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Motion monitor using lidar registration

Abstract

A motion monitor includes a lidar device, a controller, and a circuit. The lidar device is configured to perform scans of an environment proximate the ego vehicle to generate lidar point clouds related to one or more objects in the environment. The controller is configured to transform the lidar point clouds with location transform matrices to generate location point sets, aggregate the location point sets in a duration of interest to generate aggregated point sets, register the location point sets to the aggregated point sets to generate correction transform matrices, update the location transform matrices with the correction transform matrices to generate updated location transform matrices, and generate motion sets based on the updated location transform matrices. The circuit is configured to receive the motion sets.

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Background/Summary

INTRODUCTION

(1) The present disclosure relates to a system and/or a method for motion monitoring of an ego vehicle, and in particular, motion estimation of the ego vehicle using lidar registration.

(2) Ego vehicle motion estimation is used for advanced driver-assistance systems and automated vehicle features. The ego motion estimation is commonly achieved with a Global Positioning System (GPS) receiver, an inertial measurement unit (IMU), and/or a vehicle speed sensor (VSS) and/or a steering angle sensor. The GPS systems are susceptible to errors in urban environments and tunnels. The IMU systems are subject to drift. The VSS and the steering angle sensor have low accuracy. Both types of systems are costly. Lidar-based ego vehicle motion estimation approaches using scan-to-scan registration reduce costs over the GPS/IMU approaches, but have a low accuracy and are prone to drift.

(3) Accordingly, those skilled in the art continue with research and development efforts in the field of ego vehicle motion estimation using lidar sensors.

SUMMARY

(4) A motion monitor is provided herein. The motion monitor includes a lidar device, a controller, and a circuit. The lidar device is disposed in an ego vehicle and configured to perform a plurality of scans of an environment proximate the ego vehicle to generate a plurality of lidar point clouds related to one or more objects in the environment. The controller is in communication with the lidar device and configured to transform the plurality of lidar point clouds with a plurality of location transform matrices to generate a plurality of location point sets, aggregate the plurality of location point sets in a duration of interest to generate a plurality of aggregated point sets, register the plurality of location point sets to the plurality of aggregated point sets to generate a plurality of correction transform matrices, update the plurality of location transform matrices with the plurality of correction transform matrices to generate a plurality of updated location transform matrices, and generate a plurality of motion sets based on the plurality of updated location transform matrices. The circuit is in communication with the controller and configured to receive the plurality of motion sets.

(5) In one or more embodiments of the motion monitor, the registration of the plurality of location point sets includes a non-causal registration that utilizes one or more future location point sets of the plurality of location point sets to noncausally register one or more current location point sets of the plurality of location point sets.

(6) In one or more embodiments of the motion monitor, the registration of the plurality of location point sets is a causal registration that solely utilizes past location point sets of the plurality of location point sets to causally register each current location point set of the plurality of location point sets.

(7) In one or more embodiments of the motion monitor, the aggregation of the plurality of location point sets includes identification of a number of aggregated points among the plurality of aggregated point sets that are within a neighborhood proximate each current location point in the plurality of location point sets, and removal of the neighborhood in response to the number of the aggregated points being less than a lower threshold number.

(8) In one or more embodiments of the motion monitor, the aggregation of the plurality of location point sets further includes reduction of the neighborhood to a random sample of the aggregated points within the neighborhood in response to the number of the aggregated points exceeding an upper threshold value.

(9) In one or more embodiments of the motion monitor, the aggregation of the plurality of location point sets further includes calculation of a singular value decomposition of the aggregated points in the neighborhood to determine a first singular vector, a first singular value, a second singular vector, a third singular vector, and a third singular value, where the first singular vector and the second singular vector define a best-fit plane to the aggregated points, and the third singular vector

is normal to the best-fit plane, and filtering of the neighborhood in response to a ratio of the third singular value to the first singular value being greater than a ratio threshold value.

(10) In one or more embodiments of the motion monitor, generation of the plurality of correction transform matrices is calculated using a least mean squares technique under a low angle correction assumption.

(11) In one or more embodiments of the motion monitor, the circuit is a storage device configured to record the plurality of motion sets, and the plurality of motion sets form a training dataset for an autonomous driving training system.

(12) In one or more embodiments of the motion monitor, the circuit is a drive system disposed in the ego vehicle, and is configured to control movement of the ego vehicle in response to the plurality of motion sets.

(13) A method for motion estimation of an ego vehicle is provided herein. The method includes scanning an environment proximate the ego vehicle a plurality of times with a lidar device to generate a plurality of lidar point clouds related to one or more objects in the environment, transforming the plurality of lidar point clouds with a plurality of location transform matrices to generate a plurality of location point sets, aggregating the plurality of location point sets in a duration of interest to generate a plurality of aggregated point sets, registering the plurality of location point sets to the plurality of aggregated point sets to generate a plurality of correction transform matrices, updating the plurality of location transform matrices with the plurality of correction transform matrices to generate a plurality of updated location transform matrices, generating a plurality of motion sets based on the plurality of updated location transform matrices, and receiving the plurality of motion sets at a circuit.

(14) In one or more embodiments of the method, the registering of each one of the plurality of location point sets includes a noncausal registering that utilizes one or more future location point sets of the plurality of location point sets to noncausally register one or more current location point sets of the plurality of location point sets.

(15) In one or more embodiments of the method, the registering of each one of the plurality of location point sets includes a causal registering that solely utilizes past location point sets of the plurality of location point sets to causally register each current location point set of the plurality of location point sets.

(16) In one or more embodiments of the method, the aggregating of the plurality of location point sets includes identifying a number of aggregated points of the plurality of aggregated point sets that are within a neighborhood of each current location point in the plurality of location point sets, and removing the neighborhood in response to the number of the aggregated points being less than a lower threshold number.

(17) In one or more embodiments of the method, the aggregating of the plurality of location point sets further includes reducing the neighborhood to a random sample of the aggregated points within the neighborhood in response to the number of the aggregated points exceeding an upper threshold value.

(18) In one or more embodiments of the method, the aggregating of the plurality of location point sets further includes calculating a singular value decomposition of the aggregated points in the neighborhood to determine a first singular vector, a first singular value, a second singular vector, a third singular vector, and a third singular value, where the first singular vector and the second singular vector define a best-fit plane to the aggregated points and the third singular vector is normal to the best-fit plane, and filtering the neighborhood in response to a ratio of the third singular value to the first singular value being greater than a ratio threshold value.

(19) In one or more embodiments of the method, the generation of the plurality of correction transform matrices is calculated using a least mean squares technique under a low angle correction assumption.

(20) An ego vehicle is provided herein. The ego vehicle includes a lidar device, a controller, a

circuit, and a drive system. The lidar device is configured to perform a plurality of scans of an environment proximate the ego vehicle to generate a plurality of lidar point clouds related to one or more objects in the environment. The controller is in communication with the lidar device and is configured to transform the plurality of lidar point clouds with a plurality of location transform matrices to generate a plurality of location point sets, aggregate the plurality of location point sets in a duration of interest to generate a plurality of aggregated point sets, register the plurality of location point sets to the plurality of aggregated point sets to generate a plurality of correction transform matrices, update the plurality of location transform matrices with the plurality of correction transform matrices to generate a plurality of updated location transform matrices, and generate a plurality of motion sets based on the plurality of updated location transform matrices. The circuit is in communication with the controller, is configured to receive the plurality of motion sets, and generate a plurality of commands in response to the plurality of motion sets. The drive system is configured to control movement of the ego vehicle in response to the plurality of commands.

(21) In one or more embodiments of the ego vehicle, the registering of the plurality of location point sets is a causal registering that solely utilizes past location point sets of the plurality of location point sets to causally register each current location point set of the plurality of location point sets.

(22) In one or more embodiments, the ego vehicle further includes a camera configured to sense the environment proximate the ego vehicle to generate a plurality of images.

(23) In one or more embodiments of the ego vehicle, the plurality of location transform matrices aligns the plurality of motion sets with the plurality of images.

(24) The above features and advantages and other features and advantages of the present disclosure are readily apparent from the following detailed description of the best modes for carrying out the disclosure when taken in connection with the accompanying drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** is a schematic diagram illustrating a context of a system.
(2) FIG. **2** is a schematic diagram illustrating an ego vehicle in another system in accordance with one or more exemplary embodiments.
(3) FIG. **3** is a flow diagram of a method for motion estimation of the ego vehicle in accordance with one or more exemplary embodiments.
(4) FIG. **4** is a schematic diagram of a noncausal aggregation in accordance with one or more exemplary embodiments.
(5) FIG. **5** is a schematic diagram of a noncausal registration in accordance with one or more exemplary embodiments.
(6) FIG. **6** is a schematic diagram of a causal aggregation in accordance with one or more exemplary embodiments.
(7) FIG. **7** is a schematic diagram of a causal registration is shown in accordance with one or more exemplary embodiments.
(8) FIG. **8** is a flow diagram of the registration step in accordance with one or more exemplary embodiments.
(9) FIG. **9** is a schematic diagram of an aggregated point set in accordance with one or more exemplary embodiments.
(10) FIG. **10** is a schematic diagram of a crowed aggregated point set in accordance with one or more exemplary embodiments.
(11) FIG. **11** is a schematic diagram of a best-fit plane in accordance with one or more exemplary

embodiments.

DETAILED DESCRIPTION

(12) Embodiments of the present disclosure provide a system and/or method for a lidar-based ego vehicle motion estimation. In various embodiments, the approach enables high ego vehicle motion accuracy by performing noncausal registration between the lidar device scans to aggregated scans before and after the current scan. The noncausal relationship means that the aggregated scans are not marked by cause and effect. Thus, the aggregated scans may be recorded during a trip and the noncausal registration of the current scans take place after the trip has been completed. By performing the process iteratively, estimation errors and drift errors are minimized, achieving high accuracy. In other embodiments, the registrations of the current scans may be performed in real time solely using past aggregated scans (e.g., causal registration).

(13) The lidar device generally measures the environment around the ego vehicle at a constant interval, referred to as a scan. For real time approaches, scan-to-scan registration is used to produce real-time ego vehicle motion estimations suitable for real-time driver assistance. The ego motion estimation accuracy appropriate for a training dataset may be higher than the scan-to-scan registration approach may provide. Therefore, a non-real-time approach is provided for generating datasets suitable to train autonomous driving systems. The non-real-time approach uses the noncausal solution for offline implementation with improved accuracy that mitigates random walk errors, and further improves the registration process.

(14) Referring to FIG. **1**, a schematic diagram illustrating a context of a system **80***a* is shown. The system **80***a* may include an environment **82**, one or more objects (one shown) **84**, an ego vehicle **90***a*, and a navigation monitor **100***a*. The ego vehicle **90***a* generally includes one or more cameras (one shown) **92**, a lidar device **102**, and a transmitter **104**. The navigation monitor **100***a* includes a receiver **108**, a controller **110**, a circuit **112**, a storage device **114**, and an autonomous driving training system **116**. The ego vehicle **90***a* and the navigation monitor **100***a* are configured for recording and non-real-time (e.g., noncausal) analysis of the motion of the ego vehicle **90***a*.

(15) A transmit signal (Tx) may be generated and presented by the lidar device **102**. A receive signal (Rx) may be received by the lidar device **102**. The receive signal Rx is the transmit signal Tx as reflected by the object **84**. A lidar point cloud signal (LPC) is generally by the lidar device **102** and presented to the transmitter **104**. The signal LPC conveys point clouds of the object **84** as measured by the lidar device **102**. An image signal (IMG) is generated by the camera **92** and presented to the transmitter **104**. The signal IMG transfers a sequence of visual images of the surrounding environment **82** as recorded by the camera **92**.

(16) A data signal (DT) is generated by the transmitter **104** and received by the receiver **108** and transferred to the controller **110**. The signal DT is a wired or wireless signal that conveys the lidar point cloud data from the vehicle **90***a* to the navigation monitor **100***a*. A motion sets signal (MS) is generated by the controller **110** and presented to storage device **114** in the circuit **112**. The signal MS carries sets of motion data derived from the lidar point cloud data. A stored data signal (SD) is generated by the storage device **114** and transferred to autonomous driving training system **116**. The signal SD is the sets of motion data generated by the controller **110** and buffered in the storage device **114**.

(17) The objects **84** may include, but are not limited to, mobile objects (or targets) such as bicycles, carts, automobiles, trucks, motorcycles, boats, trains and/or aircraft. In some embodiments, the objects **84** may include stationary objects (or targets) such as signs, posts, buildings, mailboxes, lane markings, sidewalks, curbs, and/or walls. Other types of objects **84** capable of reflecting the signal Tx may be implemented to meet the design criteria of a particular application.

(18) The ego vehicle **90***a* includes, but is not limited to, mobile vehicles (or objects) such as automobiles, trucks, motorcycles, boats, trains and/or aircraft. Other types of ego vehicles may be implemented to meet the design criteria of a particular application.

(19) The camera **92** implements one or more optical cameras. The camera **92** is operational to

capture images of the environment **82**. The images (e.g., video) are presented in the signal IMG to the transmitter **104** for subsequent use by the autonomous driving training system **116**.

(20) The navigation monitor (or system) **100***a* implements a navigation measuring, recording, an analysis system. In various embodiments, the navigation monitor **100***a* is split between the ego vehicle **90***a* and the analysis system **106**. The navigation monitor **100***a* is operational to repeatedly scan the environment **82** proximate the ego vehicle **90***a* with the lidar device **102** to generate the lidar point clouds related to the object(s) **84** in the environment **82**. The navigation monitor **100***a* may also be operational to transform the lidar point clouds with multiple location transform matrices to generate multiple location point sets, aggregate the location point sets in a duration of interest to generate multiple aggregated point sets, and register the location point sets to the aggregated point sets to generate multiple correction transform matrices. The navigation monitor **100***a* may subsequently update the location transform matrices with the correction transform matrices to generate multiple updated location transform matrices, generate multiple motion sets based on the updated location transform matrices, and store the motion sets in the circuit **112** (e.g., in the storage device **114**). From the circuit **112**/storage device **114**, the motion sets are used as a learning database by the autonomous driving training system **116**.

(21) The lidar device **102** implements a light detection and ranging device. The lidar device **102** uses pulsed laser waves to map the distance to the object **84** surrounding the ego vehicle **90***a*. The lidar device **102** is operational to measure distances to the object **84** to within a few centimeters, up to 60 meters away. In a first pass of the ego vehicle **90***a* through the environment **82**, the lidar device **102** generate the lidar point clouds that accurately describe the environment **82** and the motion of the ego vehicle **90***a*. In the event that the ego vehicle **90***a* returns to the environment **82**, the returning ego vehicle **90***a* can navigate the environment **82** in a predictable manner.

(22) The transmitter **104** implements a wireless transmitter. The transmitter **104** is operational to transfer the lidar point cloud data from the lidar device **102** and the image data from the camera **92** to the analysis system **106**.

(23) The analysis system **106** implements one or more computers (or processors). The analysis system **106** is operational to record and analyze the lidar point cloud data and the image data received from the ego vehicle **90***a* to determine the motion of the ego vehicle **90***a*. The lidar point cloud data and the image data generally form a basis for an autonomous vehicle training dataset.

(24) The receiver **108** implements a wireless receiver. The receiver **108** is operational to transfer the lidar point cloud data and the image data from the transmitter **104** to the controller **110**.

(25) The controller **110** implements one or more computers (or processors). The controller **110** is in communication with the receiver **108** and the circuit **112**. The controller **110** is operational to transform the lidar point cloud data with the multiple location transform matrices to generate the multiple location point sets, aggregate the location point sets in a duration of interest to generate the aggregated point sets, register the location point sets to the aggregated point sets to generate the correction transform matrices, update the location transform matrices with the correction transform matrices to generate the updated location transform matrices, generate the motion sets based on the updated location transform matrices, and store the motion sets in the storage device **114**.

(26) The circuit **112** implements a processing circuit. The circuit **112** includes the storage device **114**. The storage device **114** is operational to store the processed lidar cloud point data and the image data as received from the ego vehicle **90***a* for later use by the autonomous driving training system **116**. The storage device **114** is in communication with the autonomous driving training system **116**.

(27) The autonomous driving training system **116** implements a training system for autonomous vehicles (e.g., the ego vehicle **90***a*). The autonomous driving training system **116** is operational to utilize the processed motion recorded for the ego vehicle **90***a* and the image data to teach autonomous vehicles how to react in various situations.

(28) Referring to FIG. **2**, a schematic diagram illustrating another ego vehicle **90***b* in another

system **80***b* is shown in accordance with one or more exemplary embodiments. The system **80***b* may include the environment **82**, the object **84**, the ego vehicle **90***b*, and a navigation monitor **100***b*. The ego vehicle **90***b* generally includes the camera **92**, a power plant **94**, and the navigation monitor **100***b*. A portion of the navigation monitor **100***b* on the ego vehicle **90***b* includes the lidar device **102**, the controller **110**, the circuit **112**, the storage device **114**, and driver system **118**. An optional portion of the navigation monitor **100***b* external to the ego vehicle **90***b* includes the autonomous driving training system **116**. The ego vehicle **90***b* and the navigation monitor **100***b* are configured for real-time (e.g., causal) recording and analysis of the motion of the ego vehicle **90***a*. The controller **110** is in communication with the lidar device **102** and the circuit **112**.

(29) A command signal (CMD) may be generated by the driver system **118** and presented to the power plant **94**. The command signal CMD carries throttle, braking, gear selection, and/or steering commands generated by the driver system **118** to aid in control of the ego vehicle **90***b*.

(30) The ego vehicle **90***b* is a variation of the ego vehicle **90***a*. The ego vehicle **90***b* is operational to use the causal registration of the lidar scans to the aggregate scans to aid in control of the ego vehicle **90***b*.

(31) The power plant **94** implements a propulsion, braking, and steering system of the ego vehicle **90***b*. The power plant **94** is operational to provide power, gear selection, braking and/or steering controls in response to the command signal CMD.

(32) The driver system **118** implements a driver assistance system. The driver system **118** is in communication with the power plant **94**. The driver system **118** is operational to provide commands to the power plant **94** to assist the driver of the ego vehicle **90***b* with real-time control of the ego vehicle **90***b*.

(33) The storage device **114** implements a removable and/or a downloadable device. The storage device **114** may communicate with the autonomous driving training system **116**, where implemented. The processed lidar scans and/or image data may be transferred from the storage device **114** to the autonomous driving training system **116**.

(34) By implementing a causal registration of the lidar scans to the aggregated scans in the ego vehicle **90***b*, the navigation monitor **100***b* may determine real-time motion of the ego vehicle **90***b*. The real-time motion may include acceleration, speed, deceleration, and yaw of the ego vehicle **90***b*. The real-time motion may be provided to the driver system **118** to aid in control of the ego vehicle **90***b*.

(35) Referring to FIG. **3**, a flow diagram of an example implementation of method **140** for motion estimation of an ego vehicle is shown in accordance with one or more exemplary embodiments. The method (or process) **140** may be used for noncausal registration and causal registration embodiments. The method **140** generally includes steps **142** to **168**, as shown. The sequence of steps is shown as a representative example. Other step orders may be implemented to meet the criteria of a particular application.

(36) In the step **142**, the lidar device **102** scans the environment **82** proximate the ego vehicle **90***a*/**90***b* to generate the lidar point clouds related to the object(s) **84** in the environment **82**. The camera **92** may generate the image data in the step **142**. For the ego vehicle **90***a*, the transmitter **104** transfers the lidar point cloud data and the image data from the ego vehicle in the step **144**. For the ego vehicle **90***b*, the storage device **114** records the aggregated lidar point cloud data and the image data for later subsequent driving assistance, and optional downloading to the autonomous driving training system **116**.

(37) In the step **146**, the receiver **108** in the motion navigation monitor **100***a* receives the lidar data and the image data. The controller **110** in the navigation monitor **100***b* reads the aggregated lidar point cloud data and the image data from the storage device **114**. In the step **148**, the controller **110** reads initial location transform matrices from the storage device **114**, or another available storage device. The transform matrices generally allow the lidar point cloud data to be changed from a local coordinate system into another coordinate system, such as the coordinate system of the image

data from the camera **92**. The lidar scans are transformed in the controller **110** with the location transform matrices to generate the location point sets in the step **150**.

(38) The location point steps are aggregated in a duration of interest by the controller **110** in the step **152** to create the aggregated point sets. The aggregated point sets are stored in the storage device **114**. A current lidar scan (from the history of recorded lidar scans stored in the storage device **114** in the navigation monitor **100***a*, or from the lidar device **102** in the ego vehicle **90***b*) is obtained by the controller **110** in the step **154**. The controller **110** registers the current lidar scan to the aggregated point sets as part of the step **154** to create the correction transform matrices. In the step **154**, the controller **110** receives the aggregated scans and returns a correction of the location transform (Mk_opt) for each scan.

(39) In the step **156**, the controller **110** updates the location transform matrices with the correction transform matrices to generate updated location transform matrices. Each existing location transform (Lk_old) is updated according to the correction transform matrix Mk_opt, which is the output of the scan to aggregation registration process. The update may be performed according to equation 1 as follows:

Lk_new=Mk_opt.Math.Lk_old   (1)

(40) Where k is the scan index. The updating may utilize a least mean squares technique under a low angle correction assumption.

(41) The steps **152-156** may be repeated a number of times to improve the accuracy of the data registration. A number of iterations through the steps **152** to **156** is checked in the step **158**. If the number of iterations is less than a threshold value, the method **140** returns to the step **152** to register the current lidar scan to the updated aggregated data. Once the number of iterations reaches the threshold value, the method **140** continues with the step **160**.

(42) In the step **160**, the controller **110** generates the motion sets based on the updated location transform matrices and the current lidar data. The motion sets may be transferred to the circuit **112** in the step **162**. For the navigation monitor **100***b*, the motion sets may be consumed by the autonomous driving training system **116** to help control the ego vehicle **90***b* in the step **164**. In various embodiments, the motion sets generated by the ego vehicle **90***b* may be stored in the storage device **114** for later transfer to the autonomous driving training system **116**. For the navigation monitor **100***a*, the motion sets are stored in the storage device **114** for later transfer to the autonomous driving training system **116** in the step **166**. In the step **168**, the processed motion sets are aligned with the camera images for a clearer understanding of the environment **82** around the ego vehicle **90***a* when the ego vehicle **90***a* moved through the environment **82**.

(43) Referring to FIG. **4**, a schematic diagram of an example noncausal aggregation is shown in accordance with one or more exemplary embodiments. The noncausal aggregation **152***a* may be representative of the aggregation step **152** in the method **140**. A list of location point sets **170** containing recorded location point sets (e.g., past location point sets, a current location point set, and one or more future location point sets) is stored in the storage device **114**. A duration of interest **172***a* around a current location point set **174** is determined by the controller **110**. The duration of interest **172***a* includes one or more future location point sets **176** and one or more past location point sets **178** temporally relative to the current location point set **174**. Using the location point sets within the duration of interest **172***a*, not including the current location point set **174**, the controller **110** calculates a noncausal aggregated point set **182***a*. The noncausal aggregated point set **182***a* is stored as part of a list of noncausal aggregate point sets **180***a* in the storage device **114**. The calculation of the noncausal aggregate location point sets may be repeated for each current location point set **174** in the location point set **170**.

(44) Referring to FIG. **5**, a schematic diagram of an example noncausal registration is shown in accordance with one or more exemplary embodiments. The noncausal registration **154***a* may be representative of the registration step **154** in the method **140**. The controller **110** may register the current location point set **174** with a corresponding noncausal aggregated point set **182***a* from the

list of noncausal aggregate point sets **180***a*. Discrepancies between the current location point set **174** and the corresponding noncausal aggregated point set **182***a* are used to determine a noncausal correction transform matrix **192***a*. The noncausal correction transform matrix **192***a* is stored in a list of noncausal correction transform matrices **190***a*. The registration is repeated with the location point sets in the list of location point sets **170** to populate the correction transform matrices in the list of noncausal correction transform matrices **190***a*.

(45) Referring to FIG. **6**, a schematic diagram of an example noncausal aggregation is shown in accordance with one or more exemplary embodiments. The noncausal aggregation **152***b* may be representative of the aggregation step **152** in the method **140**. The list of location point sets **170** containing recorded location point sets (e.g., past location point sets, a current location point set, and possibly one or more future location point sets) is stored in the storage device **114**. A duration of interest **172***b* before the current location point set **174** is determined by the controller **110**. The duration of interest **172***b* includes multiple past location point sets **178** temporally relative to the current location point set **174**. Using the location point sets within the duration of interest **172***b*, not including the current location point set **174**, the controller **110** calculates a causal aggregate location point set **182***b*. The causal aggregated point set **182***b* is stored as part of a list of causal aggregate point sets **180***b* in the storage device **114**. The calculation of the causal aggregate location point sets may be repeated for the location point sets **174** in the list of location point sets **170**.

(46) Referring to FIG. **7**, a schematic diagram of an example causal registration is shown in accordance with one or more exemplary embodiments. The causal registration **154***b* may be representative of the registration step **154** in the method **140**. The controller **110** may register the current location point set **174** with the corresponding causal aggregated point set **182***b* from a list of causal aggregate point sets **180***b*. Discrepancies between the current location point set **174** and the corresponding causal aggregated point set **182***b* are used to determine a causal current correction transform matrix **192***b*. The registration is repeated for each location point set in the list of location point sets **170** to populate the correction transform matrices in the list of causal correction transform matrices **190***b*.

(47) Referring to FIG. **8**, a flow diagram of an example implementation of the registration step **154** of the method **140** is shown in accordance with one or more exemplary embodiments. The step **154** includes steps **200** to **218**, as illustrated. The sequence of steps is shown as a representative example. Other step orders may be implemented to meet the criteria of a particular application.

(48) Each scan is registered with the aggregated scans, excluding itself. The registration is between each point in the scan to planes in the aggregation. In the step **200**, the controller **110** selects a current scan that defines multiple location points around a current location point of interest. A number of location points are calculated in the step **202** to define a neighborhood around the current location point of interest. In the step **204**, the controller **110** identifies a number of aggregated points that are within the neighborhood. If the number of the aggregated points is lower than a lower threshold number, the neighborhood is removed in the step **206**. For a neighborhood with greater than the lower threshold number of the aggregated points, the controller **110** calculates a normal of the neighborhood in the step **208**. The normal is a vector normal to a best-fit plane through the neighborhood. If the number of the aggregated points in the neighborhood is greater than an upper threshold value, the controller **110** randomly selects some aggregated points for further processing in the step **210**.

(49) In the step **212**, the controller **110** calculates a singular value decomposition (SVD) of the aggregated points in the neighborhood after mean removal to determine a first singular vector, a first singular value, a second singular vector, a second singular value, a third singular vector, and a third singular value. The first singular vector and the second singular vector define the best-fit plane. The third singular vector is normal to the best-fit plane. The controller **110** subsequently filters the neighborhood in the step **214** in response to a ratio of the third singular value to the first

singular value being greater than a ratio threshold value to remove one or more aggregate points. A correction transform matrix (Mopt) is calculated in the step **216** using a least mean squares technique under a low angle correction assumption. The calculation may be provided by equation 2 as follows:

Mopt=A.sup.−1b   (2)

(50) Where A=[n.sub.y.Math.s.sub.x−n.sub.x.Math.s.sub.y,

n.sub.x.Math.s.sub.z−n.sub.z.Math.s.sub.x,

n.sub.z.Math.s.sub.y−n.sub.y.Math.s.sub.z,n.sub.x,n.sub.y,n.sub.z]

(51) b.sub.i=Σ(d.sub.i−s.sub.i).Math.n.sub.i, i∈{x,y,z}

(52) Where s is the scan points, d is the aggregation points and n is the normal.

(53) The dimensions of s, d, and n are 3×N, where the first dimension is composed of (x,y,z) and N is the number of points. The calculation is performed for each scan.

(54) In the step **218**, if more scans are to be considered, the processing returns to the step **200** to select another current scan. Once the scans have been processed, the step **154** continues with the updating step **156** (FIG. **3**).

(55) Referring to FIG. **9**, a schematic diagram of an example of an aggregated point set **182***c* is shown in accordance with one or more exemplary embodiments. The aggregated point set **182***c* is representative of the aggregated points sets in the list of noncausal aggregated point sets **182***a* and the list of causal aggregated point sets **182***b*.

(56) The neighborhood **230** around the current location point **174** is defined as an area within a radius **232** extending from the current location point **174**. Multiple aggregated points **234***a*-**234***h* are scattered around inside and outside the neighborhood **230**. For the purposes of the aggregation, the aggregated points **234***d*-**234***g* within the neighborhood **230** are considered. If the number of the aggregated points **234***d*-**234***g* is less than the lower threshold value, the neighborhood **230** is discarded per the step **206** in FIG. **8**. Otherwise, the aggregated point set **182***a*/**182***b* is generated from the aggregated points **234***d*-**234***g* within each neighborhood **230** around each location point **174**.

(57) Referring to FIG. **10** a schematic diagram of an example of a crowed aggregated point set **182***d* is shown in accordance with one or more exemplary embodiments. The aggregated point set **182***d* is representative of the aggregated points sets in the list of noncausal aggregated point sets **182***a* and the list of causal aggregated point sets **182***b*.

(58) Where the number of the aggregated points within the neighborhood **230** is greater than the upper threshold value, the controller **110** randomly removes some aggregated points **234***a*-**234***n* (e.g., removed aggregated points **236***a*-**236***d*) to bring the total below the upper threshold limit per the step **210** in FIG. **8**. Thereafter, the aggregated point set **182***a*/**182***b* is generated from the aggregated points **234***a*-**234***n* within each neighborhood **230** around each location point **174**.

(59) Referring to FIG. **11**, a schematic diagram of an example best-fit plane **240** is shown in accordance with one or more exemplary embodiments. The best-fit plane **240** defines a plane that is closest to fitting among the aggregated points **234***a*-**234***n*. A first singular vector with a first singular value is illustrated as a vector **242**. A second singular vector with a second singular value is illustrated as a vector **244**. The first singular vector **242** and the second singular vector **244** define the best-fit plane **240**. A third singular vector with a third singular value is illustrated as a vector **246**. The third singular vector **246** is normal to the best-fit plane **240**.

(60) Embodiments of the disclosure may provide a navigation monitor (or system) **100***a* disposed in an ego vehicle **90***a* and configured to provide accurate measurements of the motion of the ego vehicle **90***a* suitable for use as an autonomous vehicle training database. The navigation monitor **100***a* includes a lidar device **102** configured to perform a plurality of scans of an environment **82** proximate the ego vehicle **90***a* to generate a plurality of lidar point clouds related to one or more objects **84** in the environment **82**. The navigation monitor **100***a* includes a controller **110** configured to transform the plurality of lidar point clouds with a plurality of location transform

matrices to generate a plurality of location point sets, aggregate the plurality of location point sets in a duration of interest to generate a plurality of aggregated point sets, register the plurality of location point sets to the plurality of aggregated point sets to generate a plurality of correction transform matrices, update the plurality of location transform matrices with the plurality of correction transform matrices to generate a plurality of updated location transform matrices, and generate a plurality of accurate motion sets based on the plurality of updated location transform matrices. The navigation monitor **100**_a_ includes a circuit **112** configured to receive the plurality of motion sets. The motion sets are stored in a storage device **114** for subsequent consumption as a training dataset by an autonomous driving training system **116**.

(61) All numerical values of parameters (e.g., of quantities or conditions) in this specification, including the appended claims, are to be understood as being modified in all instances by the term "about" whether or not "about" actually appears before the numerical value. "About" indicates that the stated numerical value allows some slight imprecision (with some approach to exactness in the value; about or reasonably close to the value; nearly). If the imprecision provided by "about" is not otherwise understood in the art with this ordinary meaning, then "about" as used herein indicates at least variations that may arise from ordinary methods of measuring and using such parameters. In addition, disclosure of ranges includes disclosure of all values and further divided ranges within the entire range. Each value within a range and the endpoints of a range are hereby all disclosed as separate embodiments.

(62) While the best modes for carrying out the disclosure have been described in detail, those familiar with the art to which this disclosure relates will recognize various alternative designs and embodiments for practicing the disclosure within the scope of the appended claims.

Claims

1. A motion monitor comprising: a lidar device disposed in an ego vehicle and configured to perform a plurality of scans in a sequence over time of an environment proximate the ego vehicle to generate a plurality of lidar point clouds in the sequence related to one or more objects in the environment, wherein the sequence involves two or more scans of the plurality of scans at two or more different times; a controller in communication with the lidar device and configured to transform the plurality of lidar point clouds with a plurality of location transform matrices to generate a plurality of location point sets in the sequence, aggregate the plurality of location point sets in the sequence in a duration of interest that includes the two or more scans at the two or more different times to generate a plurality of aggregated point sets, register the plurality of location point sets to the plurality of aggregated point sets to generate a plurality of correction transform matrices, update the plurality of location transform matrices with the plurality of correction transform matrices to generate a plurality of updated location transform matrices in the sequence, and generate a plurality of motion sets based on the plurality of updated location transform matrices, wherein the registration of the plurality of location point sets includes: identification of a number of aggregated points among the plurality of aggregated point sets that are within a neighborhood proximate each current location point in the plurality of location point sets; removal of the neighborhood in response to the number of the aggregated points being less than a lower threshold number; reduction of the neighborhood to a random sample of the aggregated points within the neighborhood in response to the number of the aggregated points exceeding an upper threshold value; calculation of a singular value decomposition of the aggregated points in the neighborhood to determine a first singular vector, a first singular value, a second singular vector, a third singular vector, and a third singular value, where the first singular vector and the second singular vector define a best-fit plane to the aggregated points, and the third singular vector is normal to the best-fit plane; and filter the neighborhood in response to a ratio of the third singular value to the first singular value being greater than a ratio threshold value; and a circuit in

communication with the controller and configured to receive the plurality of motion sets.

2. The motion monitor according to claim 1, wherein the registration of the plurality of location point sets in the sequence includes a non-causal registration that utilizes one or more future location point sets of the plurality of location point sets in the sequence to noncausally register one or more current location point sets of the plurality of location point sets in the sequence.

3. The motion monitor according to claim 1, wherein the registration of the plurality of location point sets in the sequence is a causal registration that solely utilizes past location point sets of the plurality of location point sets in the sequence to causally register each current location point set of the plurality of location point sets in the sequence.

4. The motion monitor according to claim 1, wherein the generation of the plurality of correction transform matrices is calculated using a least mean squares technique under a low angle correction assumption.

5. The motion monitor according to claim 1, wherein the circuit is a storage device configured to record the plurality of motion sets, and the plurality of motion sets form a training dataset for an autonomous driving training system.

6. The motion monitor according to claim 1, wherein the circuit is a drive system disposed in the ego vehicle, and configured to control movement of the ego vehicle in response to the plurality of motion sets.

7. The motion monitor according to claim 1, further comprising a camera configured to sense the environment proximate the ego vehicle to generate a plurality of images.

8. The motion monitor according to claim 7, wherein the plurality of location transform matrices aligns the plurality of motion sets with the plurality of images.

9. A method for motion estimation of an ego vehicle comprising: scanning an environment proximate the ego vehicle in a plurality of scans in a sequence over time with a lidar device to generate a plurality of lidar point clouds in the sequence related to one or more objects in the environment, wherein the sequence involves two or more scans of the plurality of scans at two or more different times; transforming the plurality of lidar point clouds with a plurality of location transform matrices to generate a plurality of location point sets in the sequence; aggregating the plurality of location point sets in the sequence in a duration of interest that includes the two or more scans at the two or more different times to generate a plurality of aggregated point sets; registering the plurality of location point sets to the plurality of aggregated point sets to generate a plurality of correction transform matrices, wherein the registration of the plurality of location point sets includes: identifying a number of aggregated points among the plurality of aggregated point sets that are within a neighborhood proximate each current location point in the plurality of location point sets; removing the neighborhood in response to the number of the aggregated points being less than a lower threshold number; reducing the neighborhood to a random sample of the aggregated points within the neighborhood in response to the number of the aggregated points exceeding an upper threshold value; calculating a singular value decomposition of the aggregated points in the neighborhood to determine a first singular vector, a first singular value, a second singular vector, a third singular vector, and a third singular value, where the first singular vector and the second singular vector define a best-fit plane to the aggregated points, and the third singular vector is normal to the best-fit plane; and filtering the neighborhood in response to a ratio of the third singular value to the first singular value being greater than a ratio threshold value; updating the plurality of location transform matrices with the plurality of correction transform matrices to generate a plurality of updated location transform matrices in the sequence; generating a plurality of motion sets based on the plurality of updated location transform matrices; and receiving the plurality of motion sets at a circuit.

10. The method according to claim 9, wherein the registering of each one of the plurality of location point sets in the sequence includes a noncausal registering that utilizes one or more future location point sets of the plurality of location point sets in the sequence to noncausally register one

or more current location point sets of the plurality of location point sets in the sequence.

11. The method according to claim 9, wherein the registering of each one of the plurality of location point sets in the sequence includes a causal registering that solely utilizes past location point sets of the plurality of location point sets in the sequence to causally register each current location point set of the plurality of location point sets in the sequence.

12. The method according to claim 9, wherein the generation of the plurality of correction transform matrices is calculated using a least mean squares technique under a low angle correction assumption.

13. The method according to claim 9, wherein the circuit is a storage device configured to record the plurality of motion sets, and the plurality of motion sets form a training dataset for an autonomous driving training system.

14. The method according to claim 9, wherein the circuit is a drive system disposed in the ego vehicle, and configured to control movement of the ego vehicle in response to the plurality of motion sets.

15. An ego vehicle comprising: a lidar device configured to perform a plurality of scans in a sequence over time of an environment proximate the ego vehicle to generate a plurality of lidar point clouds in the sequence related to one or more objects in the environment, wherein the sequence involves two or more scans of the plurality of scans at two or more different times; a controller in communication with the lidar device and configured to transform the plurality of lidar point clouds with a plurality of location transform matrices to generate a plurality of location point sets in the sequence, aggregate the plurality of location point sets in the sequence in a duration of interest that includes the two or more scans at the two or more different times to generate a plurality of aggregated point sets, register the plurality of location point sets to the plurality of aggregated point sets to generate a plurality of correction transform matrices, update the plurality of location transform matrices with the plurality of correction transform matrices to generate a plurality of updated location transform matrices in the sequence, and generate a plurality of motion sets based on the plurality of updated location transform matrices, wherein the registration of the plurality of location point sets includes: identifying a number of aggregated points among the plurality of aggregated point sets that are within a neighborhood proximate each current location point in the plurality of location point sets; removing the neighborhood in response to the number of the aggregated points being less than a lower threshold number; reducing the neighborhood to a random sample of the aggregated points within the neighborhood in response to the number of the aggregated points exceeding an upper threshold value; calculating a singular value decomposition of the aggregated points in the neighborhood to determine a first singular vector, a first singular value, a second singular vector, a third singular vector, and a third singular value, where the first singular vector and the second singular vector define a best-fit plane to the aggregated points, and the third singular vector is normal to the best-fit plane; and filtering the neighborhood in response to a ratio of the third singular value to the first singular value being greater than a ratio threshold value; a circuit in communication with the controller and configured to receive the plurality of motion sets and generate a plurality of commands in response to the plurality of motion sets; and a drive system configured to control movement of the ego vehicle in response to the plurality of commands.

16. The ego vehicle according to claim 15, wherein the registering of the plurality of location point sets in the sequence is a causal registering that solely utilizes past location point sets of the plurality of location point sets in the sequence to causally register each current location point set of the plurality of location point sets in the sequence.

17. The ego vehicle according to claim 15, further comprising a camera configured to sense the environment proximate the ego vehicle to generate a plurality of images.

18. The ego vehicle according to claim 17, wherein the plurality of location transform matrices aligns the plurality of motion sets with the plurality of images.

19. The ego vehicle according to claim 15, wherein the registration of the plurality of location point sets in the sequence includes a non-causal registration that utilizes one or more future location point sets of the plurality of location point sets in the sequence to noncausally register one or more current location point sets of the plurality of location point sets in the sequence.

20. The ego vehicle according to claim 15, wherein the generation of the plurality of correction transform matrices is calculated using a least mean squares technique under a low angle correction assumption.