CLAIMS

1. A sensor calibration method, comprising:

acquiring, by an image sensor and a radar sensor disposed on an intelligent device, a plurality of scene images and a plurality of first point clouds of a target scene where the intelligent device is located, respectively;

constructing, according to the plurality of scene images, a second point cloud of the target scene in a global coordinate system;

determining, according to first feature point sets of the first point clouds and a second feature point set of the second point cloud, a first distance error between the image sensor and the radar sensor;

determining, according to a plurality of first feature point sets, a second distance error of the radar sensor;

determining a reprojection error of the image sensor according to a first global position of the second feature point set in the global coordinate system and first image positions of pixel points corresponding to the second feature point set in the scene images; and

calibrating the radar sensor and the image sensor according to the first distance error, the second distance error and the reprojection error, to obtain a first calibration result of the radar sensor and a second calibration result of the image sensor.

2. The method of claim 1, further comprising:

extracting feature points from the plurality of first point clouds, respectively, to determine a first feature point set of each of the plurality of first point clouds; and

extracting feature points from the second point cloud, to determine the second feature point set of the second point cloud,

wherein the determining, according to first feature point sets of the first point clouds and the second feature point set of the second point cloud, the first distance error between the image sensor and the radar sensor comprises:

determining, for any one set of the first feature point sets, matched first feature point pairs according to distances between first feature points in the first feature point set and second feature points in the second feature point set, each of the first feature point pairs comprising a first feature point and a second feature point;

determining, according to a plurality of matched first feature point pairs, a first sub-error between the first feature point set and the second feature point set; and

determining, according to a plurality of first sub-errors, the first distance error between the image sensor and the radar sensor.

3. The method of claim 2, wherein the extracting feature points from the plurality of first point clouds, respectively, to determine the first feature point set of each of the plurality of first point clouds comprises:

determining, for any one of the first point clouds, a point cloud sequence of the first point cloud according to a relative position of at least one laser emission point of the radar sensor;

determining, according to the point cloud sequence of the first point cloud, a plurality of first adjacent points corresponding to any one of first data points in the first point cloud;

determining, according to a coordinate of the first data point and coordinates of the plurality of first adjacent points, a curvature corresponding to the first data point; and

determining, according to curvature of a plurality of first data points in the first point cloud, the first feature point set in the first point cloud.

4. The method of claim 3, wherein the determining, according to curvature of the plurality of

first data points in the first point cloud, the first feature point set in the first point cloud comprises:

sorting the plurality of first data points according to the curvature of the plurality of first data points, to obtain a sorting result;

selecting, in a descending order, n first data points in the sorting result as n edge points; and/or,

selecting, in an ascending order, m first data points in the sorting result as m plane points,

wherein n and m are positive integers, and the first feature point set comprises at least the edge points or the plane points.

5. The method of claim 2, wherein the extracting feature points from the second point cloud, to determine the second feature point set of the second point cloud comprises:

determining, for any one of second data points in the second point cloud, a plurality of second adjacent points corresponding to the second data point from the second point cloud;

determining, according to a coordinate of the second data point and coordinates of the plurality of second adjacent points, a distance between the second data point and at least one of the second adjacent points, respectively; and

determining the second data point as the second feature point in the second feature point set, in response to the distance between the second data point and at least one of the second adjacent points being smaller than a first distance threshold.

6. The method of claim 5, wherein the second feature point set comprises a plurality of second feature points, the method further comprising: determining at least edge points or plane points from the plurality of second feature points,

wherein the determining at least edge points or plane points from the plurality of second

feature points comprises:

determining, for any one of the second feature points, a covariance matrix of a plurality of second adjacent points corresponding to the second feature point, and decomposing the covariance matrix to obtain a multi-dimensional feature value; and

determining the second feature point as the edge point, in response to a difference between any one-dimensional feature value of the multi-dimensional feature values and at least one-dimensional feature value exceeding a difference threshold.

7. The method of claim 6, wherein the determining at least edge points or plane points from the plurality of second feature points further comprises:

fitting, for any one of the second feature points, a plane equation according to the plurality of second adjacent points corresponding to the second feature point, and determining a normal vector of the plane equation; and

determining the second feature point as the plane point, in response to products of the plurality of second adjacent points corresponding to the second feature point and the normal vector falling within a threshold range.

8. The method of claim 2, wherein the determining, for any one set of the first feature point sets, matched first feature point pairs according to the distances between the first feature points in the first feature point set and the second feature points in the second feature point set comprises:

determining, for any one set of the first feature point sets, distances between the first feature points in the first feature point set and the second feature points in the second feature point set according to a pose transformation relationship between the radar sensor and the image sensor and a coordinate transformation relationship between a camera coordinate system of the image sensor and the global coordinate system; and

determining the first feature point and the second feature point between which the

distance is smaller than a second distance threshold as the matched first feature point pair.

9. The method of claim 8, wherein the determining, for any one set of the first feature point sets, the distances between the first feature points in the first feature point set and the second feature points in the second feature point set according to the pose transformation relationship between the radar sensor and the image sensor and the coordinate transformation relationship between the camera coordinate system of the image sensor and the global coordinate system comprises:

determining, for any one set of the first feature point sets, first positions of the first feature points in the first feature point set in the camera coordinate system according to the pose transformation relationship between the radar sensor and the image sensor;

determining, according to the coordinate transformation relationship between the camera coordinate system and the global coordinate system, second positions of the second feature points in the second feature point set under the camera coordinate system; and

determining, according to the first position and the second position, the distances between the first feature points in the first feature point set and the second feature points in the second feature point set.

10. The method of claim 8 or 9, wherein the determining, for any one set of the first feature point sets, the distances between the first feature points in the first feature point set and the second feature points in the second feature point set according to the pose transformation relationship between the radar sensor and the image sensor and the coordinate transformation relationship between the camera coordinate system of the image sensor and the global coordinate system further comprises:

determining, for any one set of the first feature point sets, second global positions of the first feature points in the first feature point set in the global coordinate system according to the pose transformation relationship between the radar sensor and the image sensor and the coordinate transformation relationship between the camera coordinate system and the global

coordinate system; and

determining, according to the second global positions and first global positions of the second feature points in the second feature point set, the distances between the first feature points in the first feature point set and the second feature points in the second feature point set.

11. The method of claim 2, wherein the first feature point pairs comprise at least an edge point pair or a plane point pair,

wherein the determining, according to the plurality of matched first feature point pairs, the first sub-error between the first feature point set and the second feature point set comprises:

determining, for any one of the first feature point pairs, a first vertical distance from a second feature point in the first feature point pair to a straight line where a first feature point in the first feature point pair is located, in response to the first feature point pair being the edge point pair;

determining a second vertical distance from a second feature point in the first feature point pair to a plane where a first feature point in the first feature point pair is located, in response to the first feature point pair being the plane point pair; and

determining the first sub-error according to at least a plurality of first vertical distances or a plurality of second vertical distances.

12. The method of any one of claims 1-3, wherein the determining, according to the plurality of first feature point sets, the second distance error of the radar sensor comprises:

determining matched second feature point pairs according to distances between third feature points in a third feature point set and fourth feature points in a fourth feature point set, the third feature point set and the fourth feature point set being any two of the first feature point sets, and each of the second feature point pairs comprising a third feature point and a fourth feature point;

determining, according to a plurality of matched second feature point pairs, a second sub-error between the third feature point set and the fourth feature point set; and

determining, according to a plurality of second sub-errors, the second distance error of the radar sensor.

13. The method of claim 12, wherein the determining matched second feature point pairs according to the distances between the third feature points in the third feature point set and the fourth feature points in the fourth feature point set comprises:

determining, according to a radar pose of the radar sensor when acquiring at least one of the first point clouds, the distances between the third feature points in the third feature point set and the fourth feature points in the fourth feature point set; and

determining the third feature point and the fourth feature point between which the distance is smaller than a third distance threshold as the matched second feature point pair~~.~~.

~~14. The method of claim 13,~~ wherein the determining, according to the radar pose of the radar sensor when acquiring at least one of the first point clouds, the distances between the third feature points in the third feature point set and the fourth feature points in the fourth feature point set comprises:

determining, according to the radar pose of the radar sensor when acquiring at least one of the first point clouds, third global positions of the third feature points in the third feature point set in the global coordinate system and fourth global positions of the fourth feature points in the fourth feature point set in the global coordinate system; and

determining, according to the third global position and the fourth global position, the distances between the third feature points in the third feature point set and the fourth feature points in the fourth feature point set.

~~15~~14. The method of claim 12, wherein the second feature point pairs comprise at least an edge point pair or a plane point pair,

wherein the determining, according to the plurality of matched second feature point pairs, the second sub-error between the third feature point set and the fourth feature point set comprises:

determining, for any one of the second feature point pairs, a third vertical distance from a third feature point in the second feature point pair to a straight line where a fourth feature point in the second feature point pair is located, in response to the second feature point pair being the edge point pair;

determining a fourth vertical distance from a third feature point in the second feature point pair to a plane where a fourth feature point in the first feature point pair is located, in response to the second feature point pair being the plane point pair; and

determining the second sub-error according to at least a plurality of third vertical distances or a plurality of fourth vertical distances.

~~16~~15. The method of claim 1, wherein the determining the reprojection error of the image sensor according to the first global position of the second feature point set in the global coordinate system and the first image positions of pixel points corresponding to the second feature point set in the plurality of scene images comprises:

for any one of the scene images, according to a first global position of any one of second feature points in the second feature point set and camera parameters of the image sensor, determining a second image position of the second feature point in the scene image;

determining a reprojection sub-error corresponding to the scene image according to second image positions of a plurality of second feature points and first image positions of pixel points corresponding to the plurality of second feature points in the scene image; and

determining, according to reprojection sub-errors corresponding to the plurality of scene images, the reprojection error of the image sensor.

~~17~~16. The method of claim 1 or ~~16~~15, wherein the image sensor comprises a plurality of image sensors comprising a reference image sensor and at least one non-reference image sensor, and the plurality of scene images comprise a plurality of reference images acquired by the reference image sensor and a plurality of non-reference images acquired by the non-reference image sensor,

wherein the determining the reprojection error of the image sensor according to the first global position of the second feature point set in the global coordinate system and the first image positions of pixel points corresponding to the second feature point set in the plurality of scene images comprises:

for any one of non-reference images, according to a first global position of any one of second feature points in the second feature point set, camera parameters of the reference image sensor and a pose transformation relationship between the non-reference image sensor and the reference image sensor, determining a third image position of the second feature point in the non-reference image;

determining a reprojection sub-error corresponding to the non-reference image according to third image positions of a plurality of second feature points and fourth image positions of pixel points corresponding to the second feature points in the non-reference image; and

determining, according to reprojection sub-errors corresponding to the plurality of non-reference images, the reprojection error of the non-reference image sensor.

~~18. The method of claim 1, wherein the calibrating the radar sensor and the image sensor according to the first distance error, the second distance error and the reprojection error, to obtain the first calibration result of the radar sensor and the second calibration result of the image sensor comprises:~~

~~optimizing a radar pose of the radar sensor, camera parameters of the image sensor and~~

~~the second feature point set according to the first distance error, the second distance error and the reprojection error; and~~

~~re-performing the sensor calibration method according to the optimized radar pose, optimized camera parameters and optimized second feature point set, until the radar pose of the radar sensor and the camera parameters of the image sensor are converged respectively, to obtain the first calibration result of the radar sensor and the second calibration result of the image sensor, the first calibration result comprising the converged radar pose, and the second calibration result comprising the converged camera parameters.~~

~~19. The method of any one of claims 1-18, wherein the intelligent device comprises any one of an intelligent vehicle, an intelligent robot, or an intelligent robot arm; the radar sensor comprises any one of a laser radar or a millimeter wave radar; the image sensor comprises at least one of a monocular Red-Green-Blue (RGB) camera, a binocular RGB camera, a time-of-flight (TOF) camera, or an infrared camera; and the camera parameters of the image sensor comprise camera internal parameters and camera poses.~~

~~20~~17. A sensor calibration apparatus, comprising:

an acquisition module configured to acquire, by an image sensor and a radar sensor disposed on an intelligent device, a plurality of scene images and a plurality of first point clouds of a target scene where the intelligent device is located, respectively;

a point cloud construction module configured to construct, according to the plurality of scene images, a second point cloud of the target scene in a global coordinate system;

a first distance error determination module configured to determine, according to first feature point sets of the first point clouds and a second feature point set of the second point cloud, a first distance error between the image sensor and the radar sensor;

a second distance error determination module configured to determine, according to a plurality of first feature point sets, a second distance error of the radar sensor;

a reprojection error determination module configured to determine a reprojection error of the image sensor according to a first global position of the second feature point set in the global coordinate system and first image positions of pixel points corresponding to the second feature point set in the scene images; and

a calibration module configured to calibrate the radar sensor and the image sensor according to the first distance error, the second distance error and the reprojection error, to obtain a first calibration result of the radar sensor and a second calibration result of the image sensor.

~~21~~18. An electronic device, comprising:

a processor; and

a memory configured to store instructions executable by the processor,

wherein the processor is configured to call the instructions stored in the memory, to perform the method of any one of claims 1-~~19~~16.

~~22~~19. A computer-readable storage medium having stored thereon computer program instructions that when executed by a processor, implement the method of any one of claims 1-~~19~~16.

~~23~~20. A computer program, comprising computer-readable codes that when running in an electronice device, enable a processor of the electronic device to execute to implement the method of any one of claims 1-~~19~~16.