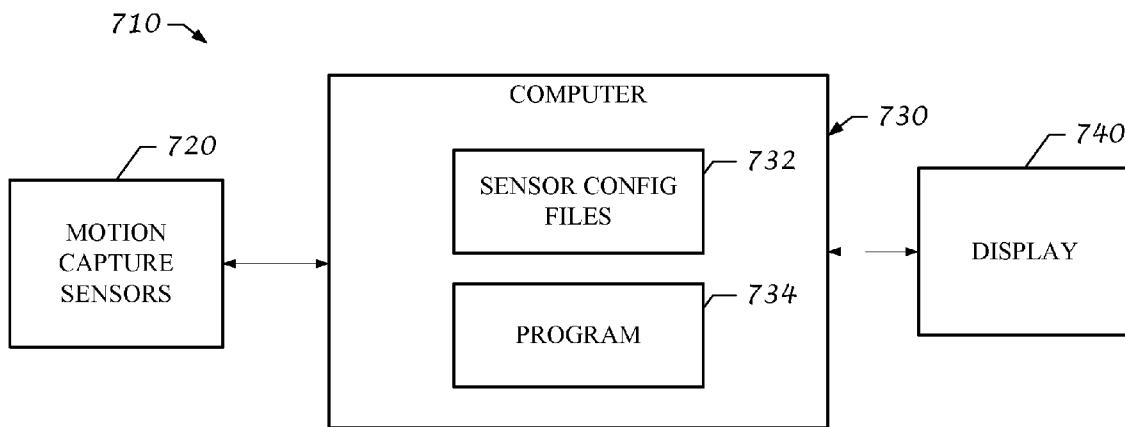


FIG. 8

FIG. 9

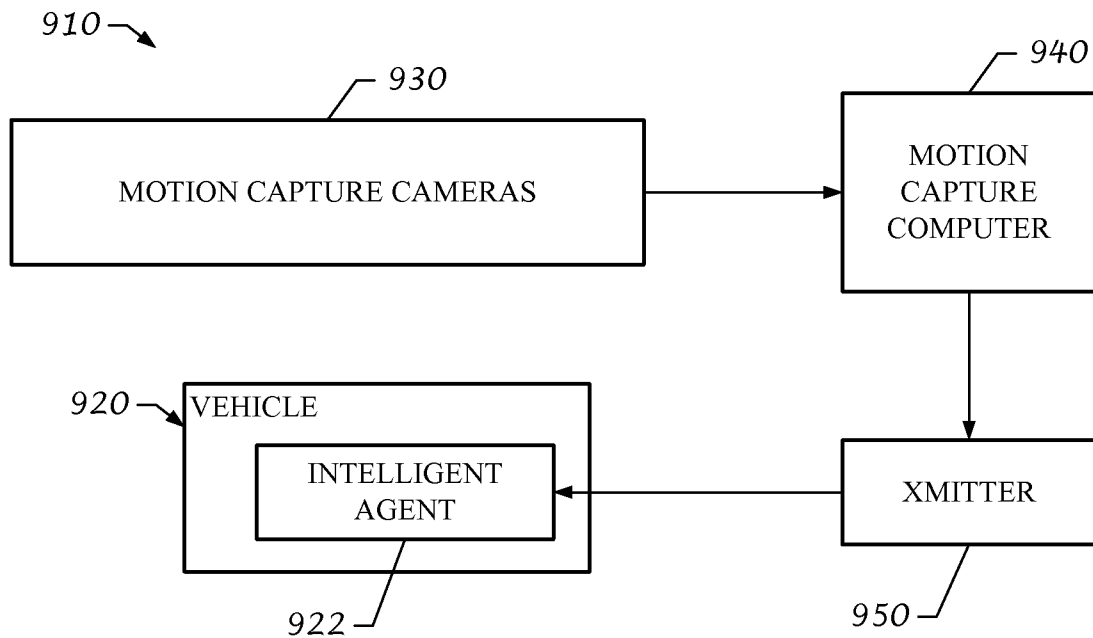
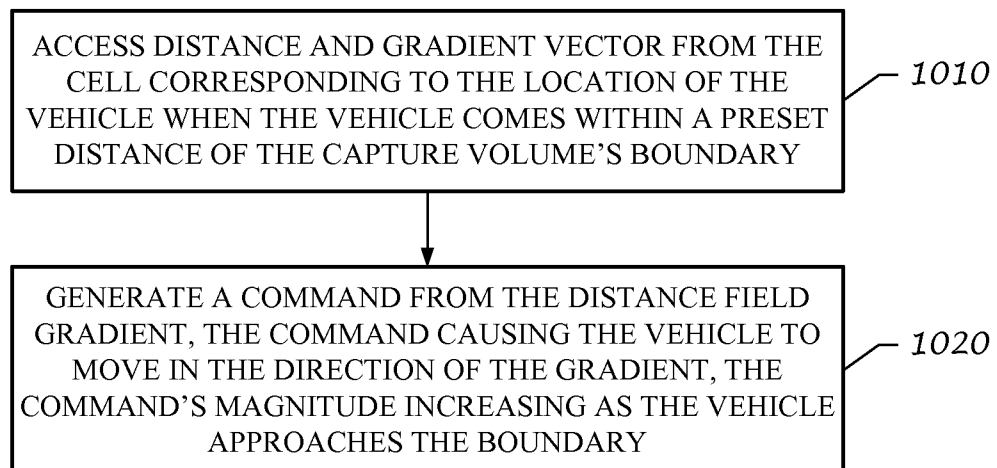


FIG. 10





## MODELING MOTION CAPTURE VOLUMES WITH DISTANCE FIELDS

### BACKGROUND

Motion capture (“mocap”) is a technique of digitally recording movements for entertainment, sports, and medical applications. In the context of filmmaking (where it is sometimes called performance capture), motion capture involves recording the actions of human actors, and using that information to animate digital character models in 3D animation.

In a typical motion capture system, an array of sensors is distributed around a motion capture stage, where a person’s motion is recorded. The person wears either passive markers or active beacons that are individually tracked by the sensors. A central processor fuses data from the sensors and computes the person’s body position based on the marker data and a-priori information about the marker position on the person’s body.

The movements are recorded within a “capture volume.” This volume refers to the workspace where the person can be tracked continuously by a certain sensor configuration. For instance, if a person can be tracked continuously within a capture volume by three cameras, that capture volume is said to have 3-coverage.

A motion capture system may be used for closed loop control of a vehicle (e.g., an electric helicopter) within a capture volume. However, visualization and analysis of the capture volume is limited.

### SUMMARY

According to an embodiment of the present invention, a k-covered motion capture volume is modeled. The modeling includes representing the k-covered motion capture volume with a distance field.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an illustration of a method in accordance with an embodiment of the present invention.

FIG. 2 is an illustration of a method of modeling a capture volume in accordance with an embodiment of the present invention.

FIG. 3 is an illustration of an example of a viewing volume of a sensor.

FIGS. 4a-4c are illustrations of recursive subdivision of a root cell, and FIG. 4d is an illustration of a data structure representing the recursive subdivision.

FIG. 5 is an illustration of a method of using a data structure to determine a true signed distance function to a boundary of a motion capture volume in accordance with an embodiment of the present invention.

FIG. 6 is an illustration of an apparatus in accordance with an embodiment of the present invention.

FIG. 7 is an illustration of a system in accordance with an embodiment of the present invention.

FIG. 8 is a screen shot of a motion capture tool in accordance with an embodiment of the present invention.

FIG. 9 is an illustration of a vehicle control system in accordance with an embodiment of the present invention.

FIG. 10 is an illustration of a method of controlling a vehicle in accordance with an embodiment of the present invention.

FIG. 11 is an illustration of a leaf cell.

### DETAILED DESCRIPTION

Reference is made to FIG. 1. At block 110, a computational model of a k-covered motion capture volume is generated.

The model is based on a configuration of motion capture sensors. The model generation includes representing the k-covered motion capture volume with a distance field.

Let  $C^k$  denote a k-covered motion capture volume for a motion capture system comprising a set C of sensors (e.g., cameras) in a specific configuration. This set C represents information about a portion of a workspace (the “viewing volume”) that is viewed by each sensor (e.g., parameters such as the position, orientation and field of view of each camera with respect to the workspace). A distance field is a scalar function  $f_C^k: R^3 \rightarrow R$  denoting the minimum distance from a point p in  $R^3$  to a boundary of the capture volume  $C^k$ . The distance field may be signed such that  $f_C^k(p)$  is positive if the point p is inside of the capture volume, and negative if the point p is outside the capture volume  $C^k$ . The distance field is zero if the point p lies on the boundary of the capture volume  $C^k$ .

An algorithm for evaluating  $f_C^k$  at a given point is computationally intensive due to the complex geometry of the capture volume (e.g., a multi-faceted boundary with very little symmetry). However, this function  $f_C^k$  may be approximated with an interpolation technique using regularly or adaptively sampled values of  $f_C^k$  within a workspace containing the capture volume. One embodiment of the present invention may use adaptive distance fields (ADFs) to model the capture volume  $C^k$  as an approximation  $h_C^k$  of  $f_C^k$ . In an adaptive distance field, sampling may be performed at higher rates in regions where the distance field contains fine detail and at lower sampling rates where the distance field varies smoothly.

At block 120, the model can be used for a wide range of applications, examples of which will be provided below. These examples include a motion capture system and a system for controlling of a vehicle to operate within a confined volume.

Reference is made to FIG. 2, which illustrates an example of modeling a motion capture volume based on a sensor configuration. The configuration includes a plurality of sensors distributed around a workspace. The sensors are not limited to any particular type. The sensors may include, but are not limited to, magnetic, ultrasonic, and optical sensors.

Each sensor has parameter settings that include field of view, placement, and orientation. The settings of a sensor can be used to identify that portion (that is, the viewing volume) of the workspace sensed by the sensor.

The volume viewed by a sensor such as a camera can be modeled as a frustum. The frustum illustrated in FIG. 3 is bounded by a set of six clipping planes  $P_i = \{\text{Left, Right, Top, Bottom, Front, Back}\}$ . The eyepoint  $o_i$  defines the origin of the camera’s local coordinate system where the z axis supports the camera’s line of sight. The Back and Front planes are perpendicular to z, and the Left and Right planes intersect at the eyepoint  $o_i$  along the y axis. Their dihedral is the camera’s horizontal field of view. The Top and Bottom planes intersect at  $o_i$  along the x axis. Their dihedral corresponds to the camera’s vertical field of view.

Each clipping plane in  $P_i$  defines a half-space and is oriented with its normal pointing inside the frustum. Thus, the frustum is formed by the intersection of all six half-spaces.

At block 210, a k-coverage function  $f_C^k$  is defined, based on the sensor configuration. Consider the example of 3-coverage by a set C of n cameras, where each camera has a viewing volume that is modeled as a frustum. Given an oriented plane P and its associated half-space  $H_P$ , a signed distance function  $d_P: R^3 \rightarrow R$  is defined such that

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$$d_p(q) = \begin{cases} \text{dist}_p(q) & \text{if } q \in H_p \\ -\text{dist}_p(q) & \text{otherwise} \end{cases}$$

where  $\text{dist}_p(q)$  computes the Euclidian distance between  $P$  and a point  $q$ .

Let  $f_i: \mathbb{R}^3 \rightarrow \mathbb{R}$  be the coverage function of camera  $c_i$  such that  $f_i(q) = \min_{p \in P_i} (d_p(q))$ . This function is positive for points inside the frustum, null for those at its boundary and negative outside of it. Furthermore, because the frustum is convex, the positive values of  $f_i$  are actual Euclidian distances to the boundary of the frustum. This does not hold for negative values of  $f_i$ .

Let  $\text{covers}: \mathbb{R}^3 \rightarrow \{\text{true}, \text{false}\}$  be the predicate that is true for a point  $q$  if and only if  $q$  is in the field of view of camera  $c_i$ . This is equivalent to  $\text{cover}_i(q) \Leftrightarrow f_i(q) \geq 0$

Let  $\text{cover}_C^k: \mathbb{R}^3 \rightarrow \{\text{true}, \text{false}\}$  be the predicate that is true for a point  $q$  if and only if  $q$  is in the field of view of at least  $k$  distinct cameras of  $C$ . This is equivalent to

$$\text{cover}_C^k(q) \Leftrightarrow \exists C_q \subseteq C, |C_q| \geq k \text{ and } \forall c_i \in C_q, \text{cover}_i(q)$$

where  $C_q$  is he subset of cameras covering point  $q$ .

Let  $f_C^k: \mathbb{R}^3 \rightarrow \mathbb{R}$  be the function that for a point  $q$  returns the  $k^{\text{th}}$  largest value of  $f_i(q)$  for  $i \in \{0, \dots, n-1\}$ . If  $f_C^k(q) \geq 0$  then there exist a set  $C_q^k = \{c_0, \dots, c_{k-1}\}$  of  $k$  cameras where  $\forall c_i \in C_q^k, f_i(q) \geq 0$ . Thus,  $f_C^k(q) \Leftrightarrow \text{cover}_C^k(q)$ , where the value of  $f_C^k$  indicates whether a point is  $k$ -covered by  $C$ .  $B_C^k = \{q \in \mathbb{R}^3 | f_C^k(q) = 0\}$  is the boundary of the capture volume where  $k$ -coverage is required. The  $k^{\text{th}}$  largest value is used as an approximation of the distance to the capture volume's boundary.

Thus, a point  $q$  is  $k$ -covered if there is a  $k$ -tuple of cameras whose frustum intersection contains that point. Those  $k$ -tuple intersections have convex boundaries because they are the convex hulls of all the planes forming the frusta of the cameras in the  $k$ -tuple.

The capture volume is the union of these intersections. Thus, the distance function  $f_C^k$  describes a capture volume that is possibly concave prismatic and that might have disconnected components.

The distance function  $f_C^k$  of each sensor is evaluated only once. Since the function  $f_C^k$  evaluates each camera only once, it has  $O(n)$  complexity to compute. The function  $f_C^k$  is a pseudo signed distance function to  $B_C^k$  because it only does  $k$ -tuple-wise computations and does not considers their union. Its zero-contour (iso-surface for field value 0) is the boundary of the capture volume  $C^k$ .

At block 220, the  $k$ -coverage function  $f_C^k$  is sampled. Let  $h_C^k$  be the ADF obtained by sampling  $f_C^k$  with a user-defined sampling error  $E$  and maximum depth  $d_{\text{max}}$ . The sampling begins with a root cell 410 that contains the frusta of the camera set  $C$  so as to encapsulate the entire capture volume. The root cell 410 has a depth of  $d=0$ .

Starting from the root cell the following process is applied to each cell. The function  $f_C^k$  is evaluated at the eight vertices located at the corners of this cell. Let  $h$  be a scalar field defined within the boundaries of the cell. This field may be computed via trilinear interpolation of the eight samples as described below. Next it is verified that, within the cell, the scalar field  $h$  approximates the function  $f_C^k$  within the maximum sampling error  $\epsilon$ . This may be done by computing the absolute value of the difference of the two fields at predefined test points such as the center of the cell. If one of these differences exceeds the sampling error  $E$  and the depth  $d$  of the cell is less than  $d_{\text{max}}$  then the cell is subdivided into eight child cells. The

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depth of these child cells is  $d+1$ . This algorithm is applied recursively to these child cells. A cell without children is referred to as a "leaf" cell.

This subdivision is repeated until the leaf cells can interpolate the distance function  $f_C^k$  within the predefined sampling error  $E$  or until a maximum depth is reached. Thus, the sampling process adaptively subdivides the cells to keep the local interpolation error bounded by a user-defined tolerance.

Additional reference is made to FIGS. 4a-4d, which illustrates a recursive subdivision. FIG. 4a illustrates the root cell 410 of the ADF. FIG. 4b illustrates the root cell 410 subdivided into eight child cells 420 having a depth  $d=1$ , and FIG. 4c illustrates one of the cells 420 further subdivided into cells 430 having a depth of  $d=2$ . Cells at the same depth (siblings) have the same size.

This recursive subdivision can be represented by a data structure such as a tree structure. For example, the recursive subdivision of FIGS. 4a-4c can be represented by an octree as illustrated in FIG. 4d. The evaluation process traverses the tree quickly down to the leaf containing the input point and linearly interpolates the field at that location based on the sampled field values at the eight vertices of the leaf.

Additional reference is made to FIG. 11. A distance field or distance field gradient (or both) may be interpolated within a cell. Each cell  $l$  has eight vertices located at its corners ( $q_0, q_1, q_2, q_3, q_4, q_5, q_6, q_7$ ). These vertices are shared with the adjacent cells. A value of the distance function  $f_C^k$  is stored for each vertex location. This value was computed during the sampling step.

Distance fields may be interpolated as follows. Given a point  $p$  contained in the domain of an ADF  $h$ ,  $h(p)$  is evaluated by trilinear interpolation of the sample values associated with the deepest leaf  $l$  containing  $p$ . Let  $Q_l = \{q_0, q_1, q_2, q_3, q_4, q_5, q_6, q_7\}$  and  $H_l = \{h_0, h_1, h_2, h_3, h_4, h_5, h_6, h_7\}$  be the set of vertices and associated field values of leaf  $l$ . The distance field  $h_l$  of leaf  $l$  is of the form

$$h_l(p) = \sum_{i \in \{0,7\}} w_i h_i$$

where ( $w_0, w_1, w_2, w_3, w_4, w_5, w_6, w_7$ ) are the barycentric coordinates of  $p$  with respect to  $Q_l$ . A leaf  $l$  is mapped to the unit cube  $[0,1]^3$  by defining a normalized coordinate system where its vertices have the following coordinates:

$$\begin{aligned} q_0(0,0,0) & q_4(0,0,1) \\ q_1(1,0,0) & q_5(1,0,1) \\ q_2(1,1,0) & q_6(1,1,1) \\ q_3(0,1,0) & q_7(0,1,1) \end{aligned}$$

Let  $(x,y,z)$  be the normalized coordinates of point  $p$  in the leaf  $l$ . The formulae for the weights are:

$$w_0 = 1 + xy + yz + xz - (xyz + x + y + z)$$

$$w_1 = xyz + x - (xy + xz)$$

$$w_2 = xy - xyz$$

$$w_3 = xyz + y - (xy + yz)$$

$$w_4 = xyz + z - (xz + yz)$$

$$w_5 = xz - xyz$$

$$w_6 = xyz$$

$$w_7 = yz - xyz$$

with

$$\sum_{i \in [0,7]} w_i = 1.$$

The function  $h_i$  is defined only inside leaf  $l$ .

Distance field gradients may be interpolated as follows. Evaluating the gradient  $\nabla h(p)$  is very similar to evaluating  $h(p)$ . The leaf  $l$  containing point  $p$  is located. The gradient of  $h_i$ , which is of the following form, is evaluated:

$$\nabla h_i(p) = \left[ \frac{\partial h_i}{\partial x}(p), \frac{\partial h_i}{\partial y}(p), \frac{\partial h_i}{\partial z}(p) \right]^T$$

where

$$\frac{\partial h_i}{\partial x}(p) = \sum_{i \in [0,7]} \frac{\partial w_i}{\partial x} h_i, \quad \frac{\partial h_i}{\partial y}(p) = \sum_{i \in [0,7]} \frac{\partial w_i}{\partial y} h_i,$$

$$\frac{\partial h_i}{\partial z}(p) = \sum_{i \in [0,7]} \frac{\partial w_i}{\partial z} h_i$$

with the weights given in Table 1.

TABLE 1

|  |  |
|--|--|
| $\frac{\partial w_0}{\partial x} = y + z - (yz + 1)$ | $\frac{\partial w_4}{\partial x} = yz - z$           |
| $\frac{\partial w_1}{\partial x} = yz + 1 - (y + z)$ | $\frac{\partial w_5}{\partial x} = z - yz$           |
| $\frac{\partial w_2}{\partial x} = y - yz$           | $\frac{\partial w_6}{\partial x} = yz$               |
| $\frac{\partial w_3}{\partial x} = yz - y$           | $\frac{\partial w_7}{\partial x} = -yz$              |
| $\frac{\partial w_0}{\partial y} = x + y - (xz + 1)$ | $\frac{\partial w_4}{\partial y} = xz - z$           |
| $\frac{\partial w_1}{\partial y} = xz - x$           | $\frac{\partial w_5}{\partial y} = -xz$              |
| $\frac{\partial w_2}{\partial y} = x - xz$           | $\frac{\partial w_6}{\partial y} = xz$               |
| $\frac{\partial w_3}{\partial y} = xz + 1 - (x + z)$ | $\frac{\partial w_7}{\partial y} = z - xz$           |
| $\frac{\partial w_0}{\partial z} = y + x - (xy + 1)$ | $\frac{\partial w_4}{\partial z} = xy + 1 - (x + y)$ |
| $\frac{\partial w_1}{\partial z} = xy - x$           | $\frac{\partial w_5}{\partial z} = x - xy$           |
| $\frac{\partial w_2}{\partial z} = -xy$              | $\frac{\partial w_6}{\partial z} = xy$               |
| $\frac{\partial w_3}{\partial z} = xy - y$           | $\frac{\partial w_7}{\partial z} = y - xy$           |

The evaluation of  $h(p)$  and  $\nabla h(p)$  can be efficiently combined in the same routine since the distance fields and gradients share the same octree traversal and barycentric coordinates computation.

ADFs are only  $C^0$  continuous because of their linear interpolation scheme. They can faithfully reproduce fields with zero or small local curvatures. Areas of high curvature force the sampling algorithm to perform fine subdivision to meet the approximation tolerance.

The combination of detail directed sampling and the use of a spatial hierarchy for data storage allows ADFs to represent complex shapes to arbitrary precision while permitting effi-

cient processing. ADFs can approximate complex distance fields by sampling them as a preprocessing step and replacing them in computations that require fast distance evaluations. ADFs are also a convenient neutral format to represent distance fields sampled from various solid representations such as polygonal meshes, parametric surfaces and constructive geometry.

At block 230, the data structure can be stored in computer memory for later use. For instance, the data structure may be saved as an XML file.

The sampling method just described is for adaptive distance fields. However, a method according to the present invention is not so limited. In some embodiments, non-adaptive (i.e., uniform) sampling could be performed by setting the maximum sampling error to zero. In some embodiments, sampling could be performed using a uniform grid.

In some embodiments, cells might have shapes (e.g., tetrahedral) other than cubes. In some embodiments, interpolation other than trilinear interpolation may be used. In some embodiments, gradients could be stored and fit to quadric surfaces. In general, other sampling methods may be used to approximate the distance function  $f_C^k$ .

A method according to an embodiment of the present invention is not limited to signed distance functions. In some embodiments, positive distance functions may be used. However, positive distance functions do not indicate whether a point is inside or outside a motion capture volume.

The method of FIG. 2 may be modified in other ways. In some embodiments, that part of the capture volume below the floor plane ( $z=0$ ) may be clipped off since it is not in free space. Thus, the sampling is performed as  $g_C^k(q) = \min(f_C^k(q), q.z)$  which is in the intersection between the half-space above  $z=0$  and  $f_C^k$ .

The stored data structure is an approximation of the distance to a boundary of the motion capture volume. In some embodiments, however, the data structure may be further refined to determine a true signed distance function to a boundary of a motion capture volume.

Reference is made to FIG. 5, which illustrates a method of using a data structure to determine a true signed distance function to a boundary of a motion capture volume. Let  $f_C^{k*}$  be the true signed distance function to the capture volume boundary  $B_C^k$ . The distance field can be derived by re-sampling a representation of the boundary  $B_C^k$ . To do so, the boundary  $B_C^k$  is assumed to be orientable within the domain (the root voxel) of  $h_C^k$ . This means that each point in the domain is either inside or outside the capture volume and that every path between an inside point and an outside point goes through the boundary  $B_C^k$ .

At block 510, one or more iso-surfaces are extracted from the modeled capture volume. A suitable iso-surface extraction method can produce a triangular mesh that approximates the iso-surface. In some embodiments, however, this step may simply involve accessing a mesh model that was generated by some other means.

At block 520, the true distance function to the capture volume boundary is approximated by modeling the iso-surface with a distance field. In certain embodiments this intermediate distance function could use an oriented bounding box tree (OBBTree) to find the nearest triangle to the point at which the function  $f_C^{k*}$  is evaluated. This re-sampling yields a second ADF  $h_C^k$ . This second ADF  $h_C^{k*}$  provides a true signed distance function to a boundary of a motion capture volume.

Reference is made to FIG. 6. A method in accordance with an embodiment of the present invention may be implemented in a machine such as a computer 610. The computer 610

includes memory **620** that is encoded with a program **630**. The program **630**, when executed, causes the computer **610** to generate a computational model of a k-covered motion capture volume based on a configuration of motion capture sensors.

A modeled capture volume can be used for a wide range of applications. Two applications will be described below: a tool for motion capture, and a control for containing a vehicle within a closed volume.

Reference is made to FIGS. **7** and **8**, which illustrate a system **710** and tool **810** for motion capture. The system **710** includes a plurality of sensors **720**, a motion capture computer **730**, and a display **740**. The sensors **720** have a particular configuration (placement, field of view, orientation, etc.), and the computer **730** stores a parameter file **732** describing the sensor configuration.

A desired coverage (i.e., the value of k) can be inputted to the computer **730**. The computer **730** executes a program **734** that accesses the parameter file **732**, models a k-coverage capture volume based on that file **732**, and renders the modeled k-coverage volume.

ADF allows quick reconstruction of the model. For a model that is stored in an octree, distance values within a cell may be reconstructed from the eight corner distance values stored per cell using standard trilinear interpolation. In addition to distance values, an operation such as rendering may also require a method for estimating surface normals from the sampled data. For distance fields, the surface normal is equal to the normalized gradient of the distance field at the surface.

The program **734** can also cause the computer **730** to display a user interface of a motion capture tool **810**. The user interface, in turn, may display an iso-surface of the modeled motion capture volume. The user interface allows a user to vary the sensor configuration. In response, the computer **730** may update the model and render the updated model.

The motion capture tool **810** can also compute the volume and bounding box of the motion capture volume. The computer **730** can then execute an algorithm that determines a sensor configuration with respect to the bounding box. For example, the computer **730** determines a number of sensors **720** that will be used, and also identifies sensor locations on the bounding box of the desired capture volume. For a motion capture stage, these locations may be on the floor plane for tripod mounted cameras or above ground, on walls, ceilings, dedicated struts, etc.

The motion capture tool **810** can be used to assess the quality of camera placement for various level of k-coverage. Users can use the feedback of this tool **810** to adjust the number, location and orientation of the cameras.

The motion capture tool **810** allows overlapping sensor coverage (or lack thereof) to be visualized. By varying the configuration, disjoint volumes can be merged to create a single volume with continuous coverage. And by varying the configuration, sensor overlap can be reduced to increase the volume that is covered.

Generating a computational model has other uses. For instance, motion capture activities can be limited to the computed volume. Moreover, sensor configurations can be evaluated prior to setup.

Reference is now made to FIG. **9**. A computational model of a k-covered volume can be used by a vehicle control system **910**. The system **910** includes an intelligent agent **922** for controlling the operation of a vehicle **920** within a k-covered capture volume. In some embodiments, the intelligent agent **922** may include a microprocessor-based control that is on-board the vehicle **920** (as shown in FIG. **9**). In other embodi-

ments, the intelligent agent **922** may be in a computer (e.g., a flight computer) that is not on-board the vehicle **920**.

The system **910** further includes a plurality of motion capture cameras **930** for collecting real time images of the vehicle **920**, and a motion capture computer **940** for processing the real time images of the vehicle **920**. Active or passive markers on the vehicle **920** may assist with the tracking.

The motion capture computer **940** tracks the vehicle **920** and computes tracking information such as real-time position and attitude. For instance, the motion capture computer **940** may triangulate the position of the markers attached to the vehicle **920** by intersecting lines of sight between several cameras **930**. The motion capture computer **940** may then cluster the markers, and compare the clustered markers to known marker configurations (i.e., vehicle models). The motion capture computer **940** may perform filtering and other signal processing as well.

The motion capture computer **940** sends the tracking information to the intelligent agent **932**. A transmitter **950** may be used to up-link the tracking information to an agent **922** that is on-board the vehicle **920**.

The intelligent agent **922** uses the tracking information to control the operation of the vehicle **920**. The intelligent agent **922** may use position, orientation, linear and angular velocity data, etc., to calculate error signals, which are then multiplied by feedback gain values, and then used to generate the control values for the vehicle's inner control loop and servos.

Reference is now made to FIG. **10**. The intelligent agent **922** may store one or more k-coverage models of the motion capture volume and use those models to confine the vehicle **920** to move autonomously or under remote operation inside the capture volume. When the vehicle **920** comes within a preset distance of the boundary of the capture volume, the intelligent agent **922** accesses distance and gradient vector from the cell corresponding to the location of the vehicle **922** (block **1010**). A command is generated from the distance field and field gradient (block **1020**). The command causes the vehicle to move in the direction of the gradient and its magnitude increases as the vehicle approaches the boundary. The gradient provides guidance to stay in the capture volume. It can be construed as a control input because the control loop will command the vehicle's velocity to line-up with the gradient.

Each k-coverage model represents a different coverage. For instance, the intelligent agent **922** might store 3-coverage, 4-coverage and 5-coverage models of the capture volume. A user may choose a distance field and field gradient from a model with a conservative k-coverage setting, such as five cameras. If the vehicle **920** escapes the 5-covered capture volume, it may still remain controllable within a k-1 or k-2 covered volume.

The system **910** is not limited to any type of vehicle. As but one example, the system **910** can be used to control the flight of an electric helicopter within a motion capture volume. Helicopter operation is confined to a k-covered motion capture volume because its control relies on at least k cameras to continuously track the helicopter and maintain stable operation. Typically, a minimum of three cameras is used to track the helicopter at any point in 3D space. The motion capture computer **940** can provide real-time position and attitude information of the helicopter. The intelligent agent **922** uses one or more k-coverage models to keep the helicopter within the capture volume.

In another embodiment of the vehicle control system, the vehicle may be teleoperated instead of controlled by an on-board intelligent agent. Such a vehicle includes servos and a control loop that are responsive to commands transmitted by

an RC transmitter. The commands may be generated in response to joystick movements.

However, when the vehicle moves outside or near the boundary of the capture volume, the motion capture computer uses the modeled capture volume to compute a command based on the field intensity and gradient at cell where the vehicle is located. The command is up-linked to the vehicle's servos and overrides any other command.

In both embodiments, the inner control loop and the containment field form a fly-by-wire system that provides augmented stability and envelope protection. Envelope protection limits the velocity of the vehicle and keeps it in the capture volume. Limiting the velocity prevents the helicopter from ramming through the envelope.

The invention claimed is:

1. A method comprising modeling a k-covered motion capture volume based on a configuration of motion capture sensors, the modeling including representing the k-covered capture volume with a distance field.

2. The method of claim 1, wherein the distance field is an adaptive distance field, the adaptive distance field providing a signed scalar field indicating whether a point is within the capture volume, on a boundary of the capture volume, or outside the capture volume.

3. The method of claim 1, wherein the modeling includes defining a k-coverage function based on the sensor configuration, and sampling the function.

4. The method of claim 2, wherein the adaptive distance field is a signed distance function, and wherein the function describes intersections of viewing volumes of the sensors.

5. The method of claim 4, wherein the sensors include motion capture cameras, and the viewing volumes have the shapes of frusta.

6. The method of claim 4, wherein the sampling includes encompassing the viewing volumes of the sensors with a root cell, performing a recursive subdivision of the root cell.

7. The method of claim 6, wherein a  $k^{th}$  largest value of  $f_i$  is used as an approximation to the distance to the capture volume's boundary, and wherein the recursive subdivision is guided by a sampling error.

8. The method of claim 6, wherein the distance function is evaluated only once for each viewing volume, whereby the model has  $O(n)$  complexity to compute.

9. The method of claim 6, wherein each cell in the modeled capture volume has a set of vertices, and wherein each vertex corresponds to a distance field.

10. The method of claim 6, wherein evaluations of  $h(p)$  and  $Vh(p)$  are combined for each leaf cell in the recursive subdivision.

11. The method of claim 3, wherein sampling is performed only for that portion of the capture volume above a floor plane.

12. The method of claim 1, further comprising storing the modeled capture volume in computer memory.

13. The method of claim 1, further comprising extracting an iso-surface of the modeled capture volume; and modeling the iso-surface with an adaptive distance field.

14. A motion capture system comprising a computer programmed to perform the method of claim 1.

15. The motion capture system of claim 14, wherein the computer renders the modeled capture volume; and wherein the computer is also programmed to provide a user interface that allows sensor configurations to be varied.

16. The motion capture system of claim 15, wherein the computer determines a bounding box for the modeled capture volume, and also determines the sensor configuration with respect to the bounding box.

17. Apparatus comprising a computer for generating a computational model of a k-covered motion capture volume based on a configuration of motion capture sensors, including representing the k-covered capture volume with a distance field.

18. A vehicle control system comprising a motion capture system for covering a capture volume; a computational model of k-covered motion capture volume, the model represented by a distance field; and a control for operating a vehicle within the modeled volume.

19. The system of claim 18, wherein if the vehicle moves within a preset distance of the capture volume's boundary, gradients from the model are accessed and used to generate commands for moving the vehicle back inside the capture volume.

20. The system of claim 18, wherein the motion capture system includes a motion capture computer for sending tracking information to the control; and wherein the control includes an intelligent agent for using the tracking information to generate control values for the vehicle's inner control loop and servos.

21. The apparatus of claim 17, wherein the modeling includes defining a k-coverage function based on the sensor configuration, and sampling the function.

22. The apparatus of claim 21, wherein sampling is performed only for that portion of the capture volume above a floor plane.

23. The apparatus of claim 17, wherein the distance field is an adaptive distance field, the adaptive distance field providing a signed scalar field indicating whether a point is within the capture volume, on a boundary of the capture volume, or outside the capture volume.

24. The apparatus of claim 23, wherein the adaptive distance field is a signed distance function, and wherein the function describes intersections of viewing volumes of the sensors.

25. The apparatus of claim 24, wherein the sensors include motion capture cameras, and the viewing volumes have the shapes of frusta.

26. The apparatus of claim 24, wherein the sampling includes encompassing the viewing volumes of the sensors with a root cell, performing a recursive subdivision of the root cell.

27. The apparatus of claim 17, wherein the computer is programmed to extract an iso-surface of the model; and model the iso-surface with an adaptive distance field.

28. The apparatus of claim 17, wherein the computer is programmed to render the model; and wherein the computer is further programmed to provide a user interface that allows sensor configurations to be varied.

29. The apparatus of claim 17, wherein the computer is further programmed to determine the sensor configuration with respect to a bounding box of the model.

30. The system of claim 18, wherein the distance field is an adaptive distance field, the adaptive distance field providing a signed scalar field indicating whether a point is within the capture volume, on a boundary of the capture volume, or outside the capture volume.

31. The system of claim 30, wherein the adaptive distance field is a signed distance function, and wherein the function describes intersections of viewing volumes of the motion capture system.

32. The system of claim 31, wherein the motion capture system includes motion capture cameras, and wherein the viewing volumes have the shapes of frusta.