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(71) Applicant: INTEL CORPORATION [US/US]; 2200 Mission College Boulevard, Santa Clara, California 95054 (US).

(72) Inventors: KILLPACK, Kip C.; 16670 SW Peninsula Ct., Beaverton, Oregon 97006 (US). HOLMAN, David R.; 10 Judo Court, Brampton, Ontario L6S 4C8can (CA). DHARMADHIKARI, Abhay A.; 4125 NW Lois Elaine Ter, Portland, Oregon 97229 (US). GAVINO, Brandon;

7854 SW Kimber Pl, Beaverton, Oregon 97007 (US). NOOJL, Vinay K.; 2111 NE 25th Ave, Hillsboro, Oregon 97124 (US). HAUSER, Katie R.; 215 NW Edgeway Dr., Apartment 106, Hillsboro, Oregon 97006 (US). LIEU, Lauren M.; 240 NW 20th Ave, Apt 9, Portland, Oregon 97209 (US).

(74) Agents: TROP, Timothy N. et al.; Trop, Pruner & Hu, P.C., 1616 S. Voss Rd., Ste. 750, Houston, Texas 77057-2631 (US).

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(54) Title: AUTO-CORRECTION OF DEPTH-SENSING CAMERA DATA FOR PLANAR TARGET SURFACES

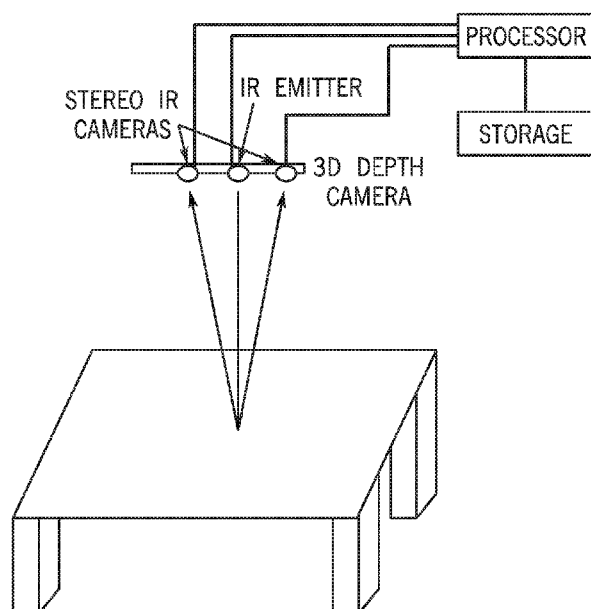


FIG. 1

(57) Abstract: A depth-sensing camera may be used to locate objects on a planar surface. A planar fit calculation is used to model the surface. One problem with the best planar fit calculation is that it is not robust over time. Firstly, this is because the depth data has a non-linear curve near its extremities because of camera lens distortion. Secondly, as the depth-sensing camera warms up and its thermal activity changes, the depth data drifts and the initial plane fit is no longer valid. The position and the amount of curvature and drift may be different for cameras of the same make and model in some cases. In accordance with some embodiments, algorithms may be used to detect and correct for these types of errors to support more robust plane fitting in real time.



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AUTO-CORRECTION OF DEPTH-SENSING CAMERA DATA FOR PLANAR TARGET SURFACES

Background

[0001] This relates to techniques for electronically specifying the location of objects on a planar surface.

[0002] Depth-sensing cameras can be used to identify the location of objects captured by the camera, because the depth data provided by the camera provides information that can be used to infer where different objects are located. Particularly in the case of objects located on a planar surface such as a table, it is valuable to know exactly where those objects are located in a variety of different operations. For example, a computer may be operated from the tabletop by simply making typing movements without any keyboard. The camera can be used to determine which finger is moved and to correlate that movement to a keystroke.

[0003] As another application, user gestures made on the tabletop may be correlated to computer commands.

[0004] Similarly objects placed on the tabletop may be located on the table using depth-sensing camera and the depth data that it produces. For example, someone playing a game could do so without having an actual board but simply move pieces on the table so they could appear on a computer screen as if they are on a game board.

[0005] In short, an ordinary depth-sensing camera can enable interactive functionality on an uninstrumented planar surface, such as a tabletop. In order to make effective use of this interactive functionality, it may be desirable to segment objects, both on and above the tabletop, to support both input sensing and interaction. An enabling step in such segmentation is a one-time calibration to compute the tabletop's planar surface. In such a calibration all the objects are removed from the tabletop and a best fit plane is calculated. This calculation identifies the table's three-dimensional position relative to the depth-sensing camera

and its extent. These values enable segmentation, even when the camera is angled, as opposed to orthogonal, to the planar surface or tabletop.

Brief Description Of The Drawings

[0006] Some embodiments are described with respect to the following figures:

Figure 1 is a schematic depiction of one embodiment;

Figure 2 is a flow chart for one embodiment;

Figure 3 shows planar drift and rotation in an illustrated embodiment;

Figure 4 is a schematic cross-section of a depth-sensing camera experiencing thermal warping caused by the camera temperature; and

Figure 5 is another flow chart for one embodiment.

Detailed Description

[0007] One problem with the best planar fit calculation is that it is not robust over time. Firstly, this is because the depth data has a non-linear curve near its extremities because of camera lens distortion. Secondly, as the camera warms up and its thermal activity changes, the depth data drifts and the initial plane fit is no longer valid. The position and the amount of curvature and drift may be different for cameras of the same make and model in some cases.

[0008] In accordance with some embodiments, algorithms may be used to detect and correct for these types of errors to support more robust plane fitting in real time.

[0009] One solution to thermal drift is to allow the camera to warm up for ten minutes before using it. However, for many users, this wait time would negatively impact the usability of an interactive tabletop product.

[0010] Typically, depth-sensing cameras have systematic errors due to artifacts remaining after lens distortion correction and dynamic errors in the form of drift and roll. A secondary lens distortion removal may de-warp the planar data. Additionally, dynamic drift and roll errors may be detected and corrected in real time in some embodiments.

[0011] While depth-sensing cameras may perform native lens distortion correction on the depth data, errors and biases remain after this correction. For example, a RealSense R200 camera available from Intel Corporation of Santa Clara, CA, positioned one meter from a planar surface, has an error specification allowing for peak to trough errors of about 8 millimeters. When a plane is fit through the depth data, the measured offset from plane error can be as high as ± 5 millimeters over 50 millimeter distance along the plane. These errors may prevent tight segmentation from the plane, making applications like small object detection on a table or sensing a user's finger contact with a surface less reliable.

[0012] Referring to Figure 1, a stereo pair of infrared (IR) cameras may be mounted over a tabletop as depicted. An IR transmitter is situated between the two cameras. The cameras image the IR reflection off the table. The depth cameras may be coupled to a hardware processor with storage.

[0013] Objects on the table such as the user's hands may reflect IR back to the cameras that then can measure the position of the user's hands on the table. Disparity between the two cameras is used to calculate a 3D depth map of the volume below the camera in some cases.

[0014] The depth data from the cameras contain a planar surface. Due to uncorrected lens distortion though, there are systematic offsets from the planar surface.

[0015] The algorithm shown in Figure 2 may be performed by the camera itself or by a computer with a wireless or wired connection to the camera. Automatic characterization may begin by taking multiple frame snapshots at startup and processing the data with no objects on the table. For example, in one embodiment, ten snapshots are taken of the table in order to factor out random noise in the depth data. For example, a typical pixel in the R200 camera has random errors on the order of ± 4 millimeters frame-to-frame.

[0016] Inter-quartile range (IQR) filtering may be used to remove extremely noisy outliers from the frames prior to computing an average plane fit through the table

data. Inter-quartile range is a measure of the variability based on dividing data into quartiles. Quartiles divide a rank ordered data set into four equal parts. The values that divide each part are called the first, second and third quartiles, denoted $Q1$, $Q2$, and $Q3$. Thus the inter-quartile range is $Q3-Q1$.

[0017] Using the median distance to a reference frame across all frames for each pixel effectively removes noisy samples. The reference frame may be determined by averaging the plane normals across all the frames. This median distance is the systematic distortion measurement for each pixel. On live captured frames, each pixel depth value may be corrected by subtracting out the systematic distortion computed at each pixel location.

[0018] Thus referring to Figure 2, the frames are grabbed and the $Q1$, $Q3$ and inter-quartile range of depth values across the frame are computed as indicated in block 10. Then outliers are removed as indicated in block 12. In one embodiment, outliers below $Q1 - 1.5 \times IQR$ are removed and outliers above $Q3 + 1.5 \times IQR$ are removed.

[0019] Then as shown in block 14, a planar random sample consensus (RANSAC) fit through the table depth data is created. RANSAC is an iterative process to estimate parameters of a mathematic model from a set of data containing outliers. A check at diamond 16 determines whether the frame count is less than N , where N is the number of frames that have been taken. If so, the flow continues to iterate back to blocks 10, 12 and 14 until all the frames have been processed.

[0020] Once all the frames are processed, then the plane normals are averaged across all the frames to get a reference frame as indicated in block 18. For each pixel for each frame, as indicated in diamond 20, the distance to the reference plane is computed as indicated in block 22. Thus the flow iterates between diamond 20 and block 22 until each pixel for each frame is processed and then the flow goes on to diamond 24. For each pixel, the systematic distortion, which is equal to the median distance across all the frames, is computed as indicated in block 26. When this is completed for each pixel, the flow ends.

[0021] On live captured frames, lens distortion is corrected for each pixel depth value by subtracting out the systematic distortion computed at each pixel location in block 26.

[0022] Even though the camera and the planar surface are stationary, the planar surface appears to drift and rotate away from the camera over time as illustrated in Figure 3. This occurs due to thermal heating which warps the relative position of the camera's internal components and changes the location of the two stereo infrared cameras with respect to each other as shown in Figure 4. Thus when one looks at a cross-section of the table, one expects a stable line but instead one may see the slope and intercept changing over time. Because the warping happens along the x axis of the camera, it appears that the plane of the table rotates around some arbitrary point on the y axis of the plane. Each camera may have a different rotation point, different rotation amount and stable settle time.

[0023] By first calibrating to find a horizontal reference line (the one opposite the edge closest to the user sitting at the table, for example) of the planar surface or table, one can compensate for drift and rotation. This line has some lens distortion of the raw data, so the distortion may be removed using the same distortion data computed by the algorithm of Figure 2.

[0024] In one embodiment, the top edge is chosen because it is unlikely that any large objects or the user's hands and arms will occlude this entire line. But a different edge may be chosen in other embodiments. Again because multiple snapshots of this line are taken, one should be able to compensate for random noise. For each snapshot, a RANSAC line fit through the top edge line is performed and then all the line fits are averaged to provide the final reference line.

[0025] During live screening of data, the depth data for the top edge of the frame is collected and the rolling RANSAC calculation shown in Figure 5 is implemented. The 5 millimeter filter on the line points acts as a low pass filter because the drift is slow and any large jumps in depth data are likely due to hands or objects temporarily crossing the line. The delta in slope and intercept for the top edge line is a measure of drift and roll. These deltas are applied to all pixels in the combined frame to

compensate for the thermal related delta drift. In addition, this correction can be applied to a subset of the frame, such as a region, individual pixel, or every other pixel in order to reduce processing time.

[0026] Referring to Figure 5, a rolling RANSAC sequence may be implemented in software, firmware and/or hardware. In software and firmware embodiments it may be implemented by computer executed instructions stored in one or more non-transitory computer readable media such as magnetic, semiconductor or optical storage.

[0027] Thus in Figure 5, at block 30 the lens distortion is removed from the top edge line. Systematic distortion for each pixel is computed in the algorithm in Figure 2 as indicated in block 26. This per-pixel systematic distortion is subtracted from each pixel in the top edge line. Then for each point on the line in diamond 32, points greater than a given distance (e.g. 5 millimeters) from the previous frame line are removed, as indicated in block 34. A threshold other than 5 millimeters may be used in other embodiments. Once this is completed for each point on the line, a linear RANSAC is performed (block 36) on the remaining points to get a line $Z = mX + b$ where m is the slope and b is the intercept. Three-dimensional data for each pixel specified as 3 values, x, y, z , in millimeters. One ignores y , and fits a line through the pair of values x, z for all points across the top edge of the frame. These x, z are the values used to fit the line $Z = mX + b$.

[0028] Then in block 38 the difference in slope and intercept of the current frame line to the reference line is computed. Finally for each pixel in each frame, as implemented in diamond 40, drift and roll are corrected by subtracting the delta in slope * X + delta in intercept (block 42). Once this is done for each pixel in the frame, the flow ends.

[0029] By using the algorithm of Figure 5 to calculate drift and roll, one is able to calibrate one time at start-up and then allow regular interaction of hands and objects on the table immediately. If live data is always referenced to the calibrated tabletop plane, it is possible to optimize the algorithm of Figure 5 by adjusting the reference

table plane by the delta in slope and intercept, which is a constant time operation, rather than adjusting all pixels in the final loop of the algorithm.

[0030] With the lens distortion removal and drift and roll correction, the tabletop depth data is forced to be both stationary and planar. With these combined algorithms, one is able to segment by thresholding relative to the table plane reliably.

[0031] These algorithms are applicable to all depth-sensing cameras that have dynamic warping that changes the infrared camera relative position, or that have remaining errors and biases after lens distortion correction. In some embodiments, these techniques may be implemented within the camera themselves.

[0032] The following clauses and/or examples pertain to further embodiments:

One example embodiment may be a method comprising correcting for curvature caused by thermal warping, depth data for a planar surface from a depth-sensing camera, and correcting the depth data for planar drift and rotation. The method may also include using the median distance of a plurality of frames depicting said planar surface to remove systematic error. The method may also include establishing said reference frame by averaging plane normals across said frames. The method may also include calibrating to find a horizontal reference line. The method may also include calibrating to find a horizontal reference line across a top edge of the planar surface. The method may also include filtering out points for a current frame that are more than a given distance from the reference line of a previous frame line. The method may also include computing a difference in slope and intercept of a current frame line to the reference line. The method may also include for each pixel, subtracting a delta in slope * X plus a delta in intercept. The method may also include capturing a plurality of snapshots with the cameras to factor out random noise. The method may also include removing depth data outliers below $Q1 - 1.5 * IQR$ or above $Q3 + 1.5 * IQR$, where $Q1$ is first quartile, $Q3$ is a third quartile and IQR is inter-quartile range.

[0033] Another example embodiment may be one or more non-transitory computer readable media storing instructions to enable a hardware processor to perform a

sequence comprising correcting for curvature caused by thermal warping, depth data for a planar surface from a depth-sensing camera, and correcting the depth data for planar drift and rotation. The media may perform said sequence including using the median distance of a plurality of frames depicting said planar surface to remove systematic error. The media may perform said sequence including establishing said reference frame by averaging plane normals across said frames. The media may perform said sequence including calibrating to find a horizontal reference line. The media may perform said sequence including calibrating to find a horizontal reference line across a top edge of the planar surface. The media may perform said sequence including filtering out points for a current frame that are more than a given distance from the reference line of a previous frame line. The media may perform said sequence including computing a difference in slope and intercept of a current frame line to the reference line. The media may perform said sequence including for each pixel, subtracting a delta in slope * X plus a delta in intercept. The media may perform said sequence including capturing a plurality of snapshots with the cameras to factor out random noise. The media may perform said sequence including removing depth data outliers below $Q1 - 1.5 * IQR$ or above $Q3 + 1.5 * IQR$, where $Q1$ is first quartile, $Q3$ is a third quartile and IQR is inter-quartile range.

[0034] In another example embodiment may be an apparatus comprising a hardware processor to correct for curvature caused by thermal warping, depth data for a planar surface from a depth-sensing camera, and correct the depth data for planar drift and rotation, and a storage coupled to said processor. The apparatus may include said processor to use the median distance of a plurality of frames depicting said planar surface to remove systematic error. The apparatus may include said processor to establish said reference frame by averaging plane normals across said frames. The apparatus may include said processor to calibrate to find a horizontal reference line. The apparatus may include said processor to calibrate to find a horizontal reference line across a top edge of the planar surface. The apparatus may include said processor to filter out points for a current frame that are more than a given distance from the reference line of a previous frame line. The apparatus may include said processor to compute a difference in slope and intercept of a current frame line to the reference line. The apparatus may include said

processor to subtract a delta in slope * X plus a delta in intercept. The apparatus may include said processor to capture a plurality of snapshots with the cameras to factor out random noise. The apparatus may include said apparatus includes a depth-sensing camera.

[0035] The graphics processing techniques described herein may be implemented in various hardware architectures. For example, graphics functionality may be integrated within a chipset. Alternatively, a discrete graphics processor may be used. As still another embodiment, the graphics functions may be implemented by a general purpose processor, including a multicore processor.

[0036] References throughout this specification to “one embodiment” or “an embodiment” mean that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one implementation encompassed within the present disclosure. Thus, appearances of the phrase “one embodiment” or “in an embodiment” are not necessarily referring to the same embodiment. Furthermore, the particular features, structures, or characteristics may be instituted in other suitable forms other than the particular embodiment illustrated and all such forms may be encompassed within the claims of the present application.

[0037] While a limited number of embodiments have been described, those skilled in the art will appreciate numerous modifications and variations therefrom. It is intended that the appended claims cover all such modifications and variations as fall within the true spirit and scope of this disclosure.

What is claimed is:

- 1 1. A method comprising:
2 correcting, for curvature from lens distortion, depth data for a planar surface
3 from a depth-sensing camera; and
4 correcting the depth data for planar drift and rotation from thermal warping.
- 1 2. The method of claim 1 including using the median distance of a plurality of
2 frames depicting said planar surface to remove systematic error.
- 1 3. The method of claim 1 including establishing said reference frame by
2 averaging plane normals across said frames.
- 1 4. The method of claim 1 including calibrating to find a horizontal reference line.
- 1 5. The method of claim 4 including calibrating to find a horizontal reference line
2 across a top edge of the planar surface.
- 1 6. The method of claim 5 including filtering out points for a current frame that are
2 more than a given distance from the reference line of a previous frame line.
- 1 7. The method of claim 6 including computing a difference in slope and intercept
2 of a current frame line to the reference line.
- 1 8. The method of claim 7 including for each pixel, subtracting a delta in slope
2 * X plus a delta in intercept.
- 1 9. The method of claim 1 including capturing a plurality of snapshots with the
2 cameras to factor out random noise.

- 1 10. The method of claim 9 including removing depth data outliers below $Q1 - 1.5 * IQR$
2 or above $Q3 + 1.5 * IQR$, where $Q1$ is first quartile, $Q3$ is a third quartile and IQR is
3 inter-quartile range.
- 1 11. One or more non-transitory computer readable media storing instructions to
2 enable a hardware processor to perform a sequence comprising:
3 correcting, for curvature from lens distortion, depth data for a planar surface
4 from a depth-sensing camera; and
5 correcting the depth data for planar drift and rotation from thermal warping.
- 1 12. The media of claim 11, said sequence including using the median distance of
2 a plurality of frames depicting said planar surface to remove systematic error.
- 1 13. The media of claim 11, said sequence including establishing said reference
2 frame by averaging plane normals across said frames.
- 1 14. The media of claim 11, said sequence including calibrating to find a horizontal
2 reference line.
- 1 15. The media of claim 14, said sequence including calibrating to find a horizontal
2 reference line across a top edge of the planar surface.
- 1 16. The media of claim 15, said sequence including filtering out points for a
2 current frame that are more than a given distance from the reference line of a
3 previous frame line.
- 1 17. The media of claim 16, said sequence including computing a difference in
2 slope and intercept of a current frame line to the reference line.
- 1 18. The media of claim 17, said sequence including for each pixel, subtracting a
2 delta in slope * X plus a delta in intercept.

- 1 19. The media of claim 11, said sequence including capturing a plurality of
2 snapshots with the cameras to factor out random noise.
- 1 20. The media of claim 19, said sequence including removing depth data outliers
2 below $Q1 - 1.5 * IQR$ or above $Q3 + 1.5 * IQR$, where $Q1$ is first quartile, $Q3$ is a third
3 quartile and IQR is inter-quartile range.
- 1 21. An apparatus comprising:
2 a hardware processor to correct, for curvature caused by lens distortion,
3 depth data for a planar surface from a depth-sensing camera, and
4 correct the depth data for planar drift and rotation from thermal warping; and
5 a storage coupled to said processor.
- 1 22. The apparatus of claim 21, said processor to use the median distance of a
2 plurality of frames depicting said planar surface to remove systematic error.
- 1 23. The apparatus of claim 21, said processor to establish said reference frame
2 by averaging plane normals across said frames.
- 1 24. The apparatus of claim 21, said processor to calibrate to find a horizontal
2 reference line.
- 1 25. The apparatus of claim 24, said processor to calibrate to find a horizontal
2 reference line across a top edge of the planar surface.

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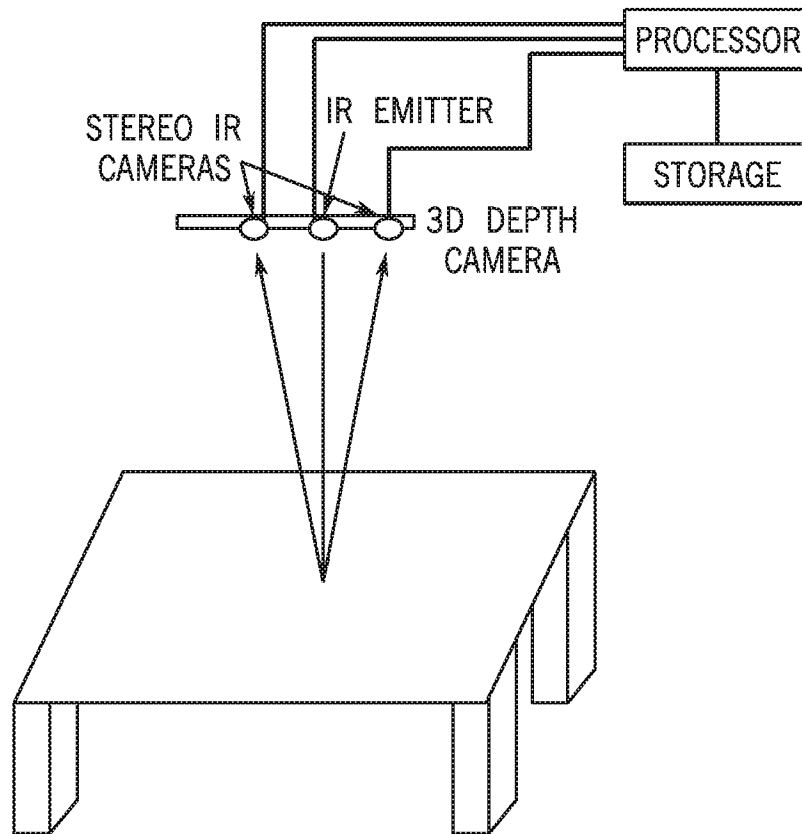


FIG. 1

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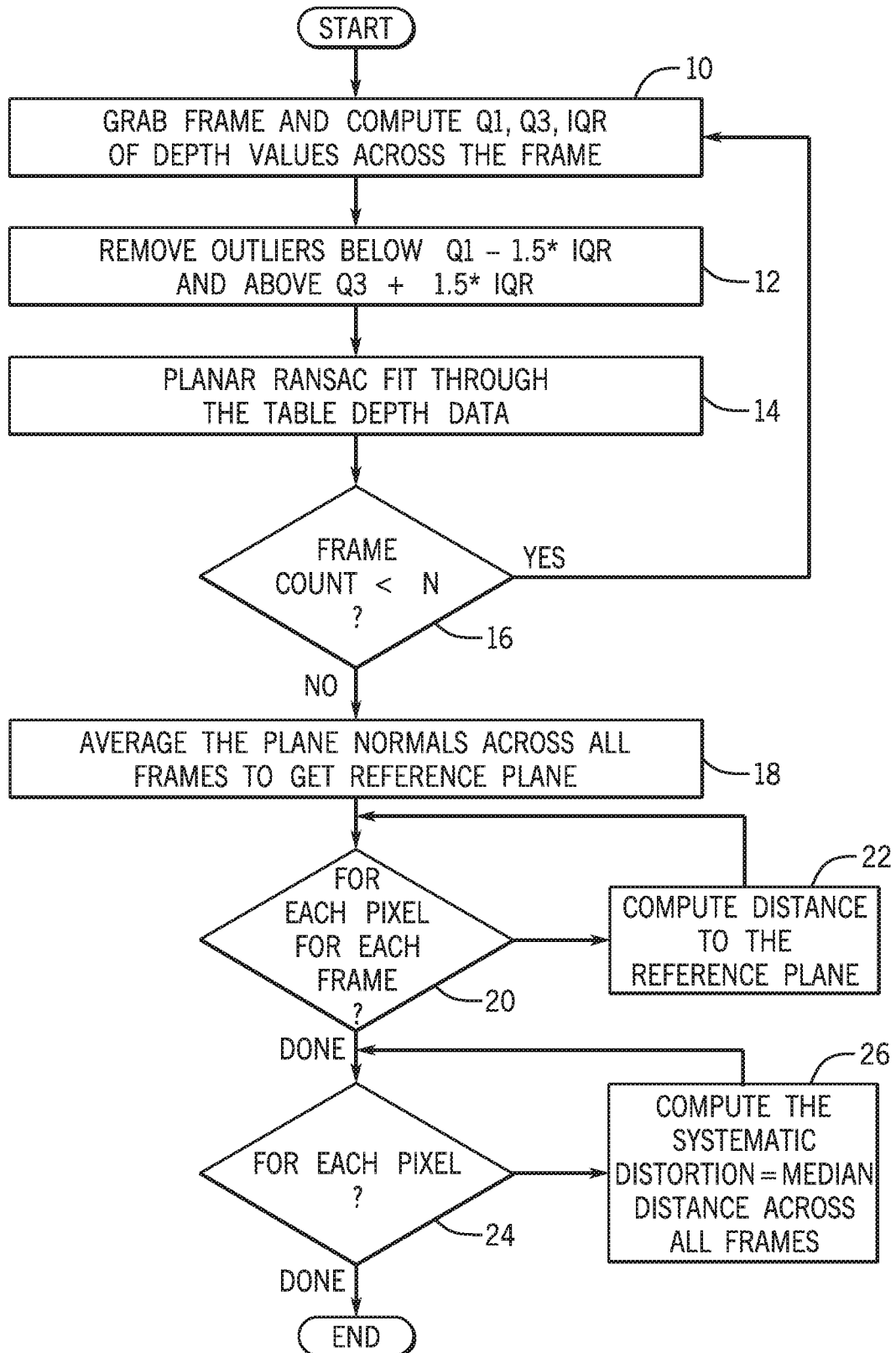


FIG. 2

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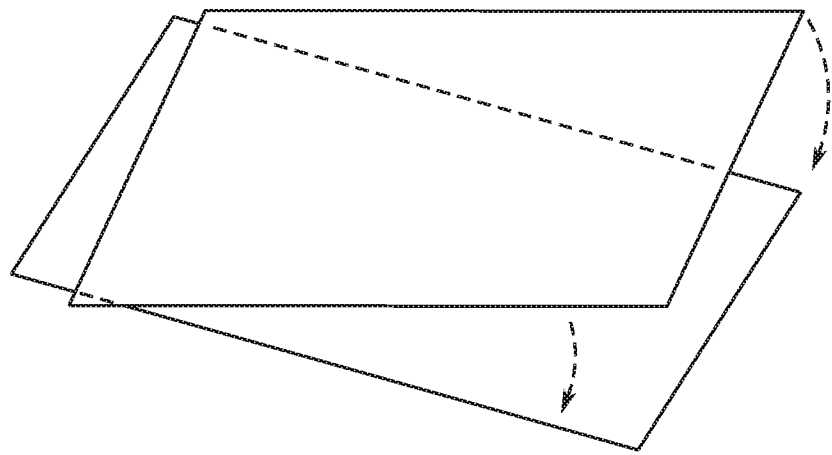


FIG. 3

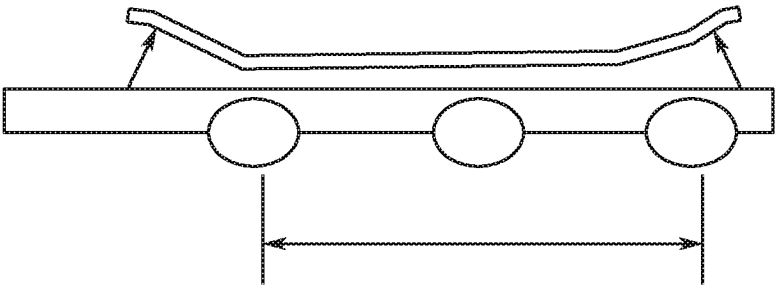
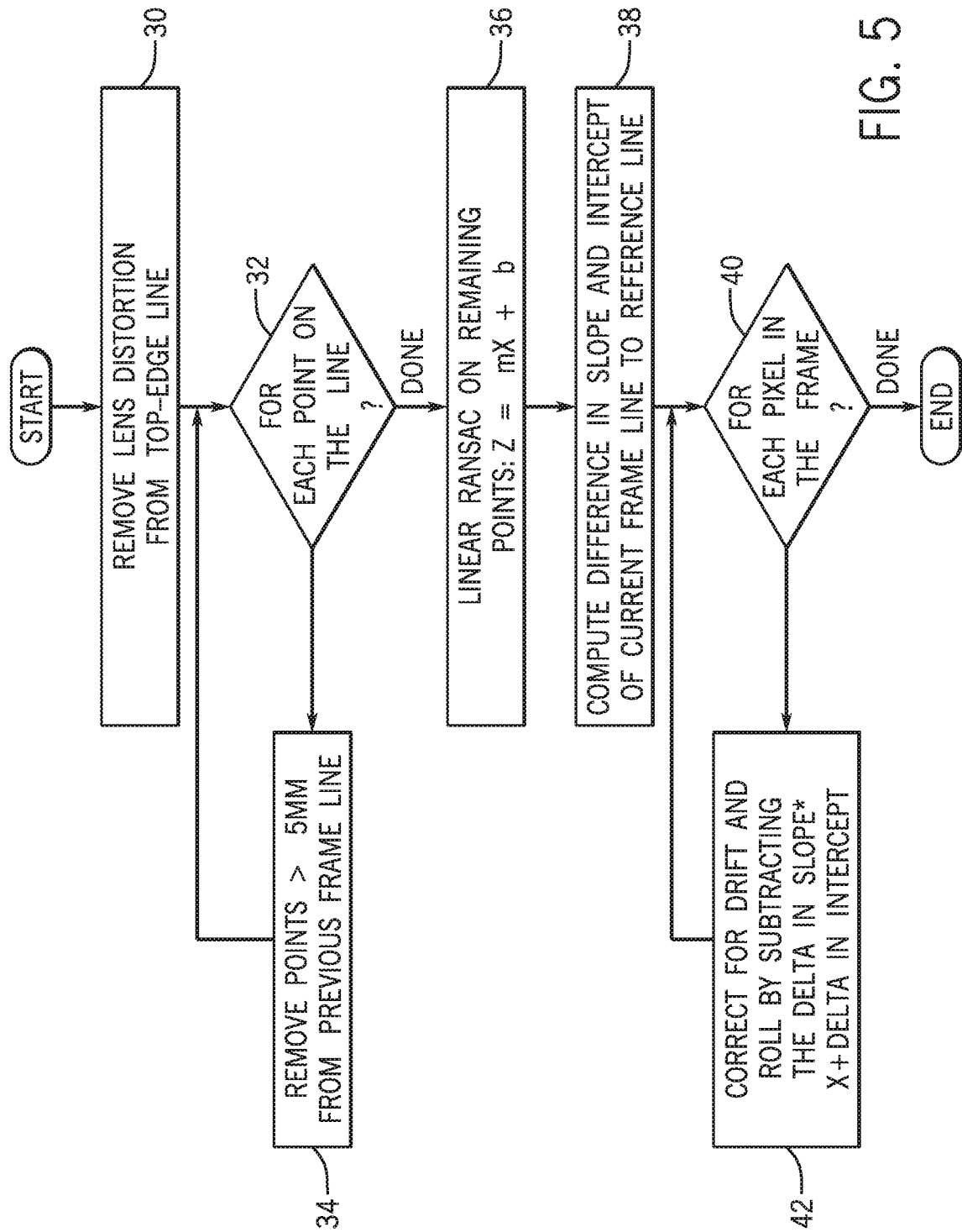


FIG. 4



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/035354**A. CLASSIFICATION OF SUBJECT MATTER****G06T 7/00(2006.01)I, H04N 13/00(2006.01)I, H04N 13/02(2006.01)I**

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G06T 7/00; H04N 5/232; G06T 17/20; H04N 5/217; H04N 13/00; H04N 13/02

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & keywords: distortion, depth data, planar surface, depth-sensing camera, planar drift and rotation, median distance, reference frame, horizontal reference line, and similar terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	CAROLINA RAPOSO et al., `Fast and Accurate Calibration of a Kinect Sensor`, In: 2013 International Conference on 3D Vision - 3DV 2013, Seattle, WA, 01 July 2013, pp. 342-349 <URL: http://ieeexplore.ieee.org/xpl/abstractAuthors.jsp?arnumber=6599095&tag=1 > See pages 342-349.	1-5, 9, 11-15, 19 , 21-25
A		6-8, 10, 16-18, 20
Y	KATHERINE O'REGAN, `Investigation into the use of the Microsoft Kinect and the Hough transform for mobile robotics`, May 2014, pp. 1-133 <URL: https://open.uct.ac.za/handle/11427/13202 > See pages 21-23, 32.	1-5, 9, 11-15, 19 , 21-25
Y	US 2013-0258047 A1 (TAKUJI MORIMOTO et al.) 03 October 2013 See paragraphs [0061]-[0063]; claim 16; and figure 4.	4-5, 14-15, 24-25
Y	US 2011-0273595 A1 (YUTAKA TSUDA) 10 November 2011 See paragraphs [0054]-[0073]; claim 6; and figure 2.	9, 19
A	US 2007-0253618 A1 (KEUN-HO KIM et al.) 01 November 2007 See paragraph [0060]; claim 1; and figure 2.	1-25



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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Date of the actual completion of the international search

01 September 2016 (01.09.2016)

Date of mailing of the international search report

02 September 2016 (02.09.2016)

Name and mailing address of the ISA/KR

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Korean Intellectual Property Office

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BYUN, Sung Cheal

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/035354

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