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(54) **CALIBRATION BETWEEN DEPTH AND COLOR SENSORS FOR DEPTH CAMERAS**

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G06T 7/00	(2006.01)
H04N 13/00	(2006.01)

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

CPC ***H04N 13/0246*** (2013.01); ***G06T 7/002*** (2013.01); ***H04N 13/025*** (2013.01); ***H04N 13/0207*** (2013.01); ***H04N 13/0271*** (2013.01); *H04N 13/02* (2013.01); *H04N 13/0257* (2013.01)

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USPC 382/154; 702/97; 438/199; 345/161; 600/407
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(56) **References Cited**

U.S. PATENT DOCUMENTS

6,373,518	B1 *	4/2002	Sogawa	G06K 9/03 348/218.1
6,633,664	B1	10/2003	Minamida et al.	
6,768,509	B1	7/2004	Bradski et al.	
6,816,187	B1	11/2004	Iwai et al.	
6,858,826	B2	2/2005	Mueller et al.	
7,912,252	B2	3/2011	Ren et al.	
8,090,194	B2 *	1/2012	Golrdon et al.	382/154
2005/0231476	A1 *	10/2005	Armstrong	345/161
2006/0128087	A1 *	6/2006	Bamji et al.	438/199
2007/0115484	A1	5/2007	Huang et al.	
2009/0201384	A1	8/2009	Kang et al.	
2009/0213240	A1	8/2009	Sim et al.	
2009/0231425	A1	9/2009	Zalweski	
2010/0207938	A1	8/2010	Yau et al.	
2010/0225743	A1	9/2010	Florencio et al.	
2010/0235129	A1 *	9/2010	Sharma et al.	702/97
2010/0303341	A1 *	12/2010	Hausler	382/154
2011/0018973	A1 *	1/2011	Takayama	348/47
2011/0054295	A1 *	3/2011	Masumoto et al.	600/407
2011/0069892	A1	3/2011	Tsai et al.	
2011/0150101	A1 *	6/2011	Liu	H04N 13/00 375/240.26
2012/0026296	A1 *	2/2012	Lee	H04N 13/0246 348/47

OTHER PUBLICATIONS

J. Smisek, J. Jancosek, & T. Pajdla, "3D with Kinect", 2011 IEEE Int'l conf. on Computer Vision Workshops 1154-1160 (Nov. 2011).*

(Continued)

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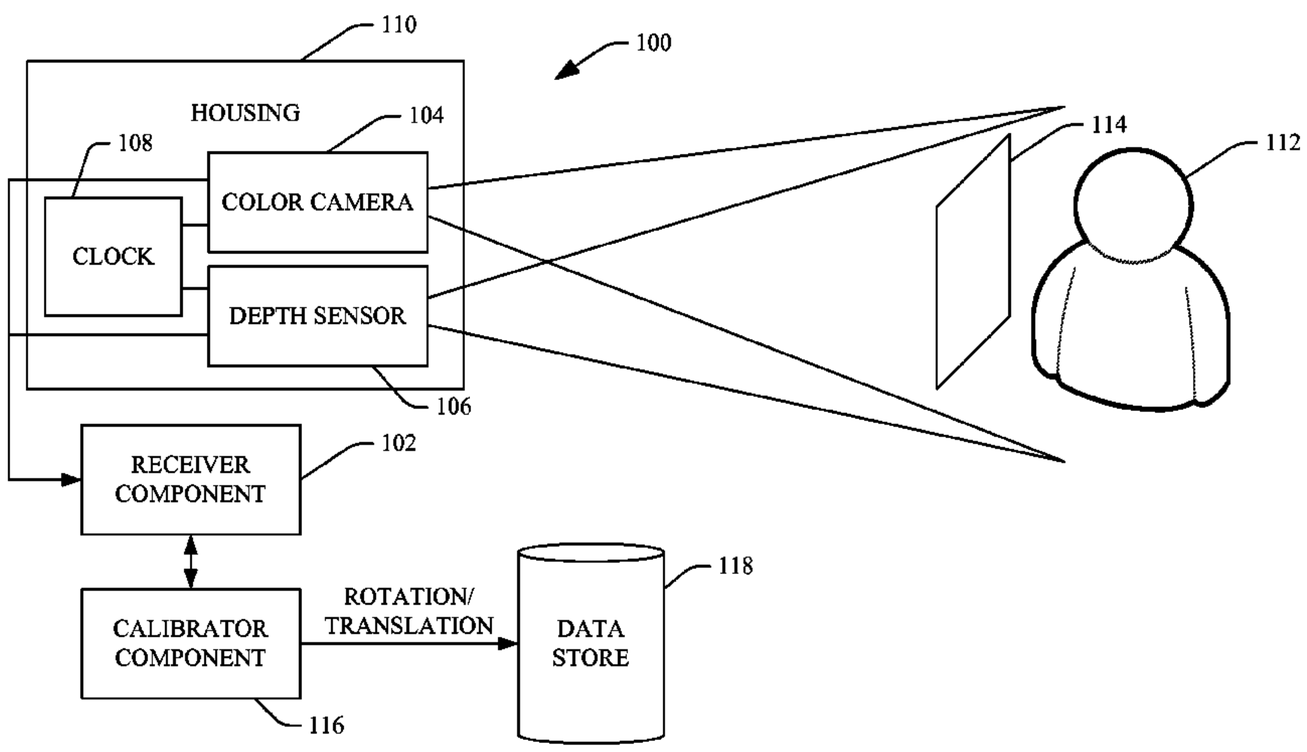
(57) **ABSTRACT**

A system described herein includes a receiver component that receives a first digital image from a color camera, wherein the first digital image comprises a planar object, and a second digital image from a depth sensor, wherein the second digital image comprises the planar object. The system also includes a calibrator component that jointly calibrates the color camera and the depth sensor based at least in part upon the first digital image and the second digital image.

20 Claims, 5 Drawing Sheets



(56) **References Cited**

OTHER PUBLICATIONS

C. Daniel Herrera, J. Kannala, & J. Heikkila, "Accurate and Practical Calibration of a Calibration of a Depth and Color Camera Pair", 6855 Lecture Notes in Computer Sci. 437-445 (Aug. 2011).*

C. Daniel Herrera, J. Kannala, & J. Heikkila, "Joint Depth and Color Camera Calibration with Distortion Correction", 34 IEEE Transactions on Patern Analysis & Machine Intelligence 2058-2064 (May 2012).*

C. Raposo, J.P. Barreto, & U. Nunes, Fast and Accurate Calibration of a Kinect Sensor, 2013 Int'l Conf. on 3D Vision 342-349 (2013).*

Frick, et al., "Generation of 3D-TV LDV-Content with Time of Flight Camera", Retrieved at <<http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.155.5198&rep=rep1&type=pdf>>, 3DTV Conference: The True Vision—Capture, Transmission and Display of 3D Video, May 4-6, 2009, pp. 1-4.

Guan, et al., "3D Object Reconstruction with Heterogeneous Sensor Data", Retrieved at <<http://www.cc.gatech.edu/conferences/3DPVT08/Program/Papers/paper108.pdf>>, The Fourth International Symposium on 3D Data Processing, Visualization and Transmission, 2008, pp. 1-8.

Cui, et al., "3D Shape Scanning with a Time-of-Flight Camera", Retrieved at <<http://ai.stanford.edu/~schuon/sr/cvpr10_scanning.pdf>>, IEEE Conference on Computer Vision and Pattern Recognition, Jun. 13-18, 2010, pp. 1-8.

Crabb, et al., "Real-Time Foreground Segmentation via Range and Color Imaging", Retrieved at <<http://mplab.ucsd.edu/wp-content/uploads/CVPR2008/WorkShops/data/papers/221.pdf>>, IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops, Jun. 23-28, 2008, pp. 1-5.

Cai, et al., "3D Deformable Face Tracking with a Commodity Depth Camera", Retrieved at <<http://research.microsoft.com/en-us/um/people/zhang/papers/eccv2010-facetrackingwithdepthcamera.pdf>>, Proceedings of the 11th European conference on computer vision: Part III, 2010, pp. 229-242.

Tsai, Roger Y., "A Versatile Camera Calibration Technique for High-Accuracy 3D Machine Vision Metrology using Off-the-Shelf TV Cameras and Lenses", Retrieved at <<http://www.vision.caltech.edu/bouguetj/calib_doc/papers/Tsai.pdf>>, IEEE Journal of Robotics and Automation, vol. 3, No. 4, Aug. 1987, pp. 323-344.

Zhang, et al., "A Flexible New Technique for Camera Calibration", Retrieved at <<http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=888718>>, IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 22, No. 11, Nov. 2000, pp. 1330-1334.

Arun, et al., "Least-Squares Fitting of Two 3-D Point Sets", Retrieved at <<http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4767965>>, IEEE Transactions on Pattern Analysis and Machine Intelligenc, vol. PAMI-9, No. 5, Sep. 1987, pp. 698-700.

Fischler, et al., "Random Sample Consensus : A Paradigm for Model Fitting with Apphcatlons to Image Analysis and Automated Cartography", Retrieved at <<http://www.ai.sri.com/pubs/files/836.pdf>>, Communications of the ACM, vol. 24, No. 6, 1981, pp. 381-395.

Yuan, Joseph S. C., "A General Photogrammetric Method for Determining Object Position and Orientation", Retrieved at <<http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=88034>>, IEEE Transactions on Robotics and Automation, vol. 5, No. 2, Apr. 1989, pp. 129-142.

Dementhon, et al., "Model-Based Object Pose in 25 Lines of Code", Retrieved at <<http://www.cfar.umd.edu/~daniel/daniel_papersfordownload/Pose25Lines.ps.gz>>, Computer Vision—ECCV'95, 1995, pp. 1-30.

"International Search Report", Mailed Date: Dec. 21, 2012, Application No. PCT/US2012/045879, Filed Date: Dec. 21, 2012, pp. 1-9.

* cited by examiner

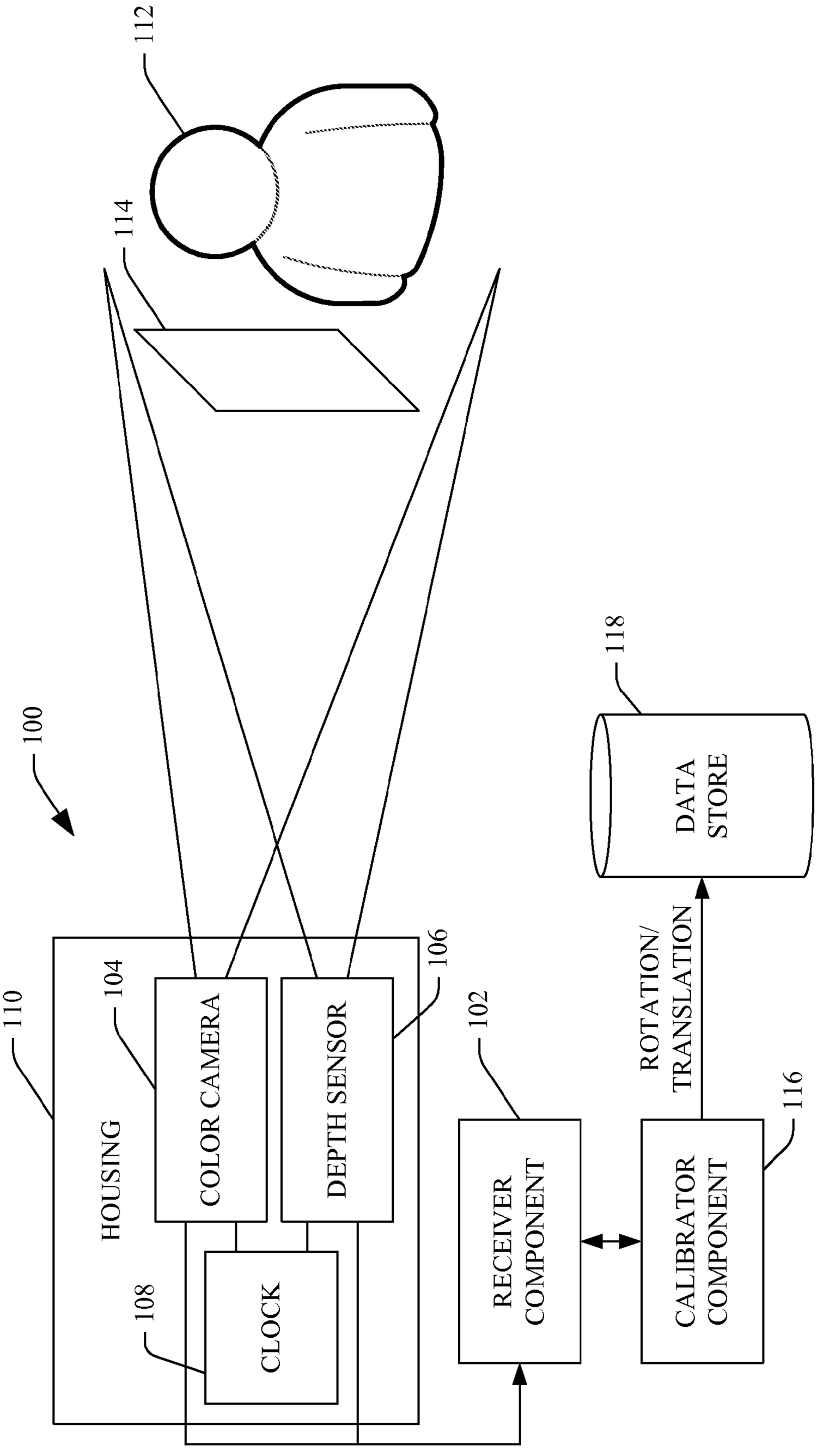
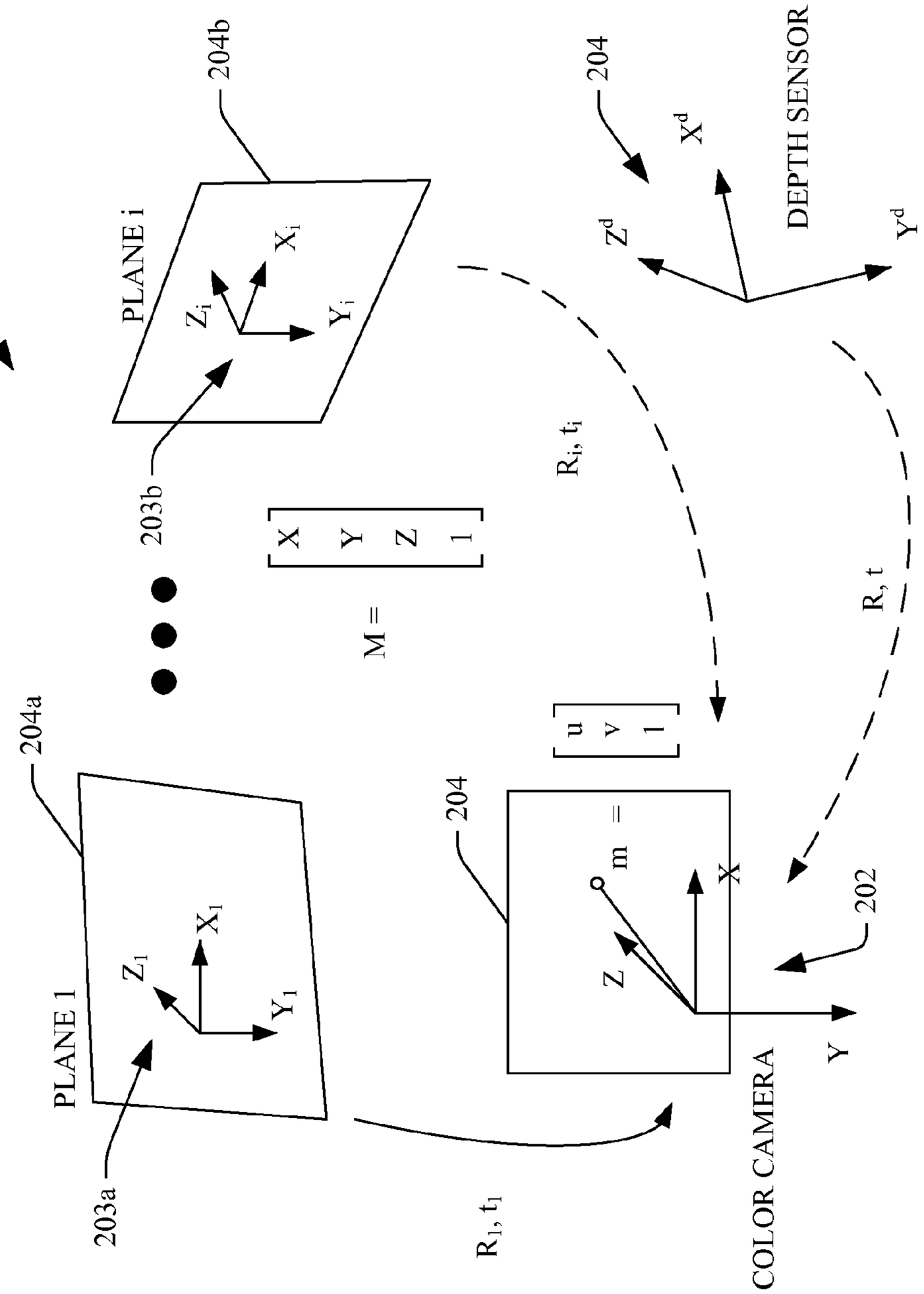

112
114
100
110
HOUSING
104
COLOR CAMERA
106
DEPTH SENSOR
108
CLOCK
102
RECEIVER COMPONENT
118
DATA STORE
ROTATION/ TRANSLATION
116
CALIBRATOR COMPONENT

FIG. 1

FIG. 2


200
PLANE i
203b
Z_i
X_i
Y_i
M =
X Y Z 1
R_i, t_i
204b
204
DEPTH SENSOR
Z^d
X^d
Y^d
R, t
u v 1
m =
X Y Z
202
204a
PLANE 1
203a
Z_1
X_1
Y_1
R_1, t_1
COLOR CAMERA

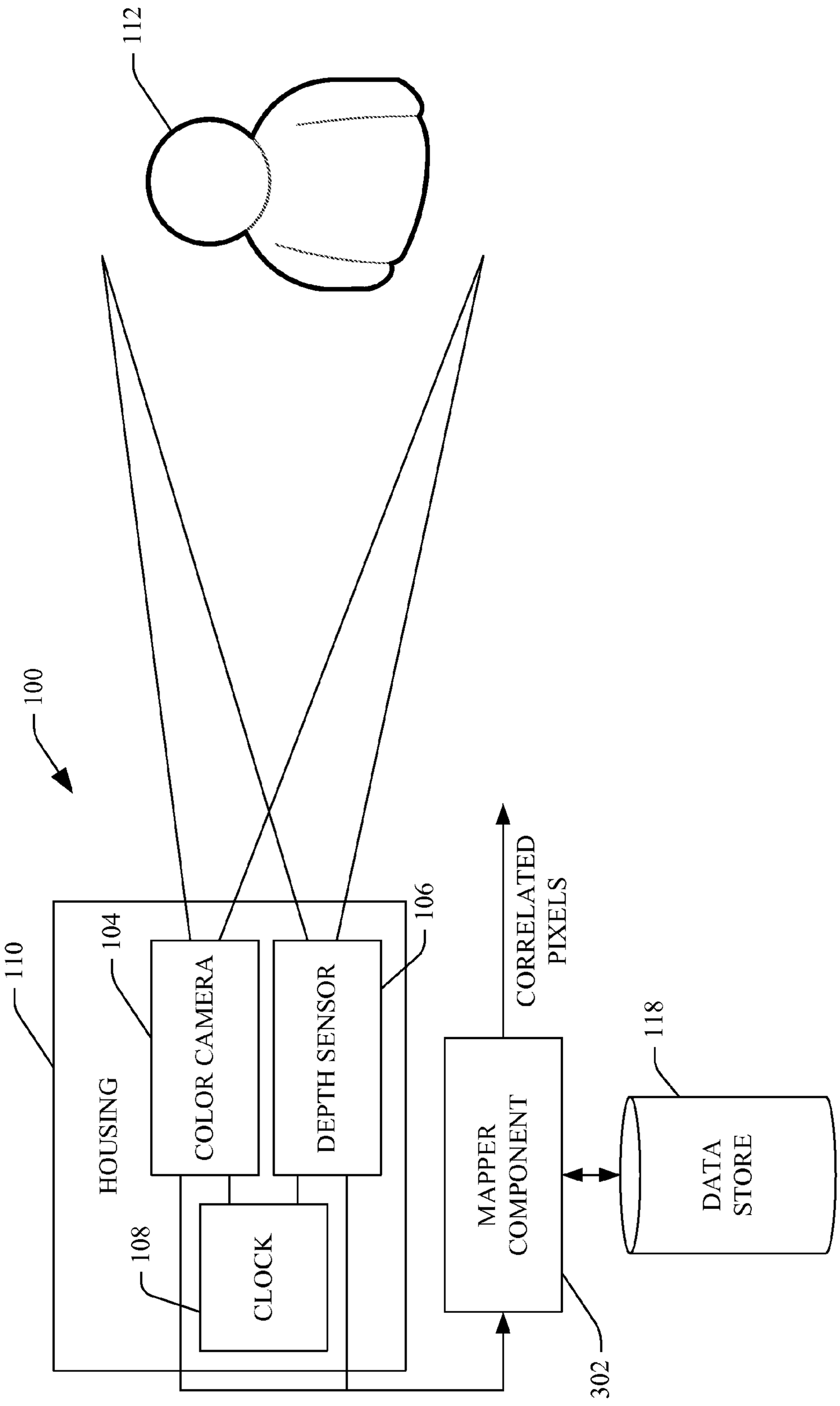

112
100
110
HOUSING
104
COLOR CAMERA
106
DEPTH SENSOR
108
CLOCK
MAPPER COMPONENT
302
CORRELATED PIXELS
118
DATA STORE

FIG. 3

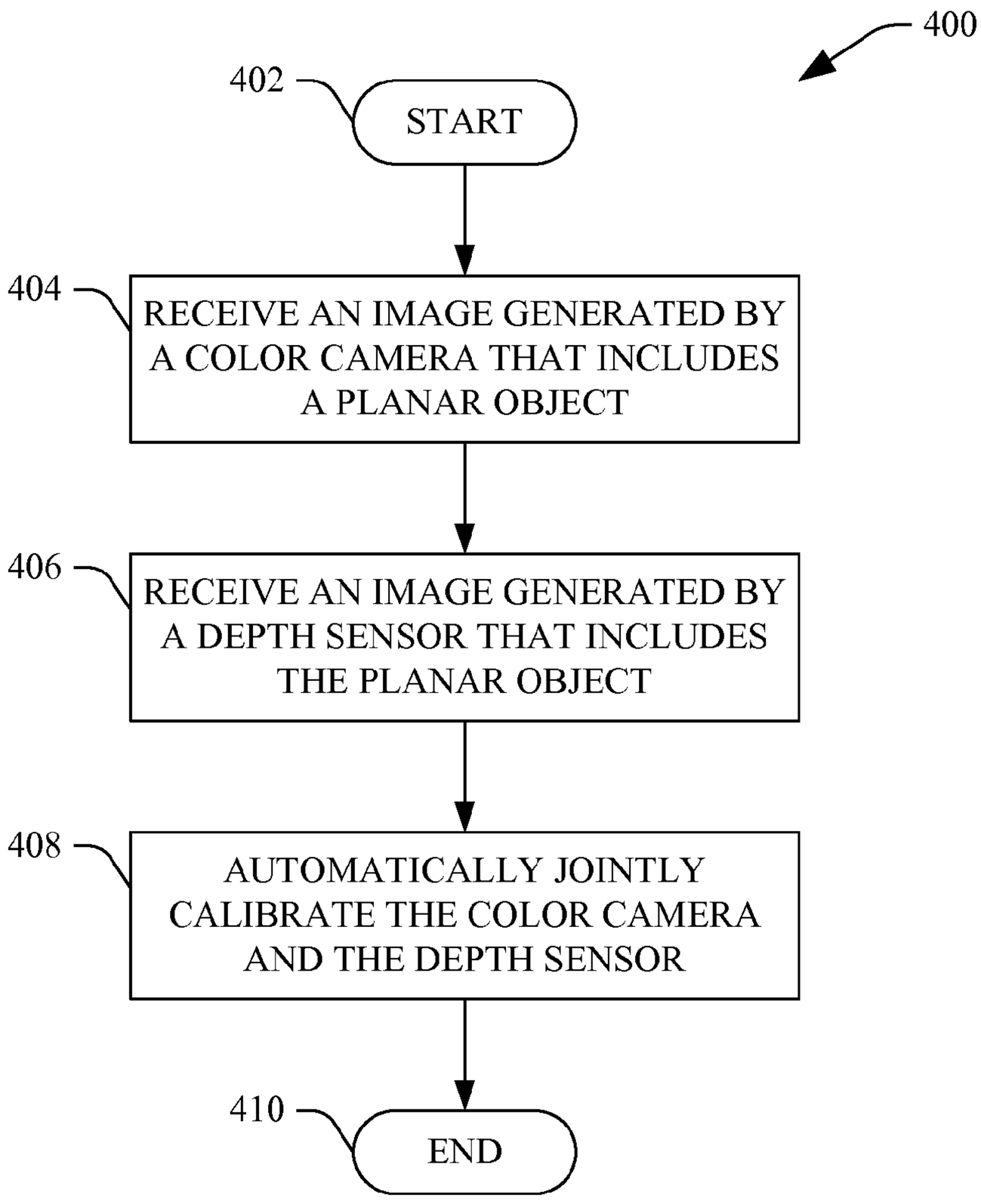

400
402
START
404
RECEIVE AN IMAGE GENERATED BY A COLOR CAMERA THAT INCLUDES A PLANAR OBJECT
406
RECEIVE AN IMAGE GENERATED BY A DEPTH SENSOR THAT INCLUDES THE PLANAR OBJECT
408
AUTOMATICALLY JOINTLY CALIBRATE THE COLOR CAMERA AND THE DEPTH SENSOR
410
END

FIG. 4

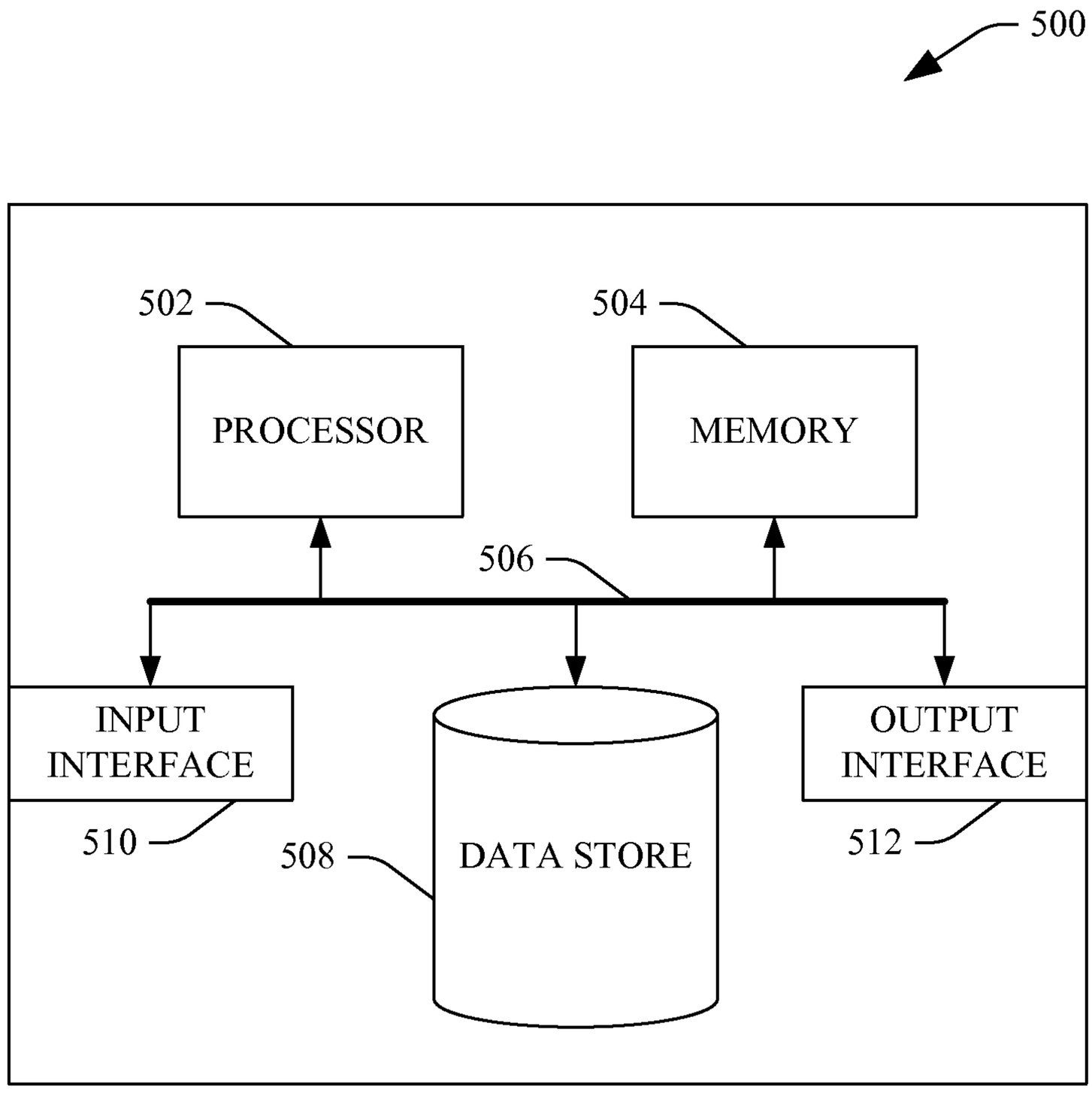

500
502
PROCESSOR
504
MEMORY
506
INPUT INTERFACE
510
508
DATA STORE
OUTPUT INTERFACE
512

FIG. 5

CALIBRATION BETWEEN DEPTH AND COLOR SENSORS FOR DEPTH CAMERAS

BACKGROUND

Recently there have been an increasing number of depth sensors that are available at relatively low prices. In an example, a sensor unit that communicates with a video game console includes a depth sensor. In another example, computing devices (desktops, laptops, tablet computing devices) are being manufactured with depth sensors therein. A sensor unit that includes both a color camera as well as a depth sensor can be referred to herein as a depth camera. Depth cameras have created a significant amount of interest in applications such as three-dimensional shape scanning, foreground-background segmentation, facial expression tracking, amongst others.

Depth cameras generate simultaneous streams of color images and depth images. To facilitate the applications discussed above (and other applications that employ color images and depth images), the depth sensor and color camera may be desirably calibrated. More specifically, both the color camera and the depth sensor have their own respective coordinate systems, and how such coordinate systems are aligned with respect to one another may be desirably determined to allow pixels in a color image generated by the color camera to be effectively mapped to pixels in a depth image generated by the depth sensor and vice versa.

Many difficulties exist with respect to calibrating a color camera and depth sensor. For example, color cameras have been calibrated utilizing colored patterns. Colored patterns, however, cannot be analyzed in a depth image, as such image does not include captured colors (e.g., corners of a pattern are often indistinguishable from other surface points in a depth image). Furthermore, although depth discontinuity can be observed in a depth image, boundary points of an object are generally unreliable due to unknown depth reconstruction mechanisms utilized in the depth sensor.

An exemplary approach to calibrate a color camera and depth sensor is to co-center an infrared image with a depth image. This may require, however, external infrared illumination. Additionally, commodity depth cameras typically produce relatively noisy depth images, rendering it difficult to calibrate the depth sensor with the color camera.

SUMMARY

The following is a brief summary of subject matter that is described in greater detail herein. This summary is not intended to be limiting as to the scope of the claims.

Described herein are various technologies pertaining to jointly calibrating a color camera and a depth sensor based at least in part upon images of a scene captured by the color camera and the depth sensor, wherein the scene includes a planar object. For instance, the planar object may be a checkerboard. Further, the depth sensor may be any suitable type of depth sensing system, including a triangulation system (such as stereo vision or structured light system), a depth from focus system, a depth from shape system, a depth from motion system, a time of flight system, or other suitable type of depth sensor system.

As will be described in greater detail herein, jointly calibrating the color camera and the depth sensor includes ascertaining a rotation and a translation between coordinate systems of the color camera and the depth sensor, respectively. In connection with computing these values, instructions can be output to a user that instructs the user to move a planar object, such as a checkerboard, to different positions in front of the color camera and the depth sensor. The color camera and the depth sensor may be synchronized, such that an image pair (an image from the color camera and an image from the depth sensor) include the planar object at a particular position and orientation. Rotation and translation between the coordinate systems of the color camera and the depth sensor can be ascertained based at least in part upon a plurality of such image pairs that include the planar object at various positions and orientations.

Two exemplary techniques for ascertaining the rotation and translation between the coordinate systems of the color camera and the depth sensor are described herein. In a first exemplary technique, an image generated by the color camera can be analyzed to locate the known pattern of the planar object that has been captured in such image. Because the pattern in the planar object is known, such planar object can be automatically located in the color image, and the three-dimensional orientation and position of the planar object in the color image can be computed relative to the color camera. A corresponding plane may be then fit into a corresponding image generated by the depth sensor. The plane can be fit based at least in part upon depth values in the image generated by the depth sensor. The plane fit in the image generated by the depth sensor corresponds to the observed plane in the color image after application of a rotation and translation to the plane in the depth image. Through such approach the rotation and translation between the coordinate systems of the color camera and the depth sensor can be computed.

In another exemplary approach, rather than fitting a plane into the depth image, a set of points in the depth image can be randomly sampled. A relatively large number of points in the depth image can be sampled, and at least some of such points will correspond to points of the planar object in the color image by way of a desirably computed rotation and translation between coordinate systems of the color camera and the depth sensor. If a sufficient number of points are sampled, a likelihood function can be learned and evaluated to compute the rotation and translation mentioned above.

Other aspects will be appreciated upon reading and understanding the attached Figs. and description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a functional block diagram of an exemplary system that facilitates jointly calibrating a color camera and a depth sensor.

FIG. **2** illustrates coordinate systems of the color camera and the depth sensor.

FIG. **3** is a functional block diagram of an exemplary system that facilitates overlaying a color image onto a depth image based at least in part upon a computed rotation and translation between a color camera and a depth sensor.

FIG. **4** is a flow diagram that illustrates an exemplary methodology for automatically jointly calibrating a color camera and a depth sensor.

FIG. **5** is an exemplary computing system.

DETAILED DESCRIPTION

Various technologies pertaining to jointly calibrating a color camera and a depth sensor will now be described with reference to the drawings, where like reference numerals represent like elements throughout. In addition, several functional block diagrams of exemplary systems are illustrated and described herein for purposes of explanation; however, it is to be understood that functionality that is described as being carried out by certain system components may be performed

by multiple components. Similarly, for instance, a component may be configured to perform functionality that is described as being carried out by multiple components. Additionally, as used herein, the term "exemplary" is intended to mean serving as an illustration or example of something, and is not intended to indicate a preference.

As used herein, the terms "component" and "system" are intended to encompass computer-readable data storage that is configured with computer-executable instructions that cause certain functionality to be performed when executed by a processor. The computer-executable instructions may include a routine, a function, or the like. It is also to be understood that a component or system may be localized on a single device or distributed across several devices.

With reference now to FIG. **1**, an exemplary system **100** that facilitates jointly calibrating a color camera and depth sensor is illustrated. A combination of a color camera and a depth sensor will be referred to herein as a depth camera. As will be described in greater detail below, jointly calibrating a color camera and a depth sensor may comprise learning a rotation and translation between coordinate systems of the color camera and depth sensor, respectively. The system **100** comprises a receiver component **102** that receives a first digital image from a color camera **104** and a second digital image from a depth sensor **106**. In an exemplary embodiment, the first digital image output by the color camera **104** may have a resolution that is the same as the resolution of the second digital image output by the depth sensor **106**. Furthermore, the depth sensor **106** may be or include any suitable type of depth sensor system including, but not limited to, a stereo vision or structured light system, a depth from focus system, a depth from shape system, a depth from motion system, a time of flight system, or the like. A clock **108** can be in communication with the color camera **104** and the depth sensor **106**, and can assign timestamps to images generated by the color camera **104** and the depth sensor **106**, such that images from the color camera **104** and depth sensor **106** that correspond to one another in time can be determined.

In an exemplary embodiment, a housing **110** may comprise the color camera **104**, the depth sensor **106**, and the clock **108**. The housing **110** may be a portion of a sensor that is utilized in connection with a video game console to detect position and motion of a game player. In another exemplary embodiment, the housing **110** may be a portion of a computing system that includes the color camera **104** and the depth sensor **106** for purposes of video-based communications. In still yet another exemplary embodiment, the housing **110** may be for a video camera that is configured to generate three-dimensional video. These embodiments are presented for purposes of explanation and are not intended to limit the scope of the claims. For example, the combination of the color camera **104** and the depth sensor **106** can be utilized in connection with a variety of different types of applications, including three-dimensional shape scanning, foreground-background segmentation, facial expression tracking, three-dimensional image or video generation, amongst others.

Pursuant to an example, the color camera **104** and the depth sensor **106** may be directed at a user **112** that is holding or supporting a planar object **114**. In an example, the planar object **114** may be a patterned object such as a game board. For instance, the planar object **114** may be a checkerboard. Moreover, the user **112** can be instructed to move the planar object **114** to a plurality of different locations, and the color camera **104** and the depth sensor **106** can capture images that include the planar object **114** at these various locations.

A calibrator component **116** is in communication with the receiver component **102** and jointly calibrates the color camera **104** and the depth sensor **106** based at least in part upon the first digital image generated by the color camera **104** and the second digital image generated by the depth sensor **106**. Pursuant to an example, jointly calibrating the color camera **104** and the depth sensor **106** may comprise computing a rotation and translation between a coordinate system of the color camera **104** and a coordinate system of the depth sensor **106**. In other words, the calibrator component **116** can output values that indicate how the color camera **104** is aligned and rotated with respect to the depth sensor **106**.

A data store **118** can be accessible to the calibrator component **116**, and the calibrator component **116** can cause the rotation and translation to be retained in the data store **118**. The data store **118** may be any suitable hardware data store, including a hard drive, memory, or the like. The calibrator component **116** may utilize any suitable technique for jointly calibrating the color camera **104** and the depth sensor **106**. In an exemplary embodiment, the calibrator component **116** can have knowledge of the three-dimensional orientation and position of the planar object **114** in the first digital image generated by the color camera **104** based at least in part upon a priori knowledge of the pattern of the planar object **114**. As the depth sensor **106** is also directed to capture an image of the planar object **114**, the calibrator component **116** can leverage the knowledge of the existence of the planar object **114** in the second digital image generated by the depth sensor **106** to compute the rotation and translation between the coordinate systems of the color camera **104** and the depth sensor **106**, respectively. Specifically, the calibrator component **116** can fit a plane that corresponds to the planar object **114** in the image generated by the color camera **104** onto the second digital image generated by the depth sensor **106**. Such plane can be fit based at least in part upon three-dimensional points in the second digital image generated by the depth sensor **106**. The plane fit onto the image generated by the depth sensor **106** and the plane corresponding to the planar object **114** observed in the first digital image generated by the color camera **104** correspond to one another by the rotation and translation that is desirably computed. The calibrator component **116** can compute such rotation and translation and cause these values to be retained in the data store **118**.

In another exemplary embodiment, the calibrator component **116** can randomly sample points in the second digital image generated by the depth sensor **106** that are known to correspond to the planar object **114** in the second digital image. Each randomly sampled point in the image generated by the depth sensor **106** will correspond to a point in the color image that corresponds to the planar object **114**. Each point in the image generated by the depth sensor **106** that corresponds to the planar object **114** is related to a point in the image generated by the color camera **104** that corresponds to the planar object **114** by the desirably computed rotation and translation values. If a sufficient number of points are sampled, the calibrator component **116** can compute the values for rotation and translation. Still further, a combination of these approaches can be employed.

Moreover, while the examples provided above have referred to a single image pair (a color image and a depth image), it is to be understood that the calibrator component **116** can consider multiple image pairs with the planar object **114** placed at various different locations and orientations relative to the color camera **104** and the depth sensor **106**. For instance, a minimum number of image pairs used by the calibrator component **116** to determine a rotation matrix can be 2, while a minimum number of image pairs used by the calibrator component **116** to determine a translation can be 3. The rotation and translation between the color camera **104**

and the depth sensor **106** may then be computed based upon correspondence of the planar object **114** across various color image/depth image pairs.

Further, while the calibrator component **116** has been described above as jointly calibrating the color camera **104** and the depth sensor **106** through analysis of images generated thereby that include the planar object **114**, in other exemplary embodiments an object captured in the images need not be entirely planar. For instance, a planar board that includes a plurality of apertures in a pattern can be utilized such that the pattern can be recognized in the first digital image generated by the color camera **104** and the pattern can also be recognized in the second digital image generated by the depth sensor **106**. A correspondence between the located patterns in the first digital image and the second digital image may then be employed by the calibrator component **116** to compute the rotation and translation between respective coordinate systems of the color camera **104** and the depth sensor **106**.

In yet another exemplary embodiment, the calibrator component **116** can consider point correspondences between the first digital image generated by the color camera **104** and the second digital image generated by the depth sensor **106** in connection with jointly calibrating the color camera **104** and the depth sensor **106**. For instance, a user may manually indicate a point in the color image and a point in the depth image, wherein these two points correspond to one another across the images. Additionally or alternatively, image analysis techniques can be employed to automatically locate corresponding points across images generated by the color camera **104** and the depth sensor **106**. For instance, the calibrator component **116** can learn a likelihood function that minimizes projected distance between corresponding point pairs across images generated by the color camera **104** and images generated by the depth sensor **106**.

In yet another exemplary embodiment, the calibrator component **116** may consider distortion in the depth sensor **106** when jointly calibrating the color camera **104** with the depth sensor **106**. For example, depth values generated by the depth sensor **106** may have some distortion associated therewith. A model of such distortion is contemplated and can be utilized by the calibrator component **116** when jointly calibrating the color camera **104** and the depth sensor **106**.

With reference now to FIG. **2**, an exemplary illustration **200** of existence of the planar object **114** across a plurality of images and notations used to describe a calibration procedure is shown. For purposes of explanation, a three-dimensional coordinate system **202** of the color camera **104** may coincide with a world coordinate system. In a homogeneous representation, a three-dimensional point in the world coordinate system can be denoted by $M=[X, Y, Z, 1]^T$, and its corresponding two-dimensional projection on a model X, Y plane **204** can be denoted $m=[u, v, 1]^T$. The color camera **104** can be modeled by the following pinhole model:

$$sm=A[I\ 0]M \tag{1}$$

where I is the identity matrix, 0 is the zero vector, and s can be a scale factor. In an exemplary embodiment, s=Z. A is the intrinsic matrix of the color camera **104**, which can be given as follows:

$$A=\begin{bmatrix}\alpha & \gamma & u_0\\ 0 & \beta & v_0\\ 0 & 0 & 1\end{bmatrix} \tag{2}$$

where α and β are the scale factors in the image coordinate system, (u_0, v_0) are the coordinates of the principal point and γ is the skewness of the two image axes.

The depth sensor **106** has a second coordinate system **204** that is different from the coordinate system **202** of the color camera **104**. The depth sensor **106** generally outputs an image with depth values denoted by $x=[u, v, z]^T$, where (u, v) are the pixel coordinates, and z is the depth value. The mapping from x to the point in the three-dimensional coordinate system **204** of the depth sensor **106**, $M^d=[X^d, Y^d, Z^d, 1]^1$, is usually known, and is denoted as $M^d=f(x)$. The rotation and translation between the color camera **104** and the depth camera or depth sensor **106** is denoted by R and t:

$$M=\begin{bmatrix}R & t\\ 0^T & 1\end{bmatrix}M^d \tag{3}$$

As mentioned above, the planar object **114** can be moved in front of the color camera **104** and the depth sensor **106**. This can create n image pairs (color and depth) captured by the depth camera (the color camera **104** and the depth sensor **106**). As shown, the position of the planar object **114** in the n images will be different. The model plane **204** thus has different positions and orientations relative to the position of the color camera **104**. Three-dimensional coordinate systems **203***a*-**203***b* (X_i, Y_i, Z_i) can be set up for each position of the model plane **204***a* and **204***b* across the images such that the $Z_i=0$ plane coincides with the model plane **204**. Additionally, it can be assumed that the model plane **204** has a set of M feature points. In an example, the feature points can be corners of a known pattern in the planar object **114**, such as a checkerboard pattern. The feature points can be denoted as P_j, j=1, . . . , m. It can be noted that the three-dimensional coordinates of such feature points in each model plane's local coordinate system are identical. Each feature point's local three-dimensional coordinate is associated with a corresponding world coordinate as follows:

$$M_{i,j}=\begin{bmatrix}R_i & t_i\\ 0^T & 1\end{bmatrix}P_j, \tag{4}$$

where M_{ij} is the jth feature point of the ith image in the world coordinate system **202**, R_i and t_i are the rotation and translation from the ith model plane's local coordinate system **203***a* to the world coordinate system **202**. The feature points are observed in the color image as $m_{i,j}$, which are associated with $M_{i,j}$ through Eq. (1).

Given the set of feature points P_j and their projections $m_{i,j}$, it is desirable to recover the intrinsic matrix A, the rotations and translations between the models planes **204***a* and **204***b* and the model plane **204** R_i and t_i, and the transform between the color camera **104** and the depth sensor **106** R and t. The intrinsic matrix A and the model plane positions R_i and t_i (relative to the global coordinate system **202**) can be computed through conventional techniques. Images generated by the depth sensor **106** can be used to compute R and t automatically.

As mentioned previously, the calibration solution for only the color camera **104** is known. Due to the use of the pinhole camera model, the following can be acquired:

$$s_{ij}m_{ij}=A[R_i,t_i]P_j. \tag{5}$$

In practice, feature points on images generated by the color camera **104** are typically extracted automatically through utilization of computer-executable algorithms, and therefore may have errors associated therewith. Accordingly, if it is assumed that $M_{i,j}$ follows a Gaussian distribution with the ground truth position as its mean, e.g.,

$$m_{ij} \sim N(\overline{m}_{ij}, \Phi_{ij}), \tag{6}$$

then the log likelihood function can be written as follows:

$$L_1 = -\frac{1}{2nm}\sum_{i=1}^{n}\sum_{j=1}^{m}\epsilon_{ij}^T\Phi_{ij}^{-1}\epsilon_{ij}, \tag{7}$$

where

$$\epsilon_{ij} = m_{ij} - \frac{1}{s_{ij}}A[R_i t_i]P_j. \tag{8}$$

Terms related to images generated by the depth sensor **106** are now discussed. There are a set of points in the image generated by the depth sensor **106** that correspond to the model plane **204**. K_i points within the quadrilateral in the depth image can be randomly sampled and denoted by $M_{ik_i}^{\ d}$, $i=1, \ldots, n$; $k_i=1, \ldots, K_i$. If the image generated by the depth sensor **106** (the depth image) is free of noise, the following is obtained:

$$[0\ 0\ 1\ 0]\begin{bmatrix} R_i & t_i \\ 0^T & 1 \end{bmatrix}^{-1}\begin{bmatrix} R & t \\ 0^T & 1 \end{bmatrix}M_{ik_i}^d = 0, \tag{9}$$

which indicates that if these points are transformed to the local coordinate system of each model plane **204***a*-**204***b*, the coordinate shall be zero.

Since images generated by the depth sensor **106** tend to be noisy, $M_{ik_i}^{\ d}$ can follow a Gaussian distribution as:

$$m_{ik_i}^{\ d} \sim N(\overline{M}_{ik_i}^{\ d}, \Phi_{ik_i}^{\ d}). \tag{10}$$

The log likelihood function can thus be written as follows:

$$L_2 = -\frac{1}{2\sum_{i=1}^{n}K_i}\sum_{i=1}^{n}\sum_{k_i=1}^{K_i}\frac{\varepsilon_{ik_i}^2}{\sigma_{ik_i}^2}, \tag{11}$$

where

$$\varepsilon_{ik_i} = a_i^T M_{ik_i}^d, \tag{12}$$

where

$$a_i = \begin{bmatrix} R^T & 0 \\ t^T & 1 \end{bmatrix}\begin{bmatrix} R_i & 0 \\ -t_i^T R_i & 1 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \tag{13}$$

and

$$\sigma_{ik_i}^2 = a_i^T\Phi_{ik_i}^d a_i. \tag{14}$$

As mentioned above, it may be helpful to have a plurality of corresponding point pairs in images generated by the color camera **104** and images generated by the depth sensor **106**. Such point pairs can be denoted as $(m_{ip_i}, M_{ip_i}^{\ d})$, $i=1, \ldots, n$; $p_i=1, \ldots, P_i$. Such point pairs shall satisfy the following:

$$s_{ip_i}m_{ip_i} = A[R\ t]M_{ip_i}^{\ d}. \tag{15}$$

Further, whether the point correspondences are manually labeled or automatically established, such point correspondences may not be accurate. According, the following can be assumed:

$$m_{ip_i} \sim N(\overline{m}_{ip_i}, \Phi_{ip_i});\ M_{ip_i}^{\ d} \sim N(\overline{M}_{ip_i}^{\ d}, \Phi_{ip_i}^{\ d}), \tag{16}$$

where Φ_{ip_i} models the inaccuracy of the point in the image generated by the color camera **104**, and $\Phi_{ip_i}^{\ d}$ models the uncertainty of the three-dimensional point in the image generated by the depth sensor **106**. The log likelihood function can then be written as follows:

$$L_3 = -\frac{1}{2\sum_{i=1}^{n}P_i}\sum_{i=1}^{n}\sum_{p_i=1}^{p_i}\xi_{ip_i}^T\tilde{\Phi}_{ip_i}^{-1}\xi_{ip_i}, \tag{17}$$

where

$$\xi_{ip_i} = m_{ip_i} - B_{ip_i}M_{ip_i}^d, \tag{18}$$

where

$$B_{ip_i} = \frac{1}{s_{ip_i}}A[R\ t], \tag{19}$$

and

$$\tilde{\Phi}_{ip_i} = \Phi_{ip_i} + B_{ip_i}\Phi_{ip_i}^d B_{ip_i}^T. \tag{20}$$

Combining the above information together, the overall log likelihood can be maximized as follows:

$$\max_{A,R_i,t_i R,t}\rho_1 L_1 + \rho_2 L_2 + \rho_3 L_3, \tag{21}$$

where ρ_i, $i=1,2,3$ are weighting parameters. This objective function can be classified as a nonlinear least squares problem, which can be solved by the calibrator component **116** using the Levenberg-Marquardt method. The result is the computation of the parameters A, R_i, t_iR, t.

The above algorithms describe calibration of the color camera **104** and the depth sensor **106** with an assumption of no distortions or noise in either of the color camera **104** or the depth sensor **106**. A few other parameters, however, may be desirably estimated during calibration by the calibrator component **116**. These parameters can include focus, camera center, and depth mapping function for both the color camera **104** and the depth sensor **106**. For instance, the color camera **104** may exhibit lens distortions and thus it may be desirable to estimate such distortions based upon the observed model planes **204***a*-**204***b* in images generated by the color camera **104**. Another set of unknown parameters may be in a depth mapping function. For example, an exemplary structured light-based depth camera may have a depth mapping function as follows:

$$f(x) = \begin{bmatrix} (\mu z + v)(A^d)^{-1}[u, v, 1]^T \\ 1 \end{bmatrix}, \tag{22}$$

where μ and υ are the scale and bias of the z value, and A^d is the intrinsic matrix of the depth sensor **106**, which is typically predetermined. The other two parameters μ and υ can be used to model the calibration of the depth sensor **106** due to temperature variation or mechanical vibration, and can be estimated within the same maximum likelihood framework by the calibrator component **116**.

The exemplary solution described above pertains to randomly sampling points in the image generated by the depth

sensor **106**. As discussed, however, the calibrator component **116** can use other approaches as alternatives to the techniques described above or in combination with such techniques. For instance, fitting the model plane **204***a*-**204***b* onto the corresponding image generated by the depth sensor **106** can be undertaken by the calibrator component **116** in connection with calibrating the color camera **104** with the depth sensor **106**. In an exemplary embodiment, this plane fitting can be undertaken during initialization to have a first estimate of unknown parameters. For instance, for the parameters related to the color camera **104**, e.g., A, R_i, t_i, a known initialization scheme can be adapted. Below, methods that can be utilized by the calibrator component **116** to provide an initial estimation of R and t between the color camera **104** and the depth sensor **106** are discussed. During the discussion below, it is assumed that A, R_i and t_i of the color camera **104** are known.

For most commodity depth cameras, the color camera **104** and the depth sensor **106** are positioned relatively proximate to one another. Accordingly, it is relatively simple to automatically identify a set of points in each image generated by the depth sensor **106** that lies on the corresponding model plane **204***a*-**204***b*. These points can be referred to as $M_{ik_i}^{\ d}$, $i=1, \ldots, n$; $k_i=1, \ldots, K_i$. For a given image i generated by the depth sensor **106**, if $K_i \geq 3$, it is possible to fit a plane to the points in that image. In other words, given the following:

$$H_i \begin{bmatrix} n_i^d \\ b_i^d \end{bmatrix} = \begin{bmatrix} (M_{i1}^d)^T \\ (M_{i2}^d)^T \\ \vdots \\ (M_{ik_i}^d)^T \end{bmatrix} \begin{bmatrix} n_i^d \\ b_i^d \end{bmatrix} = 0, \tag{23}$$

where $n_i^{\ d}$ is the normal of the model plane in the three-dimensional coordinate system of the depth sensor **106**, $\|n_i^{\ d}\|^2=1$, and $b_i^{\ d}$ is the bias from the origin. $\|n_i^{\ d}\|$ and $b_i^{\ d}$ can be found by the calibrator component **116** through least squares fitting.

In the coordinate system of the color camera **104** (the global coordinate system **202**), the model plane can also be described by the following plane equation:

$$[0\ 0\ 1\ 0] \begin{bmatrix} R_i & t_i \\ 0^T & 1 \end{bmatrix}^{-1} M = 0. \tag{24}$$

Since R_i and t_i are known, the plane's normal can be represented as n_i, $\|n_i\|^2=1$, and bias from the origin b_i.

The rotation matrix R may first be solved. For instance, R can be denoted as follows:

$$R = \begin{bmatrix} r_1^T \\ r_2^T \\ r_3^T \end{bmatrix}. \tag{25}$$

The following objective function may then be minimized with constraint:

$$J(R)=\Sigma_{i=1}^{\ n}\|n_i-Rn_i^{\ d}\|+\Sigma_{j=1}^{\ 3}\lambda_j(r_j^{\ T}r_j-1)+2\lambda_4 r_1^{\ T}r_2+ 2\lambda_5 r_1^{\ T}r_3+2\lambda 6r2Tr3. \tag{26}$$

Such objective function can be solved in closed form as follows:

$$C=\Sigma_{i=1}^{\ n}n_i^{\ d}n_i^{\ T} \tag{27}$$

The singular value decomposition of C can be written as:

$$C=UDV^T, \tag{28}$$

where U and V are orthogonal matrices and D is a diagonal matrix. The rotation matrix is as follows:

$$R=VU^T. \tag{29}$$

The minimum number of images to determine the rotation matrix R is n=2, provided that the two model planes are not parallel to one another.

For translation, the following relationship can exist:

$$(n_i^{\ d})^T t+b_i^{\ d}=b_i. \tag{30}$$

Accordingly, three non-parallel model planes can determine a unique t. If n>3, t may be solved through least squares fitting.

Another exemplary method that can be used by the calibrator component **116** to estimate the initial rotation R and translation t is through knowledge of a set of point correspondences between images generated by the color camera **104** and images generated by the depth sensor **106**. Such point pairs can be denoted as $(m_{ip_i}, M_{ip_i}^{\ d})$, $i=1, \ldots, n$; $p_i=1, \ldots, P_i$. The following relationship exists:

$$s_{ip_i}m_{ip_i}=A[R\ t]M_{ip_i}^{\ d}. \tag{31}$$

It can be noted that the intrinsic matrix A is known. In conventional methods, it has been shown that given three point pairs, there are in general four solutions to the rotation and translation. When one has four or more non-co-planar point pairs, the so-called POSIT algorithm can be used to find initial values of R and t.

With reference now to FIG. **3**, an exemplary system **300** that facilitates applying the computed rotation and translation (computed by the calibrator component **116**) to subsequently captured images from the color camera **104** and the depth sensor **106** is illustrated. The system **300** comprises the data store **118**, which includes the computed rotation and translation matrices R and t. The system **300** further comprises a mapper component **302** that receives an image pair from the color camera **104** and the depth sensor **106**. The mapper component **302** can apply the R and t to the images received from the color camera **104** and/or the depth sensor **106**, thereby, for instance, overlaying the color image on the depth image to generate a three-dimensional image. Pursuant to an example, this can be undertaken to generate a three-dimensional video stream.

With reference now to FIG. **4**, an exemplary methodology **400** is illustrated and described. While the methodology is described as being a series of acts that are performed in a sequence, it is to be understood that the methodology is not limited by the order of the sequence. For instance, some acts may occur in a different order than what is described herein. In addition, an act may occur concurrently with another act. Furthermore, in some instances, not all acts may be required to implement the methodology described herein.

Moreover, the acts described herein may be computer-executable instructions that can be implemented by one or more processors and/or stored on a computer-readable medium or media. The computer-executable instructions may include a routine, a sub-routine, programs, a thread of execution, and/or the like. Still further, results of acts of the methodologies may be stored in a computer-readable medium, displayed on a display device, and/or the like. The computer-readable medium may be any suitable computer-readable storage device, such as memory, hard drive, CD, DVD, flash drive, or the like. As used herein, the term "computer-readable medium" is not intended to encompass a propagated signal.

The exemplary methodology **400** facilitates jointly calibrating a color camera and depth sensor is illustrated. The methodology **400** starts at **402**, and at **404** an image generated by a color camera that includes a planar object is received. Prior to receiving the image, an instruction can be output to a user with respect to placement of the planar object relative to the color camera and depth sensor. At **406**, a depth image generated by a depth sensor is received, wherein the depth image additionally comprises the planar object. The image generated by the color camera and the image generated by the depth sensor may coincide with one another in time.

At **408**, the color camera and the depth sensor are automatically jointly calibrated based at least in part upon the image that comprises the planar object generated by the color camera and the depth image that comprises the planar object generated by the depth sensor. Exemplary techniques for automatically jointly calibrating the color camera in the depth sensor have been described above. Further, while the above has indicated that a single image pair is used, it is to be understood that several image pairs (color images and depth images) can be utilized to jointly calibrate the color camera and depth sensor. The methodology **400** completes at **410**.

Now referring to FIG. **5**, a high-level illustration of an exemplary computing device **500** that can be used in accordance with the systems and methodologies disclosed herein is illustrated. For instance, the computing device **500** may be used in a system that supports jointly calibrating a color camera and a depth sensor in a depth camera. In another example, at least a portion of the computing device **500** may be used in a system that supports modeling noise/distortion of a color camera and/or depth sensor. The computing device **500** includes at least one processor **502** that executes instructions that are stored in a memory **504**. The memory **504** may be or include RAM, ROM, EEPROM, Flash memory, or other suitable memory. The instructions may be, for instance, instructions for implementing functionality described as being carried out by one or more components discussed above or instructions for implementing one or more of the methods described above. The processor **502** may access the memory **504** by way of a system bus **506**. In addition to storing executable instructions, the memory **504** may also store images (depth and/or color), computed rotation and translation values, etc.

The computing device **500** additionally includes a data store **508** that is accessible by the processor **502** by way of the system bus **506**. The data store may be or include any suitable computer-readable storage, including a hard disk, memory, etc. The data store **508** may include executable instructions, images, etc. The computing device **500** also includes an input interface **510** that allows external devices to communicate with the computing device **500**. For instance, the input interface **510** may be used to receive instructions from an external computer device, from a user, etc. The computing device **500** also includes an output interface **512** that interfaces the computing device **500** with one or more external devices. For example, the computing device **500** may display text, images, etc. by way of the output interface **512**.

Additionally, while illustrated as a single system, it is to be understood that the computing device **500** may be a distributed system. Thus, for instance, several devices may be in communication by way of a network connection and may collectively perform tasks described as being performed by the computing device **500**.

It is noted that several examples have been provided for purposes of explanation. These examples are not to be construed as limiting the hereto-appended claims. Additionally, it may be recognized that the examples provided herein may be permutated while still falling under the scope of the claims.

What is claimed is:

1. A method, comprising:

receiving an image of a scene generated by a color camera, the scene comprising a planar object, the planar object having a known pattern;

locating, in the image, the pattern in the planar object based upon the pattern in the planar object being known;

computing a three-dimensional position and orientation of the planar object in the scene responsive to the pattern being located in the image, the three-dimensional position and orientation of the planar object derived from the image of the scene generated by the color camera;

receiving a depth image of the scene generated by a depth sensor, the depth image comprises pixels having depth values; and

jointly calibrating the color camera and the depth sensor based upon:

the computed three-dimensional position and orientation of the planar object; and

the depth values of the pixels in the depth image generated by the depth sensor.

2. The method of claim **1**, wherein the color camera has a first coordinate system and the depth sensor has a second coordinate system, and wherein jointly calibrating the color camera and the depth sensor comprises determining a rotation and translation between the first coordinate system and the second coordinate system.

3. The method of claim **2**, wherein jointly calibrating the color camera and the depth sensor comprises calculating a plurality of values of intrinsic parameters of the color camera and the depth sensor, the plurality of intrinsic parameters comprising a focus, a camera center, and a depth mapping function.

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

receiving a first plurality of images of the scene that are generated by the color camera over time;

receiving a second plurality of images of the scene that are generated by the depth sensor over time, wherein the planar object is at different locations in the scene relative to the color camera and the depth sensor in each of the images in the first plurality of images and the second plurality of images; and

jointly calibrating the color camera and the depth sensor based upon the first plurality of images and the second plurality of images.

5. The method of claim **1**, wherein the color camera is a video camera and the depth sensor comprises an infrared camera.

6. The method of claim **1**, wherein the depth sensor is one of a time of flight sensor or a structured light sensor.

7. The method of claim **1**, wherein the planar object is a checkerboard, the known pattern being a checkerboard pattern.

8. The method of claim **1**, wherein jointly calibrating the color camera and the depth sensor further comprises

fitting a plane on the depth image based upon the computed three-dimensional position and orientation of the planar object; and

learning a translation and rotation between a coordinate system of the depth sensor and a coordinate system of the color camera based upon an estimated correspondence between the computed three-dimensional position and orientation of the planar object and the plane fitted on the depth image.

9. The method of claim 1, wherein jointly calibrating the color camera and the depth sensor comprises:

sampling the values of the pixels in the depth image; and

learning a likelihood function that is configured to output a likelihood that a particular pixel in the depth image corresponds to the planar object.

10. The method of claim 9, wherein jointly calibrating the color camera and the depth sensor further comprises learning a translation and rotation between a coordinate system of the depth sensor and a coordinate system of the color camera based upon an evaluation of the likelihood function.

11. The method of claim 1, further comprising:

subsequent to jointly calibrating the color camera and the depth sensor, receiving a first image from the color camera;

subsequent to jointly calibrating the color camera and the depth sensor, receiving a second image from the depth sensor; and

overlaying at least a portion of the first image onto the second image to generate a three- dimensional image based upon the calibrating of the color camera and the depth sensor.

12. A system comprising:

a receiver component that receives:

a first digital image of a scene from a color camera, wherein the scene comprises a planar object that has a known pattern; and

a second digital image of the scene from a depth sensor, the first digital image and the second digital image being coincident in time; and

a calibrator component that jointly calibrates the color camera and the depth sensor based upon:

a computed position and orientation of the planar object in a coordinate system of the first digital image; and

values of pixels in the second digital image that correspond to the planar object.

13. The system of claim 12 comprised by a gaming console.

14. The system of claim 12, wherein the color camera and the depth sensor are included together in a housing.

15. The system of claim 12, wherein the planar object is a checkerboard.

16. The system of claim 12, wherein the calibrator component outputs a rotation and translation between the coordinate system of the color camera and a coordinate system of the depth sensor.

17. The system of claim 16, further comprising:

a mapper component that maps pixels of an image generated by the color camera to pixels of an image generated by the depth sensor.

18. The system of claim 17, wherein the mapper component generates a three-dimensional image based upon the pixels of the image generated by the color camera being mapped to the pixels of the image generated by the depth sensor.

19. A computer-readable data storage medium comprising instructions that, when executed by a processor, cause the processor to perform acts comprising:

outputting at least one instruction to a user with respect to placement of a planar object having a known pattern relative to a color camera and a depth sensor;

subsequent to outputting the at least one instruction, causing the color camera to capture a first image of a scene that includes the planar object;

causing the depth sensor to capture a second image of the scene, the first image and the second image being coincident in time;

computing a position and orientation of the planar object in a coordinate system of the color camera;

identifying a plane that includes the planar object in the coordinate system of the color camera, the plane identified based upon the computed position and orientation of the planar object in the coordinate system of the color camera;

identifying pixels in the second image that correspond to the planar object based upon values of the pixels;

fitting the plane in the second image based upon the values of the pixels; and

computing an estimated translation and rotation between the coordinate system of the color camera and a coordinate system of the depth sensor based upon the fitting of the plane in the second image.

20. The computer-readable data storage medium of claim 19, the acts further comprising:

subsequent to computing the estimated translation and rotation between the coordinate system of the color camera and the coordinate system of the depth sensor, generating a three-dimensional color image based upon the estimated translation and rotation.

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