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(54) **MULTI VIEW CAMERA REGISTRATION**

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(57) **ABSTRACT**

A system for registering one or more cameras and/or creating an accurate three dimensional (3D) model of a world space environment includes back projecting at least one image from at least one of a plurality of camera views to the 3D model based on a set of existing camera parameters. The back projected image is added as a texture for the 3D model. This texture is automatically compared to one or more images from other camera views using a color space comparison of images to determine a set of differences or errors. The camera parameters and the 3D model are automatically adjusted to minimize the differences or errors. Over time, the parameters and the 3D model converge on a state that can be used to track moving objects, insert virtual graphics and/or perform other functions.

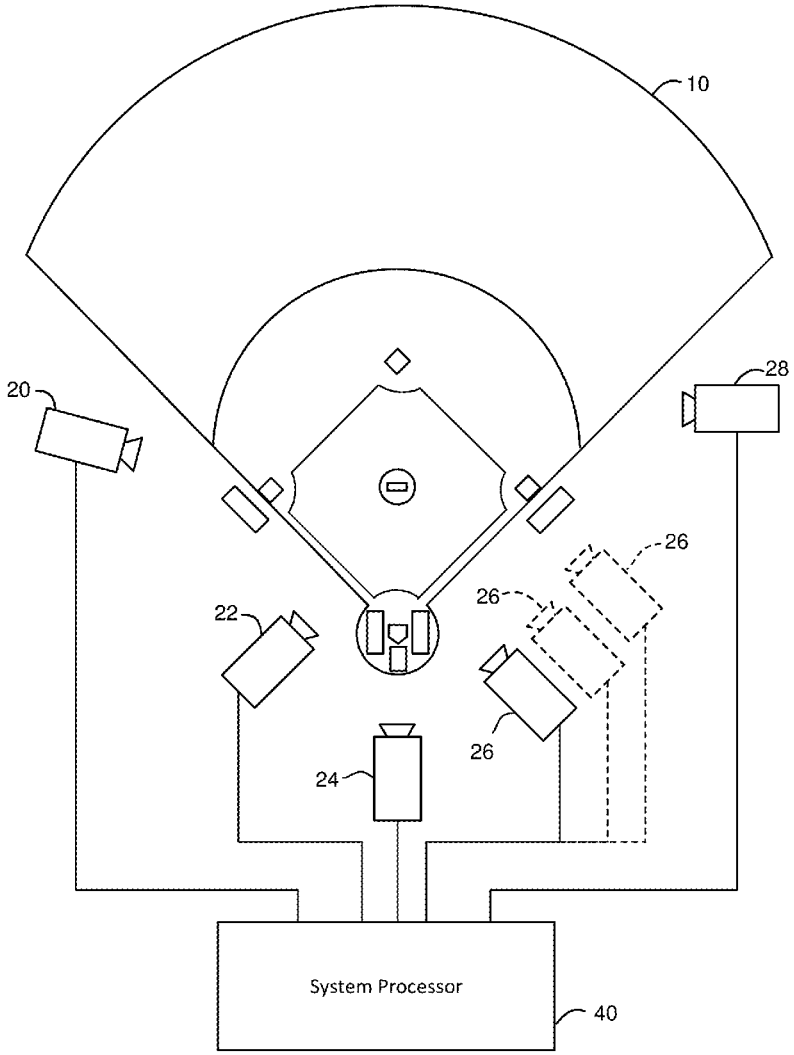


Figure 1

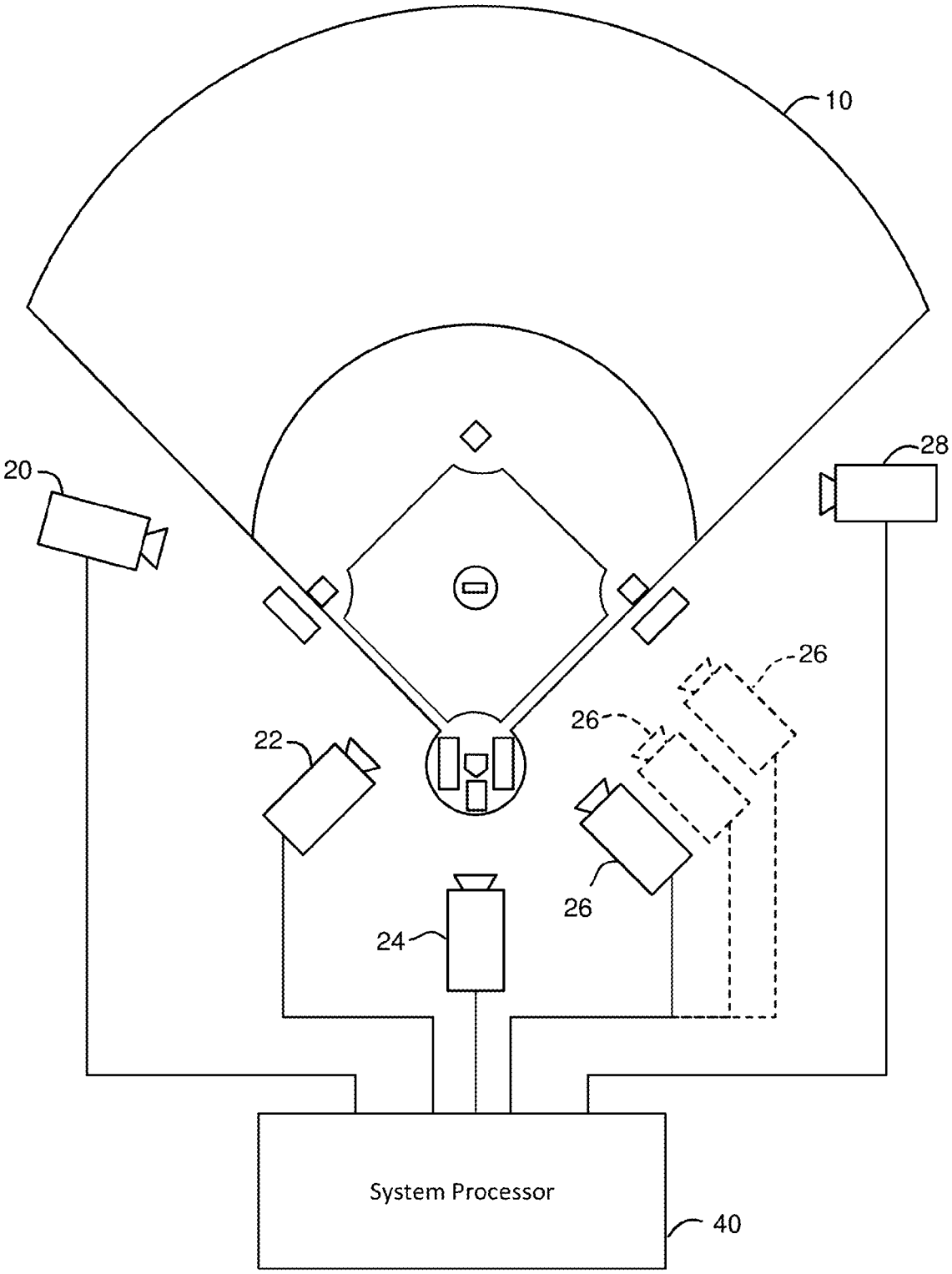


Figure 2

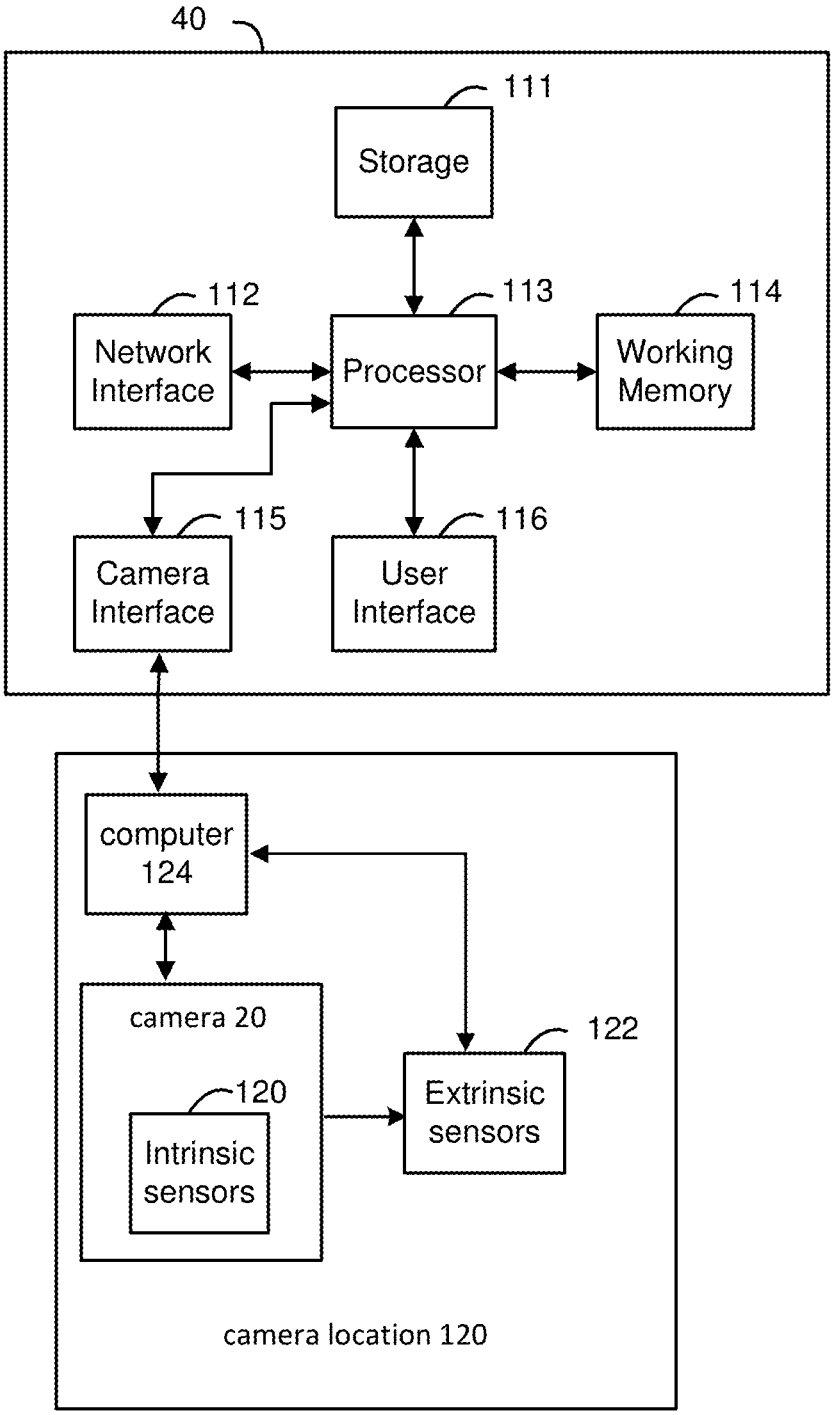

40
111
Storage
112
Network Interface
113
Processor
114
Working Memory
115
Camera Interface
116
User Interface
computer 124
camera 20
120
Intrinsic sensors
122
Extrinsic sensors
camera location 120

Figure 3

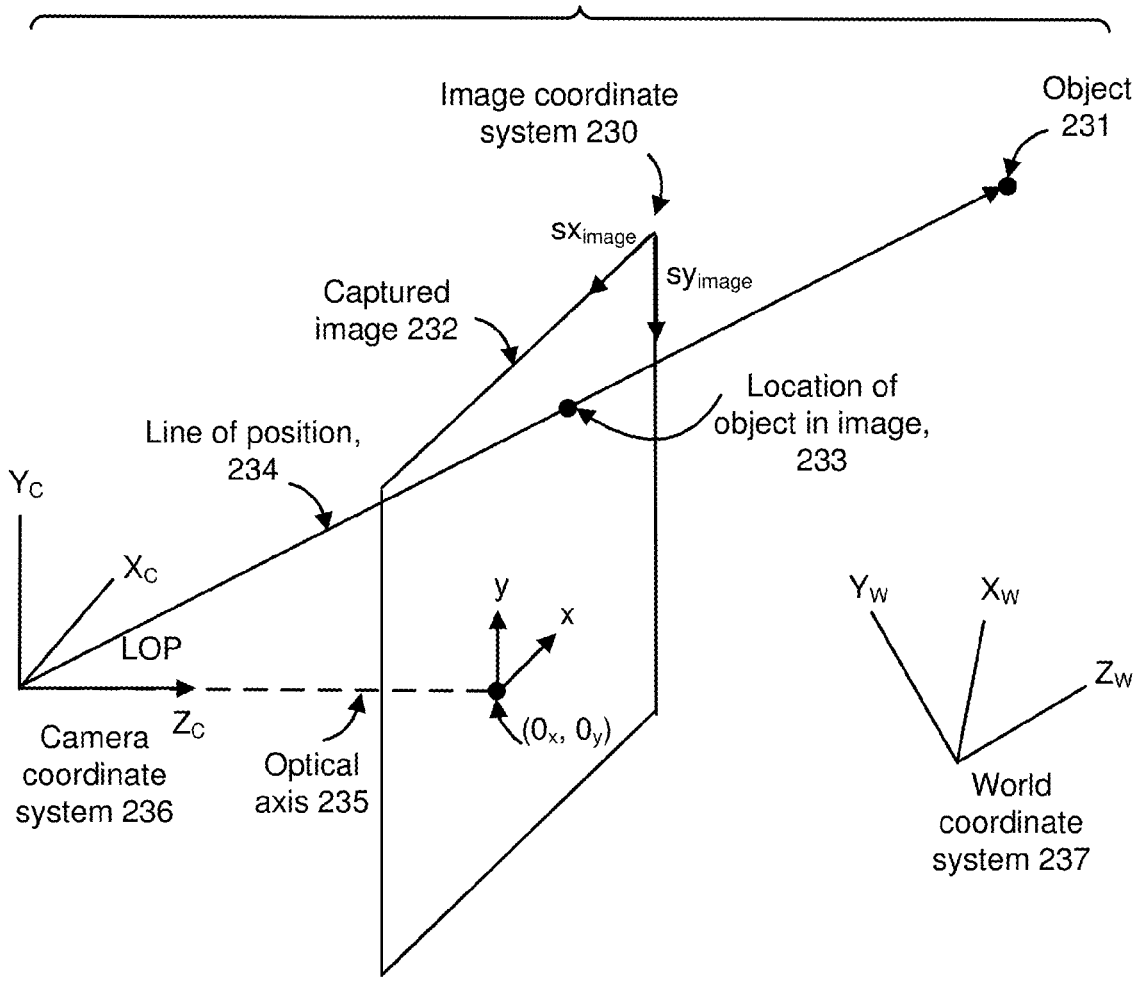
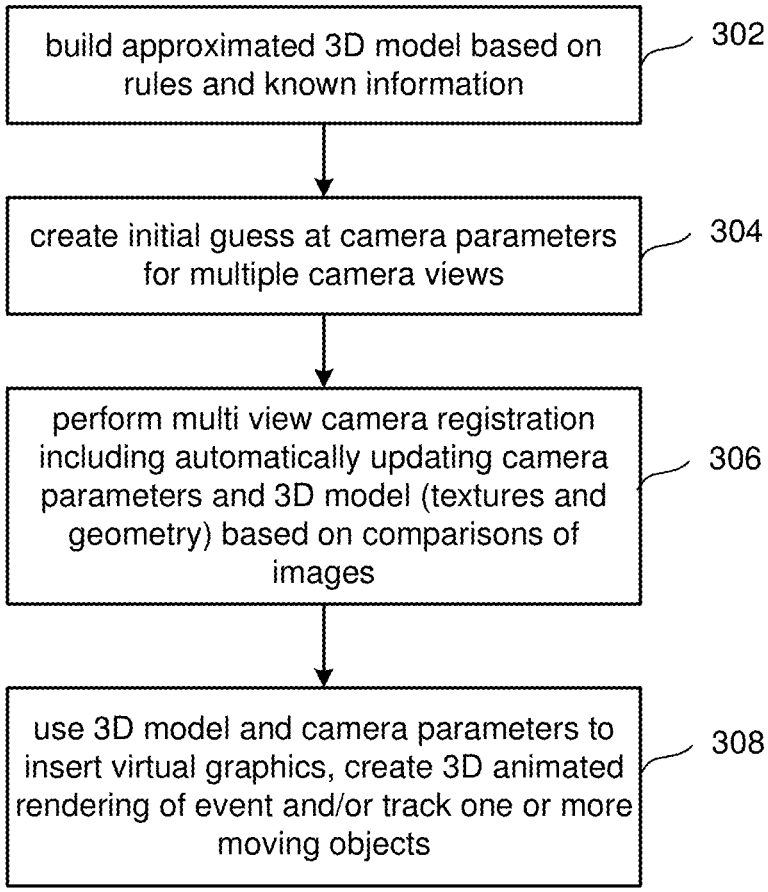


Image coordinate system 230
Object 231
sx_{image}
sy_{image}
Captured image 232
Location of object in image, 233
Line of position, 234
Y_C
X_C
LOP
Z_C
Camera coordinate system 236
Optical axis 235
y
x
$(0_x, 0_y)$
Y_W
X_W
Z_W
World coordinate system 237

Figure 4


build approximated 3D model based on rules and known information
302
create initial guess at camera parameters for multiple camera views
304
perform multi view camera registration including automatically updating camera parameters and 3D model (textures and geometry) based on comparisons of images
306
use 3D model and camera parameters to insert virtual graphics, create 3D animated rendering of event and/or track one or more moving objects
308

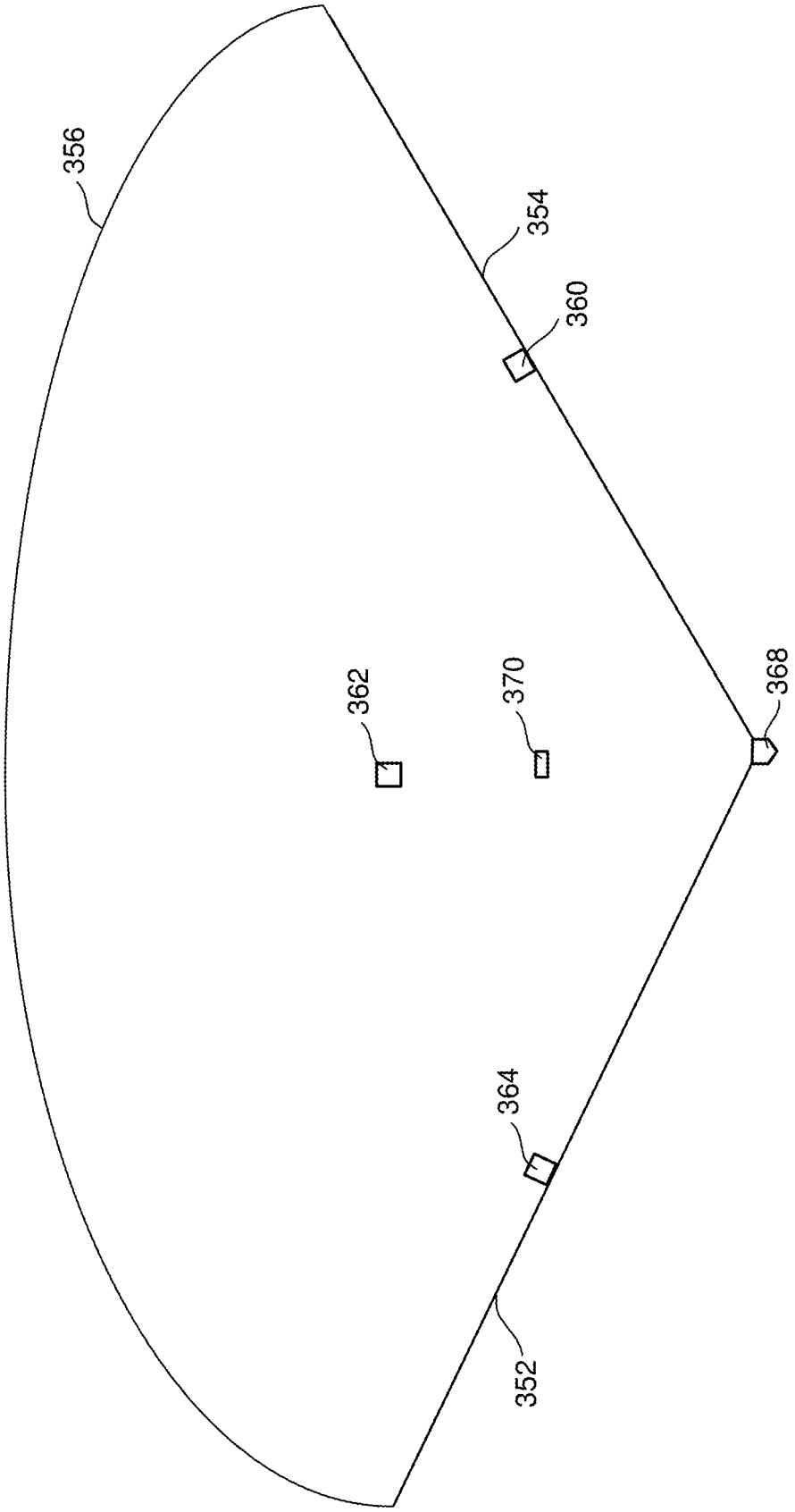


Figure 5

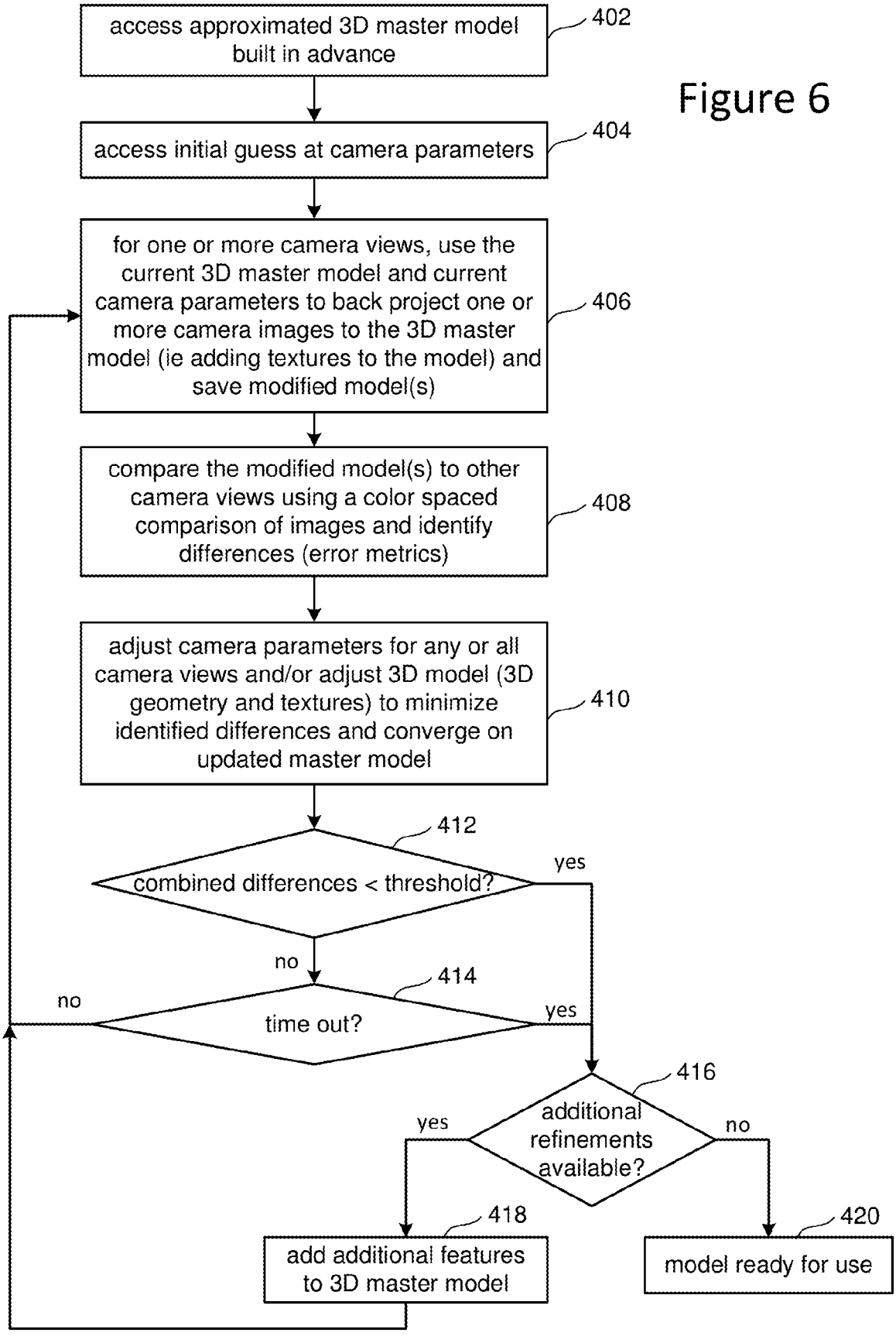

access approximated 3D master model built in advance
402
access initial guess at camera parameters
404
for one or more camera views, use the current 3D master model and current camera parameters to back project one or more camera images to the 3D master model (ie adding textures to the model) and save modified model(s)
406
compare the modified model(s) to other camera views using a color spaced comparison of images and identify differences (error metrics)
408
adjust camera parameters for any or all camera views and/or adjust 3D model (3D geometry and textures) to minimize identified differences and converge on updated master model
410
412
combined differences < threshold?
yes
no
414
time out?
no
yes
416
additional refinements available?
yes
no
418
add additional features to 3D master model
420
model ready for use

Figure 6

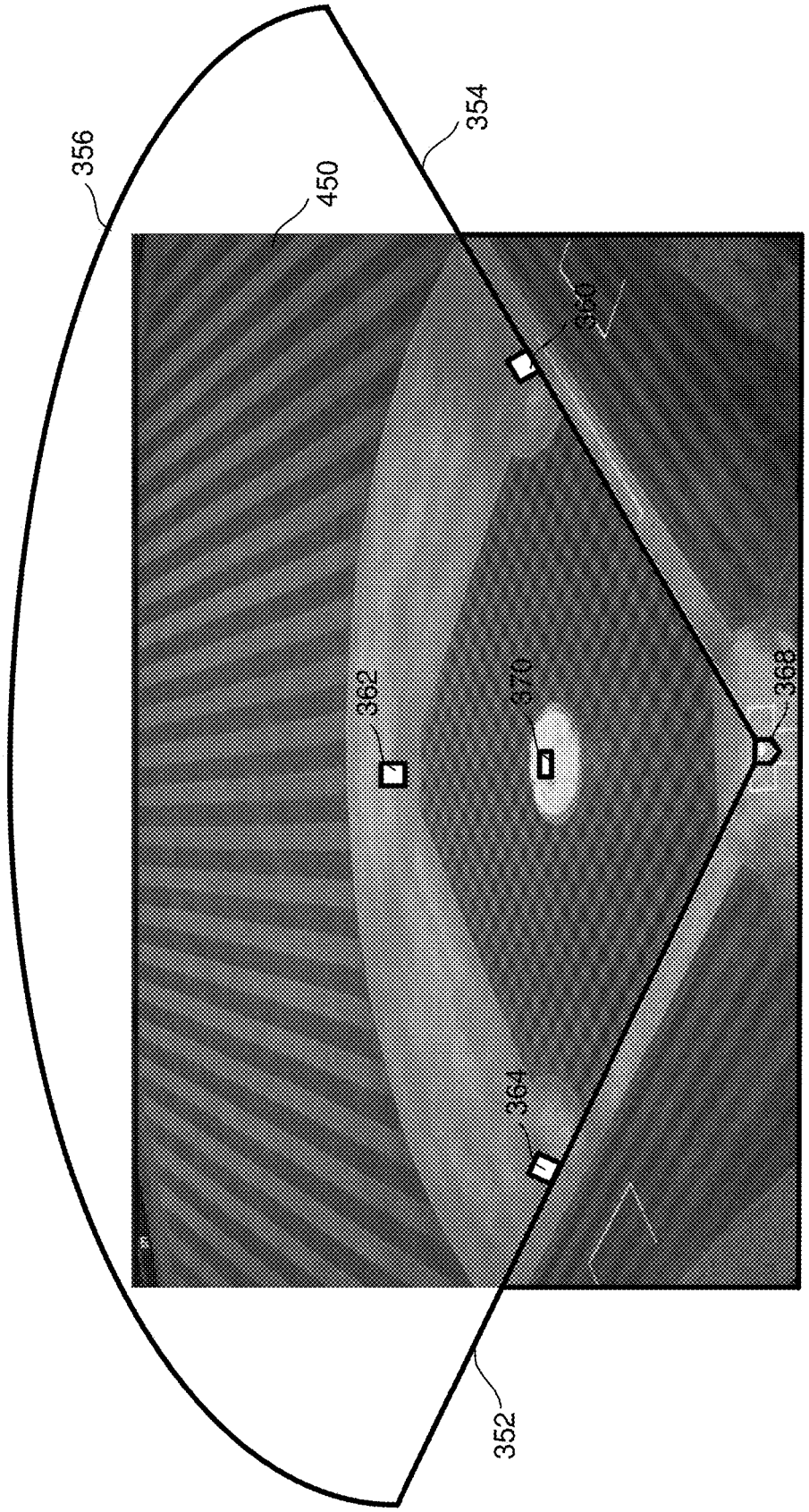


Figure 7

Figure 8

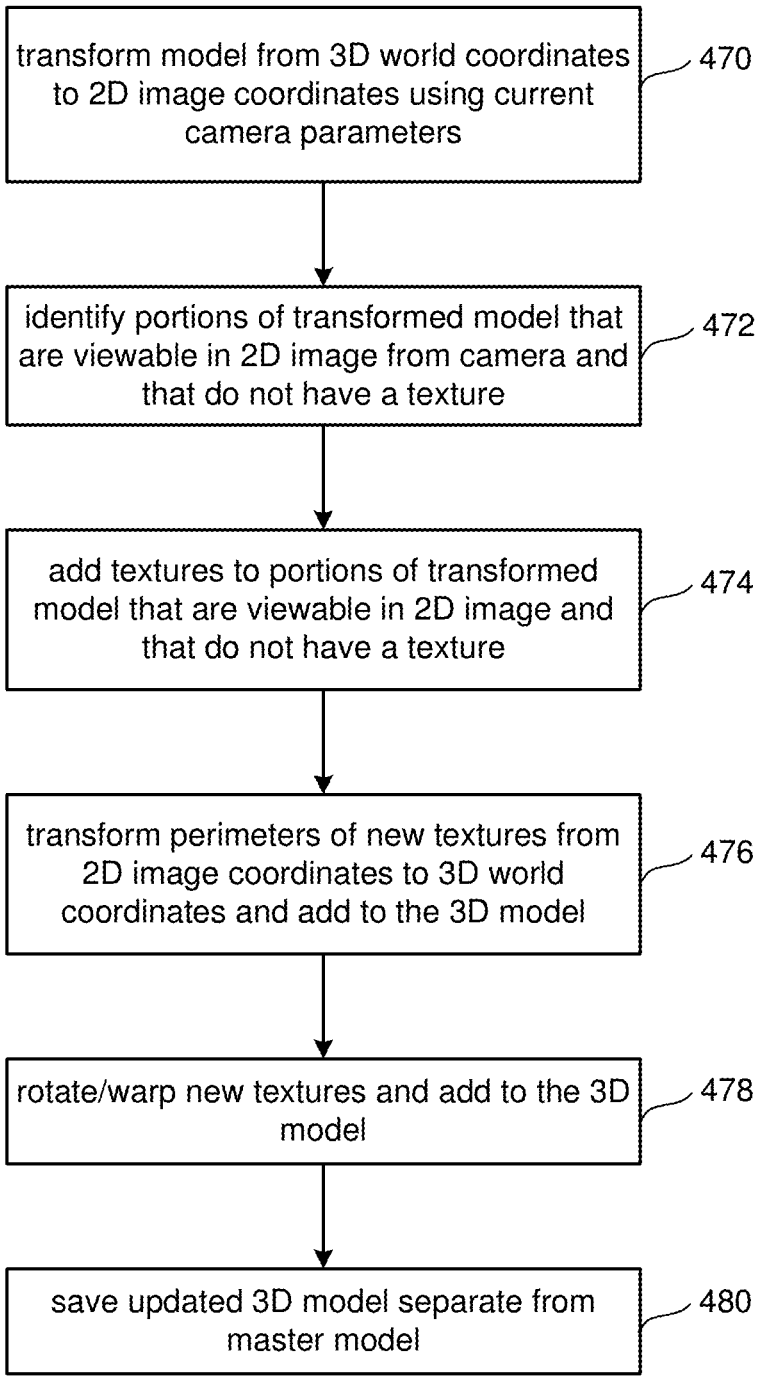

transform model from 3D world coordinates to 2D image coordinates using current camera parameters
470
identify portions of transformed model that are viewable in 2D image from camera and that do not have a texture
472
add textures to portions of transformed model that are viewable in 2D image and that do not have a texture
474
transform perimeters of new textures from 2D image coordinates to 3D world coordinates and add to the 3D model
476
rotate/warp new textures and add to the 3D model
478
save updated 3D model separate from master model
480

Figure 9

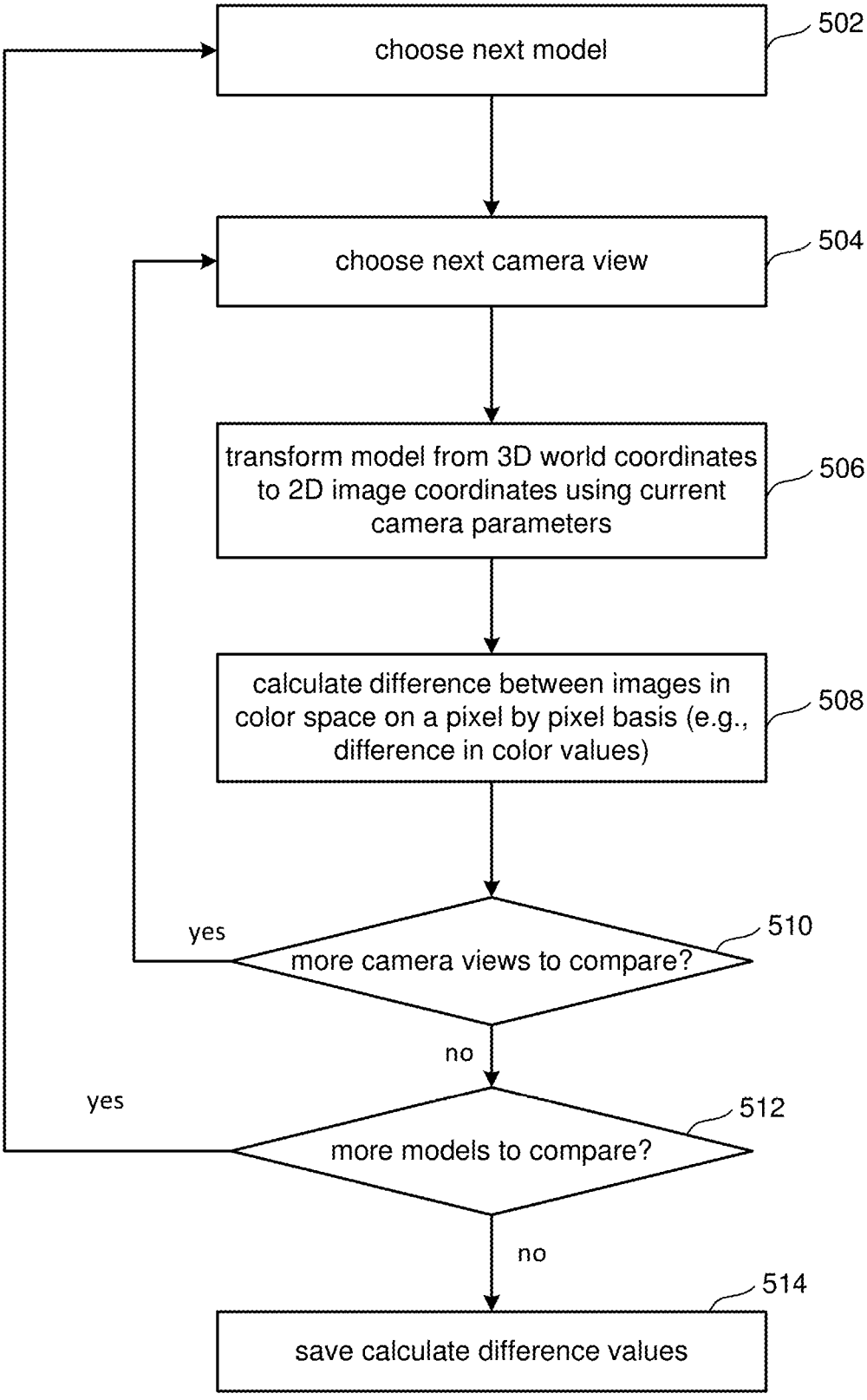

choose next model
502
choose next camera view
504
transform model from 3D world coordinates to 2D image coordinates using current camera parameters
506
calculate difference between images in color space on a pixel by pixel basis (e.g., difference in color values)
508
more camera views to compare?
510
yes
no
more models to compare?
512
yes
no
save calculate difference values
514

Figure 10

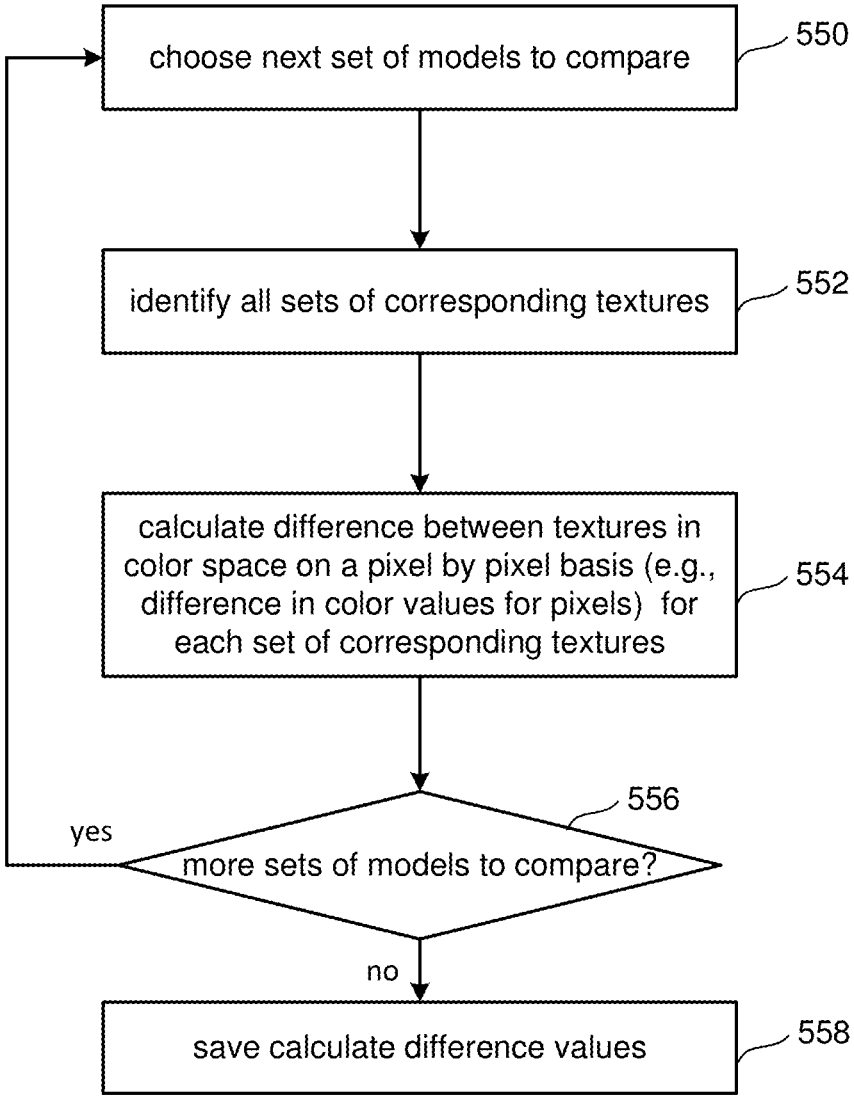
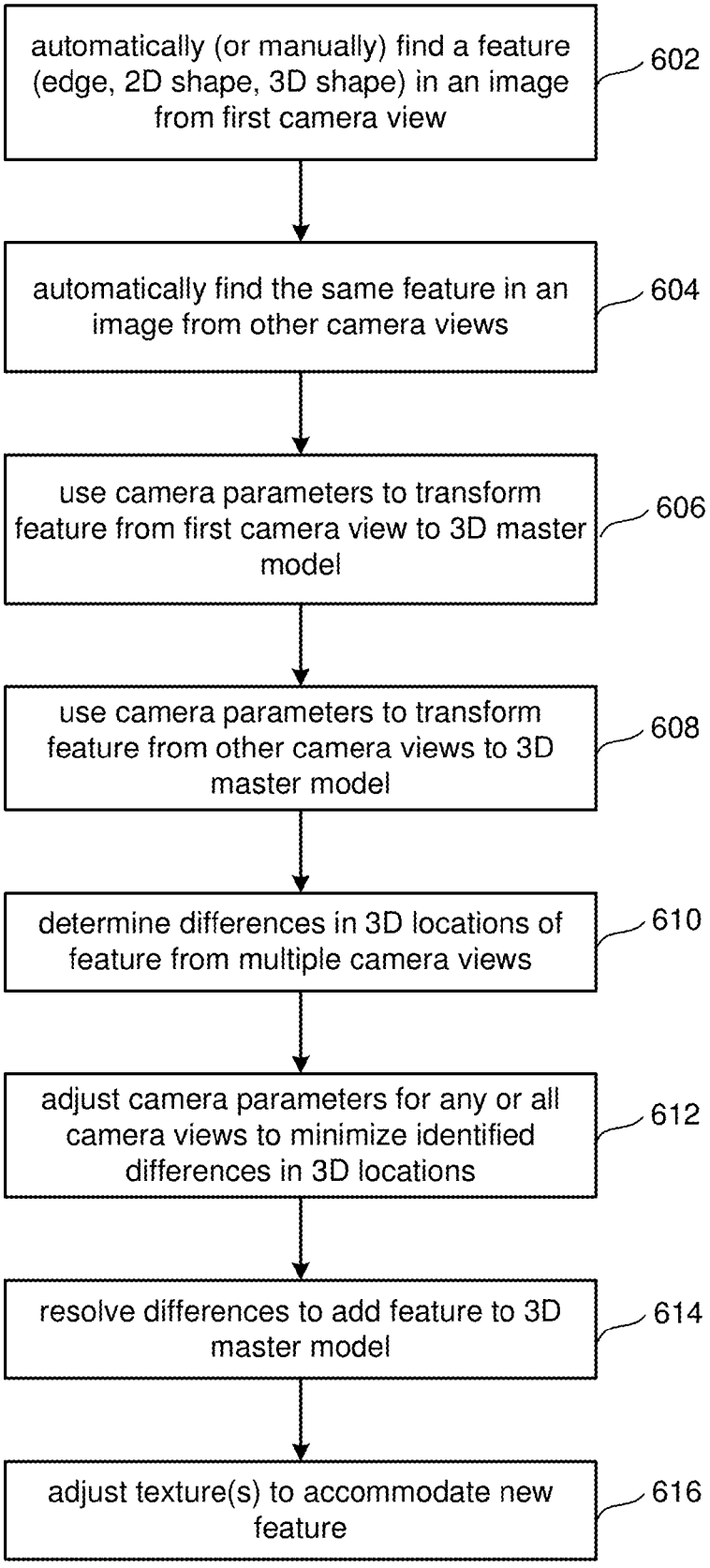

choose next set of models to compare
550
identify all sets of corresponding textures
552
calculate difference between textures in color space on a pixel by pixel basis (e.g., difference in color values for pixels) for each set of corresponding textures
554
556
yes
more sets of models to compare?
no
save calculate difference values
558

Figure 11


automatically (or manually) find a feature (edge, 2D shape, 3D shape) in an image from first camera view
602
automatically find the same feature in an image from other camera views
604
use camera parameters to transform feature from first camera view to 3D master model
606
use camera parameters to transform feature from other camera views to 3D master model
608
determine differences in 3D locations of feature from multiple camera views
610
adjust camera parameters for any or all camera views to minimize identified differences in 3D locations
612
resolve differences to add feature to 3D master model
614
adjust texture(s) to accommodate new feature
616

MULTI VIEW CAMERA REGISTRATION

BACKGROUND OF THE INVENTION

[0001] Data about the state of a camera (e.g., such as focal length, pan angle, tilt angle, zoom level and XYZ position in space) can be used in conjunction with images from the camera for many purposes, including inserting virtual graphics in perspective in images captured by the camera, using the camera as a measurement tool in order to track a moving object, or for other tasks. When using this data about the state of the camera, other information is necessary to interpret or use the data. Such information is referred to as camera parameters. The process for determining the camera parameters is referred to as camera registration.

[0002] It is well known in the art to simultaneously register a camera and to improve the accuracy of estimates of the 3D position of well-identified points in the scene. This simultaneous solving is known in the art as Bundle Adjustment (BA). Estimating 3D elements in a scene captured from a moving camera or from multiple viewpoints, called Structure from Motion (SfM), is also well known in the art. More generally, simultaneously solving for camera parameters and constructing a three dimensional (3D) model of the environment is known in the art as Simultaneous Localizaiton And Mapping (SLAM). SLAM can use BA or other methods, including Extended Kalman Filters (EKF), Unscented Kalman Filters (UKF) and particle filters. Sometimes well-identified points in the scene have well-known 3D locations, and such points are called Control Points (CPs). BA takes the prior known accuracy of positions of well-identified points into account in simultaneously improving position estimates. It is also known in the art to use lines and conic sections in addition to control points.

[0003] 3D models, especially models that represent surfaces in 3D space, are also relevant. 3D Models are well known in the art, including terrain models, animated character models, and architectural models. Such models are typically made by artists using computer-based modeling tools, resulting in a machine readable model. One such tool is Texture Mapping, which involves mapping an image or portion of an image, onto a surface of a model. Texture Mapping may also be regarded as a computerized form of painting with a brush or applying a decal to create detail and texture in a model.

[0004] It is common to register a single camera or register many cameras one at a time or register a single moving, panning, tilting and zooming camera many times (e.g., once per image captured). It is also well known in photogrammetry to simultaneously register multiple cameras viewing overlapping scenes.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. **1** is a block diagram depicting one example of a system for enhancing video and/or tracking moving objects that can perform multi view camera registration.

[0006] FIG. **2** is a block diagram depicting one example implementation of the system processor and the cameral locations of FIG. **1**.

[0007] FIG. **3** depicts a relationship between camera, image and world coordinate systems.

[0008] FIG. **4** is a flow chart describing one embodiment of a process for operating the system described herein.

[0009] FIG. **5** depicts one example of a model.

[0010] FIG. **6** is a flow chart describing one embodiment of a process for performing multi view camera registration.

[0011] FIG. **7** depicts the model of FIG. **5** after one or more textures have been added.

[0012] FIG. **8** is a flow chart describing one embodiment of a process for back projecting one or more camera images to a model.

[0013] FIG. **9** is a flow chart describing one embodiment of a process for automatically comparing the back projected image to one or more images from other camera views using a color space comparison of images to determine a set of error metrics.

[0014] FIG. **10** is a flow chart describing one embodiment of a process for automatically comparing the back projected image to one or more images from other camera views using a color space comparison of images to determine a set of error metrics.

[0015] FIG. **11** is a flow chart describing one embodiment of a process for adding additional features to a model.

DETAILED DESCRIPTION

[0016] A system is proposed that performs multi view camera registration, including registering one or more cameras and/or creating an accurate 3D model of a world space. The system includes back projecting at least one image from at least one of a plurality of camera views to the 3D model based on a set of existing camera parameters. The back projected image is automatically compared to one or more images from other camera views or prior knowledge using a color space comparison of images to determine a set of error metrics. The camera parameters and the 3D model are automatically adjusted to minimize the error metrics based on color spaced comparisons of images from the camera views.

[0017] FIG. **1** is a block diagram depicting one example of a system for enhancing video and/or tracking moving objects that can perform the multi view camera registration described herein. FIG. **1** shows a baseball field. Located around baseball field **10** are cameras **20**, **22**, **24**, **26** and **28**, all pointed at some portion of baseball field **10**. In other embodiments more or less than five cameras can be used. Each of cameras **20**, **22**, **24**, **26** and **28** are connected via a wired or wireless connection to system processor **40**.

[0018] A camera can be any sensor that captures images including visual images (e.g., still or video), depth images, images of ultra violet data, images of infra-red data. Each camera provides at least one camera view, which can be thought of as a perspective of a scene based on position. Thus, a camera that is fixed in location can only provide one camera view of a scene, while a camera that is mobile can provide many camera views. For example, FIG. **1** shows camera **26** once in solid lines, indicating the current location of camera **26**. FIG. **1** also shows camera **26** twice in dashed lines, indicating the additional location that camera **26** can be in. Since camera **26** is a mobile camera, it can be moved to many different locations, thereby, providing many different camera views. As will be discussed in more detail below, the proposed system for registering cameras uses images from multiple camera views, which can be images from different cameras at different locations, one camera at different locations, or a combination of both.

[0019] Although the example used herein is made with respect to a baseball field, the technology proposed herein is not limited to baseball or sports. Rather, the technology

proposed herein can be used at many different events and in many different environments. Baseball is only being used as a teaching example.

[0020] FIG. **2** depicts further details of system processor **40** and the equipment at cameras **20**, **22**, **24**, **26** and **28**. System processor **40** includes a storage device **111**, network interface **112**, processor **113**, working memory **114**, camera interface **115** and user interface **116**. Storage device **111** includes, for example, one or more hard disk drives and/or one or more solid state drives that utilize flash memory (or other type of noni-volatile memory). Network interface **112** can be an Ethernet interface or wireless interface for communicating with other devices via a LAN or the Internet. Processor **113** can include one or more processors single core or multi-core processors for executing code (software instructions) to perform the functions described herein. Working memory **114**, such as RAM, is used to store the code (software instructions) after the code is loaded from the storage device **111**. While in memory **114**, the code programs processor **113** to perform the functions described herein. Camera interface **115** is used to connect to and communicate with the cameras **20**, **22**, **24**, **26** and **28**. In one embodiment, there is a separate camera interface for each camera. In another embodiment, one camera interface communicated with all cameras. User interface **116** can include a touchscreen, keyboard and mouse to allow for interaction with a human operator. The storage device **111** and/or working memory **114** may be considered to be a processor readable storage device having processor readable code embodied thereon for programming the processor **13** to perform methods for providing the functionality discussed herein. The processor readable storage devices can include non-transitory, tangible computer readable media such as volatile and nonvolatile media, removable and non-removable media. Other processor readable storage devices can include DVDs or other optical disk storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other non-transitory, tangible medium which can be used to store the desired information and which can be accessed by a computer.

[0021] FIG. **2** shows system processor **40** connected to camera **20**. System processor **40** is also connected to the other cameras, but FIG. **2** only shows camera **20** to make the drawing easier to read. In one embodiment, the other cameras would have the same or similar structures as described for FIG. **20**.

[0022] Camera **20** is positioned at camera location **120**, and may include (optional) intrinsic sensors **120**, (optional) extrinsic sensors **122** and computer **124** (each of which can be mobile or stationary). The intrinsic sensors **120** are sensors inside the camera that provide state information, such as a zoom setting, whether an expander is used, current focal length, and so forth. The extrinsic sensors **122**, connected to camera **20** and computer **124**, are devices external to camera **20** that are added to determine state information. For example, extrinsic sensors **122** can be mounted directly on the camera or on a tripod to identify an orientation of the camera, such as a pan and tilt of the camera. Computer **124** receives the image data (analog or digital) from camera **20**, data from the intrinsic sensors **120** and data from the extrinsic sensors **122** and provides the images data and data from the sensors to system processor **40** via a wired or wireless (direct or indirect) connection with camera interface **115**.

[0023] In some applications, in order to use any one or more of the cameras **20-28** to insert virtual graphics into video, track an object, render a virtual animated scene, or other task, it is necessary to understand which locations in the real world correspond to which locations in the camera's image. To accomplish this, one embodiment may be to use a first coordinate system for the real world and a second coordinate system for the camera's image. The first coordinate system for the real world shall be referred to as the world coordinate system. The second coordinate system for the camera's image shall be referred to as the camera coordinate system. In some embodiments, there will be a separate camera coordinate system for each camera view. A third coordinate system can also be established for the undistorted image captured by a camera.

[0024] FIG. **3** depicts a relationship between camera, image and world coordinate systems, for use by system processor **40**. A camera coordinate system **36**, which includes orthogonal axes X_C, Y_C and Z_C in three dimensions, is fixed relative to the camera. The origin of the coordinate system may be at the center of the lens, in one possible approach, modeling the camera as a pinhole camera. An image coordinate system **230**, also referred to as pixel space, includes orthogonal axes X and Y in two-dimensions, and is fixed relative to a captured image **232**. A world coordinate system **237**, which includes orthogonal axes X_W, Y_W and Z_W, is fixed relative to, e.g., the earth, a baseball park or other event site, or other reference point or location. Generally, it is desirable to describe the position and/or path of the tracked object **231** in the world coordinate system **237** as this is typically the coordinate system in which its motion is most relevant to the user, and allows easier integration of the information from several cameras. A line of position (LOP) **234** is an imaginary line which extends from the origin of the camera coordinate system **236** through a pixel in the image **232**, intersecting the pixel at a point **233**, and through the tracked object **231**. Each pixel in the image **232** corresponds to a different line of position. Point **233** in the captured image **32** represents the location of the object **231** in the image. The location of the object in the image **232** can be represented by coordinates (sx, sy) in a coordinate system which has its origin at a corner of the image, in one example approach. The coordinates may also identify the center of the object. When the object is a tracked human participant, characteristics such as the outline of the participant can be detected. More complex relationships between camera, image and world coordinate systems are well known in the art. One example is to include lens distortion into the transformation between world coordinates and image coordinates. It is not necessary to describe such additional complexities here.

[0025] Further, in one example approach, the line of position **234** can be represented by a 3-D vector which has unity magnitude. The vector can be defined by two points along the LOP. The vector can be represented in the world coordinate system **237** using an appropriate transformation from the image coordinate system. The Zc axis of the camera coordinate system, which is the optical axis of the camera, intersects the captured image at a point represented by coordinates $(0_x, 0_y)$. A two-dimensional coordinate system extending from $(0_x, 0_y)$ can also be defined.

[0026] The camera registration process involves obtaining one or more transformation matrices which provide a conversion between the image coordinate system **30** and the

world coordinate system **37**. Further information can be found in E. Trucco and A. Verri, "Introductory techniques for 3-D computer vision," chapter 6, Prentice Hall, 1998, U.S. Pat. No. 5,912,700, issued Jun. 15, 1999, and U.S. Pat. No. 6,133,946, issued Oct. 17, 2000, each of which is incorporated herein by reference.

[0027] As described above, some (not all) applications require the system to transform locations in world coordinates to positions in image coordinates. The task is to calculate the images coordinates, (s_x, s_y), given the world coordinates (world space) of a point. In practice, the point in world space might correspond to a physical object or a part of a geometrical shape, but in general can be any arbitrary point. One example method is to break the overall mapping into three separate mappings:

[0028] A mapping from three dimensional (3D) points expressed in world coordinates (world space) to 3D points expressed in camera centered coordinates. We denote this mapping as T_{WTC}.

[0029] A mapping from 3D points expressed in camera centered coordinates, to undistorted two dimensional (2D) image coordinates (e.g., a position in the video). This mapping models the effects of cameras; i.e. producing 2D images from 3D world scenes. We will denote this mapping as K.

[0030] A mapping from undistorted screen coordinates to distorted screen coordinates (e.g., a position in the video). This mapping models various effects that occur in cameras using lenses; i.e. non-pinhole camera effects. We will denote this mapping as f.

[0031] When composited together, the three mappings create a mapping from world coordinates into image (or screen) coordinates:

$$\begin{pmatrix} X_w \\ Y_w \\ Z_w \end{pmatrix} \xmapsto{T_{WTC}} \begin{pmatrix} X_c \\ Y_c \\ Z_c \end{pmatrix} \xmapsto{K} \begin{pmatrix} s_x \\ s_y \end{pmatrix} \xmapsto{f} \begin{pmatrix} s'_x \\ s'_y \end{pmatrix} \tag{1}$$

[0032] Each of the three mapping noted above will now be described in more detail.

[0033] The mapping from 3D world coordinates to 3D camera centered coordinates (T_{WTC}) will be implemented using 4×4 homogeneous matrices and 4×1 homogeneous vectors. The simplest way to convert a 3D world point into a 3D homogeneous vector is to add a 1 into the 4th element of the 4×1 homogeneous vector:

$$\underbrace{\begin{pmatrix} X_w \\ Y_w \\ Z_w \end{pmatrix}}_{nonhomogenous} \mapsto \underbrace{\begin{pmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{pmatrix}}_{homogenous} = X_W \tag{2}$$

[0034] The way to convert from a 3D homogeneous vector back to a 3D nonhomogeneous vector is to divide the first 3 elements of the homogenous vector by the 4th element. Note that this implies there are infinitely many ways to represent the same nonhomogeneous 3D point with a 3D homogeneous vector since multiplication of the homogeneous vector by a constant does not change the nonhomogeneous 3D point due to the division required by the conversion. Formally we can write the correspondence between one nonhomogeneous vector to infinitely many homogeneous vectors as:

$$\underbrace{\begin{pmatrix} X_w \\ Y_w \\ Z_w \end{pmatrix}}_{nonhomogenous} \mapsto k \underbrace{\begin{pmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{pmatrix}}_{homogenous} \tag{3}$$

for any k≠0.

[0035] In general the mapping T_{WTC} can be expressed with a 4×4 matrix:

$$T_{WTC} = \begin{bmatrix} t_{11} & t_{12} & t_{13} & t_{14} \\ t_{21} & t_{22} & t_{23} & t_{24} \\ t_{31} & t_{32} & t_{33} & t_{34} \\ t_{41} & t_{42} & t_{43} & t_{44} \end{bmatrix} \tag{4}$$

which can be expressed using row vectors as:

$$T_{WTC} = \begin{bmatrix} t^{1T} \\ t^{2T} \\ t^{3T} \\ t^{4T} \end{bmatrix} \tag{5}$$

[0036] Finally if we use homogeneous vectors for both the world point in world coordinates, X_w, and the same point expressed in camera centered coordinates, X_c the mapping between the two is given by matrix multiplication using T_{WTC}:

$$X_c = T_{WTC} X_w \tag{6}$$

[0037] If we want the actual nonhomogeneous coordinates of the point in the camera centered coordinate system we just divide by the 4th element of X_c. For example if we want the camera centered x-component of a world point we can write:

$$X_c = \frac{t^{1T} X_w}{t^{4T} X_w} \tag{7}$$

[0038] To build the matrix T_{WTC}, we start in the world coordinate system (word space)—which is a specific UTM zone—and apply the following transformations:

[0039] Translate to the camera location: T (H_x, H_y, H_z)

[0040] Account for the rotation relative to the world coordinate system:

[0041] R_z (-Panw)

[0042] R_x (-Tiltw)

[0043] R_y (-Rollw)

[0044] Account for outer axis (outer axis of camera system) orientation relative to camera platform:

[0045] R_z (PanAdjust)

[0046] R_x (TiltAdjust)

[0047] R_y (RollAdjust)

[0048] Account for outer axis transducer measurement from camera system and offset of zero readings relative to outer axis:

[0049] R_z (Pan_{outer}+PanAdjust2)

[0050] R_x ($Tilt_{outer}$+TiltAdjust2)

Note that PanAdjust2 and TiltAdjust2 are adjustment values for imperfections in the outer axis orientation and can be determined during a camera registration process. If the output of the sensor should be 0 degrees, these parameters are used to recognize 0 degrees. Pan_{outer} and $Tilt_{outer}$ are the sensor (e.g., transducer) readings output from the camera system **102** for the outer axis.

[0051] Account for non-linearity of inner axis (of camera system) pan and tilt transducer measurements via a look-up table

[0052] $Pan_{Inner_linearized}$=L(Pan_{Inner})

[0053] $Till_{Inner_linearized}$=L'($Tilt_{Inner}$)

[0054] Account for inner axis transducer measurements and offset of zero readings relative to inner ring:

[0055] R_z($Pan_{Inner_linearized}$+PanAdjust3)

[0056] R_x($Tilt_{Inner_linearized}$+TiltAdjust3)

[0057] R_y($Roll_{Inner}$+RollAdjust3)

[0058] Note that PanAdjust3, TiltAdjust3 and RollAdjust3 are adjustment values for imperfections in the inner axis orientation. If the output, of the sensor should be 0 degrees, these parameters are used to recognize 0 degrees. Pan_{Inner}, $Tilt_{Inner}$ and $Roll_{Inner}$ are the sensor (e.g., transducer) readings output from the camera system **102** for the inner axis.

[0059] Finally, convert to standard coordinate convention for camera centered coordinate systems with x-axis pointing to the right of the image, y-axis pointing up in the image, and z-axis pointing behind the camera

$$-R_x\left(\frac{\pi}{2}\right)$$

[0060] Thus, the final rigid-body transform, T_{WTC} which converts points expressed in world coordinates to points expressed in the camera centered coordinate system and suitable for multiplication by a projection transform is given by:

$$\begin{aligned} T_{WTC} = {} & R_x\left(\frac{\pi}{2}\right)R_y(Roll_{Inner} + RollAdjust3)\cdot R_x(Tilt_{Inner_linearized} + TiltAdjust3)\cdot \\ & R_z(Pan_{Inner_linearized} + PanAdjust3)\cdot R_x(Tilt_{Outer} + TiltAdjust2)\cdot \\ & R_z(Pan_{Outer} + PanAdjust2)\cdot R_y(RollAdjust)R_x(TiltAdjust)\cdot \\ & R_z(PanAdjust)\cdot R_y(Roll_{Heli})R_x(-Tilt_W)R_z(-Pan_W)T(H_x, H_y, H_z) \end{aligned} \quad (8)$$

[0061] The form of the three rotation matrices: R_x, R_y, R_z suitable for use with 4×1 homogeneous vectors are given below. Here the rotation angle specifies the rotation between the two coordinate systems basis vectors.

$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha & 0 \\ 0 & -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

$$R_y(\alpha) = \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha & 0 \\ 0 & 1 & 0 & 0 \\ \sin\alpha & 0 & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (10)$$

$$R_z(\alpha) = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 & 0 \\ -\sin\alpha & \cos\alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

[0062] The matrix representation of the translation transform that operates on 4×1 homogeneous vectors is given by:

$$T(d_x, d_y, d_z) = \begin{bmatrix} 1 & 0 & 0 & d_x \\ 0 & 1 & 0 & d_y \\ 0 & 0 & 1 & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (12)$$

[0063] The mapping of camera centered coordinates to undistorted image coordinates (K) can also be expressed as a 4×4 matrix which operates on homogenous vectors in the camera centered coordinate system. In this form the mapping from homogeneous camera centered points X_c, to homogeneous image points, S_u is expressed:

$$S_u = KX_c \quad (13)$$

$$w\begin{pmatrix} s_x \\ s_y \\ s_z \\ 1 \end{pmatrix} = KX_c \quad (14)$$

[0064] To get the actual undistorted image coordinates from the 4×1 homogenous screen vector we divide the first three elements of S_u by the 4th element.

[0065] Note further that we can express the mapping from homogeneous world points to homogeneous undistorted image points via matrix multiplication.

$S=KT_{WTC}X_w=PX_w$

where,

$P=KT_{WTC}$ (15)

[0066] One embodiment uses a pinhole camera model for the projection transform K. If it is chosen to orient the camera centered coordinate system so that the x-axis is parallel to the s_x image coordinate axis, and the camera y-axis is parallel to the s_y image coordinate axis—which itself goes from the bottom of an image to the top of an image—then K can be expressed as:

$$K = \begin{bmatrix} -\frac{f'}{par} & 0 & u_o & 0 \\ 0 & -f' & v_o & 0 \\ 0 & 0 & A & B \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (16)$$

where,

$$f' = \frac{N_y/2}{\tan(\varphi/2)} \quad (17)$$

N_y = number of pixels in vertical screen direction.

φ = vertical field of view

par = pixel aspect ratio

u_o, v_o = optical center

A, B = Clipping plane parameters.

[0067] The clipping plane parameters, A, B, do not affect the projected image location, s_x, s_y, of a 3D point. They are used for the details of rendering graphics and are typically set ahead of time. The number of vertical pixels, N_y and the pixel aspect ratio par are predetermined by video format used by the camera. The optical center, (u_o, v_o) is determined as part of a calibration process. The remaining parameter, the vertical field of view ϕ, is the parameter that varies dynamically.

[0068] The screen width, height and pixel aspect ratio are known constants for a particular video format: for example N_x=1920, N_y=1080 and par=1 for 1080i. The values of u_o, v_o are determined as part of the camera registration process. That leaves only the field of view, ϕ, which needs to be specified before K is known.

[0069] The field of view can determined on a frame by frame basis using the following steps:

[0070] use the measured value of the 2× Extender to determine the 2× Extender state;

[0071] use the 2× Extender state to select a field of view mapping curve; Use the measured value of field of view, or equivalently zoom, and the particular field of view mapping curve determined by the 2× Extender state to compute a value for the nominal field of view;

[0072] use the known 2× Extender state, and the computed value of the nominal field of view in combination with the measured focus value, to compute a focus expansion factor; and

[0073] compute the actual field of view by multiplying the nominal field of view by the focus expansion factor.

[0074] One field of view mapping curve is required per possible 2× Extender state. The field of view mapping curves are determined ahead of time and are part of a calibration process.

[0075] One mapping between measured zoom, focus and 2× Extender and the focus expansion factor is required per possible 2× Extender state. The focus expansion factor mappings are determined ahead of time and are part of a calibration process.

[0076] The mapping (f) between undistorted image coordinates to distorted image coordinates (pixels) is not (in one embodiment) represented as a matrix. In one example, the model used accounts for radial distortion. The steps to compute the distorted screen coordinates from undistorted screen coordinates are:

[0077] start with the nonhomogenous screen pixels $s_u=(s_x,s_y)^T$

[0078] compute the undistorted radial distance vector from a center of distortion, s_o $\delta r=s_u-s_o$.

[0079] compute a scale factor $\alpha=1+k_1\|\delta r\|+k_2\|\delta r\|^2$

[0080] compute the nonhomogeneous screen pixel vector $s_d=\alpha\delta r+s_o$

Some embodiments will also normalize the data.

[0081] The two constants k_1, k_2 are termed the distortion coefficients of the radial distortion model. An offline calibration process is used to measure the distortion coefficients, k_1, k_2, for a particular type of lens at various 2× Extender states and zoom levels. Then at run time the measured values of zoom and 2× Extender are used to determine the values of k_1 and k_2 to use in the distortion process. If the calibration process is not possible to complete, the default values of $k_1=k_2=0$ are used and correspond to a camera with no distortion. In this case the distorted screen coordinates are the same as the undistorted screen coordinates.

[0082] From the above discussion, PanAdjust2, TiltAdjust2, PanAdjust3, TiltAdjust3, RollAdjust3, vertical field of view ϕ, distortion coefficients, k1, k2, and camera location T (Hx, Hy, Hz) are examples of camera parameters that need to be solved for in order for some embodiments to perform virtual insertion of graphics, tracking of moving objects, etc. In other embodiments, the camera parameters will include additional and/or other values/variables/constants/offsets needed to use the data from the camera sensors in order to transform positions between coordinate systems.

[0083] FIG. **4** is a flow chart describing one embodiment of a process for operating a system described above with respect to FIGS. **1-3**. In step **302**, an approximated 3D model of an environment is built (manually or automatically) using known information (e.g., known rules, specification, etc.). If manually, a human can create a rough model of an area in world space based on information and rules using a computer. For example when creating a model of a baseball field, the rules for how far apart bases are located, how far a pitcher's mound is from home plate, and distance/angle between sidelines can be taken into account to create a computer based model of the baseball field. If created automatically, the model can be created by a system processor **40** or another computing system. In one embodiment, the 3D model built in step **302** is flat (e.g. two dimensional), meaning that even though it is a three dimensional model, only two dimensions are represented in the first draft of the model. For example, FIG. **5** depicts one embodiment of approximated 3D model created as part of step **302** when the environment being modeled is a baseball field. The model of FIG. **5** is a two dimensional, at this point in time. The model includes left sideline **352**, right sideline **354**, outfield edge **356**, first base **360**, second base **362**, third base **364**, home plate **368** and pitcher's mound **370**. Major League Baseball rules for the dimensions of the field are used to specify the relative locations of all of the features depicted in the model of FIG. **5**, with the exception of outfield boundary **356**. When stored in memory, the model can include a set of 3D coordinates.

[0084] Looking back at FIG. **4**, in step **304**, system processor **40** automatically creates an initial guess at camera parameters for multiple camera views. In one embodiment,

a human can manually create the initial guess of the camera parameters. In step **306**, system processor **40** performs multi view camera registration, including automatically updating the camera parameters and the 3D model (including updating textures and geometry of the model) based on comparisons of images (discussed in more detail below). In step **308**, system processor **40** (or another computing system) uses the updated 3D model and the updated camera parameters to insert virtual graphics into video from one or more cameras, create a 3D animated rendering of an event depicted by the cameras, track one or more moving objects in the video captured by the cameras, or perform another function.

[0085] FIG. **6** is a flowchart describing one embodiment of a process for performing multi-view camera registration. The process of FIG. **6** is one example implementation of step **306** of FIG. **4**. In one embodiment, the process of FIG. **6** is performed by system processor **40**. In step **402** of FIG. **6**, system processor **40** accesses the approximated 3D master model that was built in advance. For example, step **402** includes accessing the model built in step **302** of FIG. **4**. In one example, the model of FIG. **5** is accessed in step **402** of FIG. **6**. In step **404**, system processor **104** accesses the initial guess at parameters (e.g., created in step **302** of FIG. **4**).

[0086] For one or more camera views, system processor **40** uses the current 3D master model (the model accessed in step **402**) and the current camera parameters to back project one or more camera images to the 3D master model in step **406** of FIG. **6**. The back projecting includes adding textures to the model. In one embodiment, textures are added for multiple camera views to a single instance of the 3D master model. In other embodiments, textures from different camera views are added to different instances of the 3D master model (with the different instances of the 3D master model being later reconciled to form on 3D master model). Step **406** includes saving the one or more instances of the modified 3D master model(s). In step **408**, system processor **40** compare the one or more modified model(s) to other camera views using a color space comparison of images in order to identify differences in the images. That is, system processor **40** automatically compares the back projected image from a camera view to one or more images from other camera views using the color space comparison of images to determine differences between the images. Note that differences between the images resulting from a color space comparison of images is one example of an error metric. Other error metrics can also be determined. In one example implementation, system processor **40** aligns images from different camera views using the current camera parameters and then determine differences in these images, representing the error metrics. Note that a color space comparison of images can include comparing multiple color images, single color images, black & white images, or grayscale images.

[0087] Step **410** includes adjusting the camera parameters for any or all of the camera views and/or adjusting the 3D model (including adjusting the three dimensional geometry and textures for the model) to minimize the identified differences (and/or other error metrics) in order to converge on an updated master model. That is, step **410** includes adjusting the 3D master model by adding additional details to the 3D master model, changing details to the 3D master model and adjusting existing camera parameters, all based on the color based comparison discussed above. Step **410** includes using SfM with BA to adjust the camera parameters and the 3D master model in order to minimize differences in the images. Thus, the current technology proposed herein employs SfM using textures as well as well-identified points, lines or conics in the scene.

[0088] Steps **408** and **410** can include comparing many sets of images; therefore, multiple difference values and/or multiple error metrics are calculated. A total set of error metrics and/or differences can be combined to create a combined differences value using any suitable formula or relationship. In step **412**, it is tested whether the combined difference or combines error metric is less than a threshold. If not, then additional BA can be performed and the process will continue in step **414**. In step **414**, it is determined whether the process is timed out. If not, then the process moves back to step **406** and steps **406-410** are repeated for the updated 3D model and updated set of camera parameters. Thus, steps **406-414** create a loop that is performed repeatedly until the differences in images (and/or other error metrics) are reduced to below a threshold, or if the process times out. When it is determined that the combined differences is less than the threshold (step **412**) or that the process is timed out (step **414**), then the method continues at step **416** and it is determined whether there are other refinements that could be made to the 3D master model. If not, the 3D master model is ready to be used, for example, to insert virtual graphics, create a 3D animated rendering of an event and/or track one or more moving objects, as well as other uses. If, however, there are other additional refinements that are available to be made to the 3D master model (step **416**), then in step **418** the additional features are added to the 3D model and the process continues in step **406**.

[0089] As discussed above, step **406** of FIG. **6** includes back projecting one or more images from any one or more of the camera views onto the master 3D model. FIG. **7** depicts the model of FIG. **5** with one or more images back projected onto that 3D master model as a texture for the 3D master model. Each time step **406** is performed, it is possible to add one or more additional images as textures to the model. Additionally, each time step **410** is performed, any one of the textures can be adjusted and/or the geometry of the model can be adjusted. For example, if textures overlap and are different, the system will adjust the textures; for example, by choosing one of the overlapping textures, combining the textures, or another operation involving the textures. When adjusting the geometry of the 3D master model, the system can add three dimensional shapes to the model, change 3D shapes, remove 3D shapes, etc. In one embodiment, the three dimensional shapes are randomly added, changed and/or removed at various boundaries identified by features in the model or textures and the system determines whether the randomly adding, changing and/or removing of three dimensional features increases or decreases the differences (and/or other error metrics).

[0090] FIG. **8** is a flowchart describing one embodiment of a process for back projecting an image to the 3D master model that is performed as part of step **406** of FIG. **6**. In step **470**, system processor **40** transform the 3D master model from 3D world coordinates to 2D image coordinates using the current camera parameters. This includes transforming known locations in the model, transforming perimeters of any textures in the model and rotating/warping any textures on the model. In step **472**, system processor **40** identifies portions of the transformed model that are viewable in the 2D image from the camera and that do not have a texture. In step **474**, one or more textures are added to the portions of

the transformed model that are viewable in the 2D image and that do not have a texture already. These textures are from the image captured by the camera being operated on. In step **476**, perimeters of the new texture(s) are transformed from the 2D image coordinates to 3D world coordinates and added to the 3D model. In step **478**, the actual texture being added to the model is rotated/warped and added to the 3D master model based on the transformation of its corners. In step **480**, the updated 3D model is saved separate from the 3D master model (at least temporarily). The process of FIG. **8** is for one camera view. When performing the process of FIG. **6**, step **406** can include performing the process of FIG. **8** multiple times for multiple different cameras views. In other embodiments, step **406** can include only performing the process of FIG. **8** for one camera view.

[0091] One embodiment of steps **406-410** of FIG. **6** includes back projecting images from multiple camera views onto one or more modified models and then comparing the images (textures) of the one or more modified models in order to create differences and adjusting the camera parameters and model to minimize those differences. Another embodiment includes back projecting images from one camera view onto the model and then transforming that updated model to image coordinates for multiple other camera views and then doing the comparison of images in the image coordinate system to create the set of differences. These two embodiments are described in more detail with respect to FIGS. **9** and **10**.

[0092] FIG. **9** is a flowchart describing one embodiment of a process automatically comparing the back projected image to one or more images from other camera views using a color space comparison of images to determine a set of error metrics. The embodiment of FIG. **9** includes back projecting images from one or more different camera views onto the 3D master model to create one or more modified models and then transforming those one or more modified models to the image space for various camera views and comparing the images from the camera views to the textures of the models in the image space to determine difference values. In step **502**, system processor **40** chooses the next model. In step **504**, system processor **40** chooses the next camera view to operate on. In step **506**, the currently chosen model is transformed from 3D world coordinates to 2D image coordinates for the camera view chosen in step **504**, using the current camera parameters for that camera view chosen in step **504**. In step **508**, the system processor **40** calculates a difference between images in a color space on a pixel-by-pixel basis (e.g., difference in color values of the pixels) for the image of the chosen camera view and the image of the textures after the model is transformed. Thus, this embodiment does a difference in images. This difference in image (representing one example of an error metric) is stored. It step **510**, it is determined whether there are more camera views to compare the model to. In one embodiment, the model will be compared to every camera view available. If there are more camera views to compare the current model to the process loops back to step **504**, chooses the next camera view and continues to step **506** and **508** to do the additional comparison(s). When all camera views for the current model have been compared, then at step **512** it is determined whether there are more modified models to compare. In one embodiment, all the modified models created in step **406** will be transformed to all the camera views. Thus if there are more modified models to operate on, then the process will loop from step **512** back to step **502**, choose the next modified model, and then iterate through all the camera views in the loop created by steps **504-510**. After all models have been used (step **512**), then all the different values calculated in all the iterations in step **508** will be saved by system processor **40** in step **514**.

[0093] FIG. **10** is a flowchart describing one embodiment of a process automatically comparing the back projected image to one or more images from other camera views using a color space comparison of images to determine a set of error metrics. The process of FIG. **10** is an alternative embodiment to the process of FIG. **9**. Both the process of FIG. **9** and the process of FIG. **10** are example implementations of step **408** of FIG. **6**. In the embodiment of FIG. **10**, textures from all (or a subset of) the different models are compared against each other to create the difference values, which are subsequently attempted to be minimized in step **410** of FIG. **6**. In step **550** of FIG. **10**, system processor **40** chooses the next set of models to compare. In one embodiment, every permutation of two, three, etc., modified models can be compared. In step **552**, for the set of modified models being compared, system processor **40** identifies all sets of corresponding textures. For example, two textures are corresponding if they overlap the same portion of the model. In step **554**, the system will calculate a difference value between the textures in color space by subtracting the textures on a pixel-by-pixel basis (e.g., subtracting color values for the pixels). In step **556**, the system determines whether there are more sets of models to compare. If so, the process loops back to step **550** and the next set of models are compared. If all permutations of sets of models to be compared have already been compared, then the process continues in step **568** and saves all the different values calculated in all the iterations in step **554**.

[0094] Step **418** in FIG. **6** includes refining the model by adding additional features to the 3D master model. FIG. **11** is a flowchart describing one embodiment of a process for adding the additional features to the 3D master model. Therefore, the process of FIG. **11** is one example implementation of step **418** of FIG. **6**.

[0095] In step **602** of FIG. **11**, system processor **40** automatically (or a human will manually) find a feature (e.g., edge, two-dimensional shape, three-dimensional shape, etc.) in an image from a first camera view. In step **604**, system processor **40** automatically (or a human manually) finds that same feature in an image from one or more other camera views. In step **606**, the current set of camera parameters for the relevant camera views are used to transform the found features from the first camera view to the 3D master model. In step **608**, the current camera parameters are used to transform the found feature from the other camera views (see step **604**) to the 3D model. In step **610**, system processor **40** determines the differences in the 3D locations of the features found based on the transformation from the multiple camera views. In step **612**, the system will continually adjust the camera parameters for any or all the camera views to minimize any identified differences in the 3D locations from step **610**. This process can utilize BA. In step **614**, system processor **40** resolves any differences in the 3D locations and adds the final location and feature to the 3D master model. That is, step **612** attempts to minimize the differences; however, it may be impossible to have zero difference. Therefore, the system may need to take an average of the location or some other mathematical approximation in order

to resolve the difference in transformed 3D locations. In step **616**, one or more textures in the model can be adjusted to accommodate the new feature. For example, if the three-dimensional shape of the pitcher's mound is being added to the 3D master model, then the texture showing the image of the pitcher's mound may be adjusted to be on a more spherical or conical surface rather than on a flat surface.

[0096] One embodiment includes a method comprising back projecting at least one image from at least one of a plurality of camera views to a 3D model of a world space environment based on a set of camera parameters; automatically comparing the back projected image to one or more images from other camera views to determine a set of error metrics; and automatically adjusting the camera parameters and the 3D model to minimize the error metrics based on the comparing.

[0097] One embodiment includes an apparatus, comprising: one or more processors; and one or more processor readable storage mediums connected to the one or more processors. The one or more processor readable storage mediums are configured to store code for programming the one or more processors to add an image from at least one of a plurality of camera views to a model of an environment based on a set of camera parameters, compare the added image to an image from a different camera view using a color spaced comparison of images to determine one or more differences between the added image and the image from the different camera view, and adjust the camera parameters and the 3D model to minimize the one or more differences between the added image and the image from the different camera view based on color spaced comparisons of images.

[0098] One embodiment includes an apparatus, comprising: one or more processors; and one or more processor readable storage mediums connected to the one or more processors. The one or more processors are configured to access sets of camera parameters for different camera views and access images from the different camera views. The one or more processors configured to attempt to align the images from the different camera views using the camera parameters. The one or more processors are configured to perform a color based comparison of the attempted aligned images and determine differences between the attempted aligned images based on the color based comparison. The one or more processors configured to adjust the camera parameters to minimize the differences between the attempted aligned images.

[0099] One embodiment includes a method, comprising: projecting an image from at least one of a plurality of camera views to a 3D model of a word space environment; performing a color based comparison of the projected image to one or more images from other camera views; and adding an additional detail to the 3D model based on the color based comparison.

[0100] One embodiment includes an apparatus, comprising: one or more processors; and one or more processor readable storage mediums connected to the one or more processors. The one or more processors are configured to add an image from at least one of a plurality of camera views to a model of a word space environment. The one or more processors are configured to perform an images based comparison of the added image to one or more images from other camera views. The one or more processors are configured to add an additional detail to the model based on the imaged based comparison.

[0101] For purposes of this document, reference in the specification to "an embodiment," "one embodiment," "some embodiments," or "another embodiment" may be used to describe different embodiments or the same embodiment.

[0102] For purposes of this document, a connection may be a direct connection or an indirect connection (e.g., via one or more others parts). In some cases, when an element is referred to as being connected or coupled to another element, the element may be directly connected to the other element or indirectly connected to the other element via intervening elements. When an element is referred to as being directly connected to another element, then there are no intervening elements between the element and the other element. Two devices are "in communication" if they are directly or indirectly connected so that they can communicate electronic signals between them.

[0103] For purposes of this document, the term "based on" may be read as "based at least in part on."

[0104] For purposes of this document, without additional context, use of numerical terms such as a "first" object, a "second" object, and a "third" object may not imply an ordering of objects, but may instead be used for identification purposes to identify different objects.

[0105] For purposes of this document, the term "set" of objects may refer to a "set" of one or more of the objects.

[0106] The foregoing detailed description has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. The described embodiments were chosen in order to best explain the principles of the proposed technology and its practical application, to thereby enable others skilled in the art to best utilize it in various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope be defined by the claims appended hereto.

What is claimed is:

1. A method, comprising:

back projecting at least one image from at least one of a plurality of camera views to a 3D model of a world space environment based on a set of camera parameters;

automatically comparing the back projected image to one or more images from other camera views to determine a set of error metrics; and

automatically adjusting the camera parameters and the 3D model to minimize the error metrics based on the comparing.

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

adding an additional detail to the 3D model based on the comparing.

3. The method of claim **1**, wherein the back projecting of at least one image includes adding the at least one image to the 3D model as a texture, the method further comprising:

automatically adjusting a texture of the 3D model based on the comparing.

4. The method of claim **1**, wherein the automatically comparing comprises:

performing a color space comparison of images including a pixel by pixel comparison of color values of the back projected image and the one or more images from other camera views.

5. The method of claim **1**, wherein:

the back projecting of at least one image from at least one of the plurality of camera views to the 3D model includes back projecting images from multiple camera views to one or more instances of the 3D model to create textures for the 3D model; and

the automatically comparing comprises comparing textures for the 3D model that originated from different camera views.

6. The method of claim **1**, wherein:

the back projecting includes adding one image from a first camera to the 3D model as a texture; and

the automatically comparing comprises transforming the 3D model to a 2D image for a second camera and comparing the 2D image to a video image captured by the second camera.

7. The method of claim **1**, wherein:

the back projecting includes adding one image from a first camera to the 3D model as a texture by transforming the 3D model from 3D world coordinates to 2D camera space for the first camera using current camera parameters for the first camera, adding the one image to the transformed model and transforming the model with the one image from 2D camera space for the first camera to 3D world coordinates.

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

adding a new feature to the 3D model and repeating the automatically comparing and the automatically adjusting.

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

using the 3D model and camera parameters to track a moving object subsequent to the automatically adjusting.

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

using the 3D model and camera parameters to insert an image into video from one of the camera views subsequent to the automatically adjusting.

11. An apparatus, comprising:

one or more processors; and

one or more processor readable storage mediums connected to the one or more processors and configured to store code for programming the one or more processors to add an image from at least one of a plurality of camera views to a model of an environment based on a set of camera parameters, compare the added image to an image from a different camera view using a color spaced comparison of images to determine one or more differences between the added image and the image from the different camera view, and adjust the camera parameters and the 3D model to minimize the one or more differences between the added image and the image from the different camera view based on color spaced comparisons of images.

12. The apparatus of claim **11**, further comprising:

the one or more processors and configured to store code for programming the one or more processors to add an additional detail to the 3D model based on the color space comparison of images.

13. The apparatus of claim **11**, wherein:

the one or more processors are configured to add the image to the model of the environment as a texture for the model, the one or more processors are configured to adjust one or more textures for the model based on color spaced comparisons of images.

14. The apparatus of claim **11**, wherein:

the model is a 3D model in 3D world coordinates;

the one or more processors are configured to add the image to the model of the environment as a texture for the model by transforming the 3D model from 3D world coordinates to 2D camera space for a first camera using current camera parameters for the first camera, adding the one image to the transformed model and transforming the model with the one image from 2D camera space for the first camera to 3D world coordinates.

15. The apparatus of claim **11**, wherein:

color spaced comparison of images comprises the one or more processors performing a pixel by pixel comparison of color values of the added image and the one or more images from other camera views.

16. The apparatus of claim **11**, wherein:

the one or more processors are configured to automatically add a new feature to the 3D model and repeat the comparing of the added image to an image from a different camera view using the color space comparison of images and the adjusting of the camera parameters and the 3D model to minimize the one or more differences.

17. An apparatus, comprising:

one or more processors; and

one or more processor readable storage mediums connected to the one or more processors, the one or more processors are configured to access sets of camera parameters for different camera views and access images from the different camera views, the one or more processors are configured to attempt to align the images from the different camera views using the camera parameters, the one or more processors configured to perform a color based comparison of the attempted aligned images and determine differences between the attempted aligned images based on the color based comparison, the one or more processors are configured to adjust the camera parameters to minimize the differences between the attempted aligned images.

18. The apparatus of claim **17**, wherein:

the one or more processors configured to attempt to align the images from the different camera views by transforming one or more of the images using the camera parameters and a model of an environment.

19. The apparatus of claim **18**, wherein:

the one or more processors configured to adjust the model to minimize the differences between the attempted aligned images.

20. A method, comprising:

projecting an image from at least one of a plurality of camera views to a 3D model of a word space environment;

performing a color based comparison of the projected image to one or more images from other camera views; and

adding an additional detail to the 3D model based on the color based comparison.

21. The method of claim **20**, wherein:
the projecting the image includes adding the image as a texture for the 3D model.
22. The method of claim **21**, wherein:
the color based comparison includes performing a pixel by pixel comparison of color values of the projected image as the texture for the 3D model to the one or more images from other camera views.
23. An apparatus, comprising:
one or more processors; and
one or more processor readable storage mediums connected to the one or more processors, the one or more processors are configured to add an image from at least one of a plurality of camera views to a model of a word space environment, the one or more processors are configured to perform an images based comparison of the added image to one or more images from other camera views, the one or more processors are configured to add an additional detail to the model based on the imaged based comparison.
24. The apparatus of claim **23**, wherein:
the adding the image includes adding the image as a texture for the model; and
the model is a 3D representation of a world space location.
25. The apparatus of claim **23**, wherein:
the image based comparison includes performing a pixel by pixel comparison of color values of the added image to the one or more images from other camera views.

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