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Anchoring tracking device space to hand tracking space

Abstract

A computing device receives a notification from a tracking device that the tracking device has entered a gripped state in which a user has securely gripped the tracking device with a hand of the user. The computing device responsively receives orientation data from the tracking device indicative of an orientation of the tracking device in a tracking device space. The computing device determines an orientation of the hand of the user in a hand tracking space from captured image data of the hand of the user and the tracking device. The computing device generates a transformation matrix to anchor the tracking device space to the hand tracking space. The tracking device resultantly enters an anchored state.

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Background/Summary

BACKGROUND

(1) Extended reality (XR) technologies include virtual reality (VR), augmented reality (AR), and mixed reality (MR) technologies, and quite literally extend the reality that users experience. XR technologies may employ head-mountable displays (HMDs). An HMD is a display device that can be worn on the head. In VR technologies, the HMD wearer is immersed in an entirely virtual world, whereas in AR technologies, the HMD wearer's direct or indirect view of the physical, real-world environment is augmented. In MR, or hybrid reality, technologies, the HMD wearer experiences the merging of real and virtual worlds.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIGS. **1**A and **1**B are perspective and block view diagrams, respectively, of an example tracking device that can be used in an extended reality (XR) environment.

(2) FIGS. **2**A and **2**B are diagrams depicting example usage of the tracking device of FIGS. **1**A and **1**B in an XR environment.

(3) FIG. **3** is a block diagram of an example XR system including the tracking device of FIGS. **1**A and **1**B.

(4) FIG. **4** is a state diagram of example states of the tracking device of FIGS. **1**A and **1**B.

(5) FIGS. **5**A, **5**B, **5**C, **5**D, **5**E, and **5**F are diagrams of example processes in which the tracking device of FIGS. **1**A and **1**B transition among the states of FIG. **4**.

(6) FIG. **6** is a flowchart of an example method.

(7) FIG. **7** is a diagram of an example non-transitory computer-readable data storage medium.

DETAILED DESCRIPTION

(8) As noted in the background, a head-mountable display (HMD) can be employed as an extended reality (XR) technology to extend the reality experienced by the HMD's wearer. An HMD can include a small display panel in front of each eye of the wearer, as well as various sensors to detect or sense the wearer and/or the wearer's environment. Images on the display panels convincingly immerse the wearer within an XR environment, be it a virtual reality (VR), augmented reality (AR), a mixed reality (MR), or another type of XR.

(9) The user wearing an HMD may manipulate virtual objects within an XR environment using his or her hands. To increase the verisimilitude of such virtual object manipulation, the user may manipulate an actual real-world physical object standing in and corresponding to a virtual object. The physical object may be a more general-purpose object that is not actually the virtual object to which it corresponds in the XR environment, and may not have an actual physical appearance corresponding to the appearance of the virtual object. The usage of such a physical object can nevertheless enhance the immersive experience of the user within the XR environment.

(10) Existing such physical objects are often relatively complex and sophisticated handheld controllers with a variety of different sensors and other electronics to permit the controllers to track their manipulation in physical space. Such tracking allows for the corresponding virtual object displayed within the XR environment to appropriately mimic and otherwise mirror the user's actual manipulation of the controller. However, due to their complexity, such handheld controllers are relatively expensive, making them cost prohibitive and limiting their usage in some cases.

(11) Described herein is a tracking device that can be used in an XR environment and which can be manufactured more cost effectively than more complex handheld XR controllers. Specifically, usage of the tracking device leverages camera devices that may already be present to track an XR user's hands in physical space to decrease the number of sensors and other electronics included in the tracking device. Once the user has picked up and securely grasped the tracking device, what is referred to as a tracking device space can be anchored to what is referred to as hand tracking space to interrelate the user's manipulation of the tracking device as detected by the device with the user's hand movements as detected by the camera devices.

(12) The tracking device space is the three-dimensional (3D) coordinate system in relation to which the tracking device monitors orientation of the device as the tracking device is manipulated by the user in physical space. The hand tracking space is the 3D coordinate system in relation to which the camera device tracks movement of the user's hands in physical space. Once the user has securely grasped the tracking device and the tracking device space resultantly anchored to the hand tracking space, subsequent pose changes of the tracking device can be mapped to hand tracking space (and subsequent motion of the user's hand that is holding the device can be mapped to tracking device space).

(13) FIGS. **1**A and **1**B show block and perspective-view diagrams, respectively, of an example

tracking device **100**. The tracking device **100** includes an enclosure **102** having a geometric shape corresponding to one or multiple poses at which the device **100** is in a stationary state in which a user is not securely gripping the tracking device **100** with his or her hand(s) and the device **100** is at rest. The geometric shape in particular can limit such poses, or positions, in which the device **100** can remain at rest on a horizontal surface such as a table or desktop. In the example, for instance, the geometric shape of the tracking device **100** is such that the device **100** has flat end surfaces **151**, flat top and bottom surfaces **153**, and round side surfaces **155**.

(14) Therefore, when in the stationary state, the tracking device **100** can rest on just one of four surfaces: either end surface **151** or either top or bottom surface **153**. If the tracking device **100** were put down on either of its side surfaces **155**, the device **100** would topple over and rest on the top or bottom surface **153**. In the example, then, the number of poses or positions in which the tracking device **100** can be in the stationary state is governed by the surfaces **151** and **153** being flat and the surfaces **155** being round. To further reduce the poses in which the tracking device **100** can be in the stationary state, the end surfaces **151** can also be round, such that placing the device **100** on either surface **151** also causes the tracking device **100** to topple over and rest on the top or bottom surface **153**.

(15) The tracking device **100** has fiducial marks **104** on the enclosure **102**. The fiducial marks **104** can be dots or other types of marks that are discernable within captured images of the tracking device **100** relative to the background of the enclosure **102**. The number of the fiducial marks **104**, and their locations on the enclosure **102**, are sufficient to permit calculation of the orientation of the tracking device **100** from such captured images (i.e., captured image data) of the tracking device. The images may be captured by camera devices that are also used to track a user's hands in hand tracking space. Therefore, the fiducial marks **104** within these images can be used to calculate the orientation of the tracking device **100** within hand tracking space as well.

(16) The number and the locations of the fiducial marks **104** on the tracking device **100** are known. Therefore, the orientation of the tracking device **100** in hand tracking space depends on which fiducial marks **104** appear within the captured images, and the pattern and/or positions of the marks **104** relative to one another within the images. Which fiducial marks **104** appear within the images and the pattern and/or positions of the marks **104** relative to one another within the images is itself dependent on the current pose of the tracking device **100** in the stationary state and the position and perspective of the camera device capturing the images. Such known and detected information thus permits calculation of the orientation of the tracking device **100** in hand tracking space.

(17) The number and the locations of the fiducial marks **104** on the tracking device **100** sufficient to permit calculation of the orientation of the device **100** in hand tracking space from captured image data are further dependent on (i.e., take into account) the poses at which the tracking device **100** can be at rest in the stationary state. For instance, the fewer poses or positions at which the tracking device **100** can be in the stationary state, in general the fewer fiducial marks **104** have to be included on the device **100** to permit calculation of the orientation of the tracking device **100** in hand tracking space. This is because the fiducial marks **104** have to account for fewer such at-rest poses of the tracking device **100**. Therefore, the geometric shape of the enclosure **102** limiting the poses of the tracking device **100** serves to simplify the number and locations of the fiducial marks **104** as well.

(18) The number and the locations of the fiducial marks **104** on the tracking device **100** sufficient to permit calculation of the orientation of the device **100** in hand tracking space from captured image data are further dependent on (i.e., take into account) on manufacturing tolerances in manufacturing the tracking device **100**. That is, how accurately the fiducial marks **104** can be imprinted at specified locations on the tracking device **100** can dictate how close together the marks **104** can be, and thus their locations. Similarly, how many fiducial marks **104** should be included may be dictated by how accurately the marks **104** can be imprinted at specified locations on the tracking device **100**.

(19) The tracking device **100** includes a grip sensor **106**, which may be a capacitive touch sensor. The grip sensor **106** is exposed at the enclosure **102** of the tracking device **100**. In the example, the grip sensor **106** is divided over four portions or rings **161** corresponding to the four fingers (not including the thumb) of a hand of the user. The grip sensor **106** can thus detect when the user has securely gripped the tracking device **100** in a gripped state. That the tracking device **100** is in the gripped state, in other words, corresponds to the user having securely gripped the tracking device **100** with the fingers of his or her hand, as detected by the grip sensor **106**.

(20) As one example, the grip sensor **106** may detect a sensor signal at each ring **161** in correspondence with how much of the surface area of the ring **161** is in contact with a corresponding finger of the user's hand. The user may be considered as having securely gripped the tracking device **100** when more than a threshold surface area of each of more than a threshold number of the rings **161** is in contact with a corresponding finger of the user's hand. For example, at least 75% of the surface area of every ring **161** may have to be in contact with a corresponding finger of the user's hand for the user to be considered as securely gripping the tracking device **100** such that the tracking device **100** is in the gripped state.

(21) The tracking device **100** further includes an inertial measurement sensor **108**, which may also be referred to as an inertial measurement unit (IMU). The inertial measurement sensor **108** can be situated within the enclosure **102** of the tracking device **100**. The inertial measurement sensor **108** detects orientation data indicative of the orientation of the tracking device **100** in tracking device space. For instance, when the user is holding the tracking device **100** and moving, rotating, or otherwise manipulating the device **100** in physical space, the inertial measurement sensor **108** can generate orientation data from which the orientation of the tracking device **100** in tracking device space can be calculated.

(22) The tracking device **100** may be unaware of any camera device tracking the user's hand in a separate hand tracking space, and may otherwise have no knowledge of the hand tracking space. This is why the orientation data captured by the inertial measurement sensor **108** is indicative of the orientation of the tracking device **100** in tracking device space as opposed to hand tracking space. The orientation of the tracking device **100** in tracking device space may be used when the tracking device **100** enters a gripped state in which the user has securely gripped the device **100**.

(23) For instance, the orientation of the user's hand grasping the tracking device **100** in hand tracking space may be detected at that time from captured image data, so that a transformation matrix anchoring the tracking device space to the hand tracking space can be resultantly generated. The tracking device **100** is then said to enter an anchored state. Subsequently received orientation data from the tracking device **100** can therefore be transformed from the tracking device to the hand tracking space via application of the transformation matrix.

(24) The orientation of the tracking device **100** in tracking device space may also be used when the device **100** enters an ungripped state, in which the user is no longer securely gripping the tracking device **100** in his or her hand. In this state, the tracking device **100** may be in motion. For instance, the user may have dropped the tracking device **100**, or the user may still be holding the device **100** but the tracking device **100** may have slipped in the user's hand or the user may be manipulating the device **100** in such a way that he or she is not firmly gripping the grip sensor **106** of the tracking device **100**.

(25) The inertial measurement sensor **108** may be or include magnetometer, compass, accelerometer, and/or gyroscope sensors, among other types of sensors. The inertial measurement sensor **108** may be a six degree-of-freedom ("6DOF") sensor providing measurement signals corresponding to forward/backward (surge), up/down (heave), and left/right (sway) translational motion, as well as pitch, yaw, and roll rotational motion. the inertial measurement sensor **108** may be a nine degree-of-freedom ("9DOF") sensor that also provides measurement signals corresponding to acceleration, magnetic orientation, and angular velocity. In another implementation, the inertial measurement sensor **108** may just be a three degree-of-freedom

("3DOF") sensor providing measurement signals corresponding to pitch, yaw, and roll rotational measurement.

(26) The tracking device **100** includes a transceiver **110** by which the device **100** can send and receive information. For example, when the grip sensor **106** has detected that the tracking device **100** has entered a gripped state or an ungripped (and in motion) state, the transceiver **110** may transmit a corresponding notification to a computing device to which the tracking device **100** is communicatively connected. The transceiver **110** may also transmit a notification when the inertial measurement sensor **108** has detected that the tracking device **100** has entered a stationary (and ungripped) state, and can transmit orientation data captured by the sensor **108** responsive to entry of the device **100** in various states. The transceiver **110** may further receive a notification from a computing device that the tracking device **100** has entered an anchored state in which the tracking device space has been anchored to the hand tracking space as a result of the computing device generating a transformation matrix.

(27) FIGS. **2**A and **2**B show example usage of the tracking device **100** in an XR environment. A user **200** is wearing an HMD **202**. For example, the HMD **202** may include a display device to project images viewable by the user to immerse the user **200** in the XR environment. The HMD **202** may also include sensors, such as eye-tracking sensors to track the focus of the user **200**'s gaze, sensors to track rotation and movement of the user **200**'s head, and so on. Per the side view of FIG. **2**A, the XR environment can include a camera device **204**. The camera device **204** captures images of the space in front of the user, including the tracking device **100** and, per FIG. **2**B, the user's hand **201**. The camera device **204** may be part of the HMD **202** instead of separate from the HMD **202** as depicted.

(28) In FIG. **2**A, the user **200** is not holding the tracking device **100**, and instead the device **100** is at rest on a horizontal surface in front of the user **200**. From images captured by the camera device **204**, the orientation of the tracking device **100** in hand tracking space can be determined, based on the number and positions of the fiducial marks **104** within the captured images as has been described. This 3D coordinate system is the coordinate system in which orientations of objects appearing in images captured by the camera device **204** can be detected. This space is referred to as hand tracking space, however, in that it was originally intended to track the hands of the user **200** (such as the hand **201** in FIG. **2**B), but is leveraged herein to also determine the orientation of the tracking device **100** when in the stationary state.

(29) In FIG. **2**B, the user **200** has picked up and is securely grasping the tracking device **100** in the gripped state. The orientation of the hand **201** in which the user **200** is holding the tracking device **100** can be determined in hand tracking space from images captured by the camera device **204**. Furthermore, the orientation of the tracking device **100** can be determined in tracking device space from orientation data captured by the inertial measurement sensor **108** of the device **100**. The tracking device space is the 3D coordinate system of the inertial measurement sensor **108**.

(30) Because the user **200** is securely gripping the tracking device **100** in FIG. **2**B, as the user **200** rotates or moves his or her hand **201**, the tracking device **100** correspondingly rotates or moves. That is, the tracking device **100** cannot rotate or move without a corresponding rotation or movement of the user's hand **201**. For example, if the user **200** rotates his or her hand **201** twenty degrees clockwise, the tracking device **100** also rotates twenty degrees clockwise, and does not differently rotate, because the tracking device **100** is being securely grasped by the user **200**. Similarly, if the user **200**'s hand **201** moves four inches to the left, the tracking device **100** also moves four inches to the left, and so on.

(31) Therefore, when the tracking device **100** is in the gripped state in which the user **200** is securely gripping the device **100**, as detected by the grip sensor **106** of the tracking device **100**, tracking device space can be anchored to hand tracking space, with the device **100** resultantly entering an anchored state. That is, at the time when the tracking device **100** enters the gripped state, the device **100** has an orientation in tracking device space as indicated by the orientation data

that the inertial measurement sensor **108** captures. At this same time, the user **200**'s hand **201** has a corresponding orientation in hand tracking space as can be determined from the images that the camera device **204** captures.

(32) A transformation matrix can thus be calculated that transforms tracking device space to hand tracking space, from the corresponding orientations of the tracking device **100** and the hand **201** of the user **200**. Any subsequent change in orientation of the tracking device **100** (as indicated by the orientation data captured by the inertial measurement sensor **108**) can be transformed from the tracking device space to the hand tracking space by applying (e.g., multiplying) the transformation matrix. Similarly, any subsequent change in orientation of the user **200**'s hand **201** (as determined from images captured by the camera device **204**) can be transformed from the hand tracking space to the tracking device space by applying (e.g., multiplying) an inverse of the transformation matrix.

(33) The transformation matrix, in other words, links or anchors tracking device space to hand tracking space (and vice-versa). The transformation matrix therefore permits changes in orientation of the tracking device **100** as detected by the device **100** itself to be mapped to hand tracking space, and likewise permits changes in orientation of the hand **201** of the user **200** as detected from images captured by the camera device **204** to be mapped to tracking device space. The linking or anchoring of the two spaces by the transformation matrix remains in effect so long as the tracking device **100** remains in its (currently) anchored state. Once the user **200** lets go of or is no longer securely gripping the tracking device **100**, tracking device space becomes unanchored and unlinked from hand tracking space, with the device **100** resultantly exiting the anchored state.

(34) FIG. **3** shows an example XR system **300** including the tracking device **100**. The XR system **300** also includes the camera device **204** that has been described, as well a computing device **302** and a display device **304**. The computing device **302** may be a desktop, laptop, or notebook computer, or another type of computing device, such as a smartphone, tablet computing device, and so on. The display device **304** displays images to immerse the user **200** in an XR environment, and may be part of the HMD **202** worn by the user **200**.

(35) In the system **300**, the computing device **302** is communicatively connected to the tracking device **100**, the camera device **204**, and the display device **304**. The computing device **302** can thus receive orientation data from the tracking device **100** that is indicative of the orientation of the device **100** in tracking device space, and from which the computing device **302** can calculate the orientation of the tracking device **100** in tracking device space. The computing device **302** can further receive images captured by the camera device **204** from which the device **302** can calculate the orientation of the hand **201** of the user **200** in hand tracking space. Therefore, when the tracking device **100** has entered the gripped state, the computing device **302** can anchor the tracking device space to the hand tracking space via generation of a transformation matrix to cause the tracking device **100** to enter the anchored state.

(36) The computing device **302** can then correspondingly adjust or modify the XR environment in which the user **200** is participating. Specifically, the computing device **302** can cause the display device **304** to display images based on the orientations of the user **200**'s hand **201** and the tracking device **100** as transformed into a common 3D coordinate system (i.e., either the hand tracking space or the tracking device space). As one example, in a VR or AR environment, the virtual object to which the tracking device **100** corresponds can be correctly displayed in orientation relative to the user **200**'s hand **201** because the tracking device space has been anchored to the hand tracking space.

(37) FIG. **4** shows a state diagram of the example states of the tracking device **100**. The tracking device **100** may specifically have four states: a stationary state **402**, a gripped state **404**, an anchored state **406**, and an ungripped state **408**. In the stationary state **402**, the tracking device **100** is at rest in a given pose or position in which the device **100** is lying on a surface such as a table or desktop. In the stationary state **402**, the tracking device **100** is not being securely gripped by the user **200**, and indeed the user **200** may not be in contact with the device **100** at all. The stationary

state **402** is a non-transitory state, in that the tracking device **100** can remain indefinitely in the stationary state **402** and not immediately transition to another state.

(38) From the stationary state **402**, the tracking device **100** may transition to the gripped state **404** or to the ungripped state **408**. In the gripped state **404**, the user has securely grasped or gripped the tracking device **100**, as detected by the inertial measurement sensor **108** of the device **100**. The tracking device **100** may or may not be in motion. For example, the user **200** may securely pick up the tracking device **100**, or may securely grip the device **100** while it remains stationary. The gripped state **404** is a transitory state, however, in that the tracking device **100** does not remain in the gripped state **404** indefinitely but rather transitions to the anchored state **406** once the tracking device space has been anchored to the hand tracking space.

(39) From the gripped state **404**, the tracking device **100** therefore transitions to the anchored state **406** in which tracking device space is anchored to hand tracking space. From a physical perspective, there may be no difference between the gripped state **404** and the anchored state **406**: in each, the tracking device **100** is securely gripped by the user **200**. The tracking device **100** transitions from the gripped state **404** to the anchored state **406** once the tracking device space has been anchored to the hand tracking space—i.e., once the transformation matrix has been generated. The anchored state **406** is a non-transitory state, and the tracking device **100** can remain in the anchored state **406** so long as the user **200** continues to securely grip the device **100** with his or her hand **201** without slippage.

(40) From the anchored state **406**, the tracking device **100** can transition back to the stationary state **402**, or to the ungripped state **408**. If the user **200** puts the tracking device **100** down in a pose in which the device **100** can remain stationary and at rest when the user **200** lets go of the tracking device **100** with his or her hand **201**, the device **100** transitions to the stationary state **402**. However, if the user **200** instead puts the tracking device **100** down in an unstable position in which the device **100** then topples over to a stable position when the user **200** lets go of the tracking device **100**, the device **100** transitions to the ungripped state **408**.

(41) The tracking device **100** also transitions from the anchored state **406** to the ungripped state **408** if the device **100** slips in the user **200**'s hand **201**, or is otherwise manipulated by the user **200** such that it is no longer being securely gripped as detected by the grip sensor **106** of the tracking device **100**. The tracking device **100** further transitions from the anchored state **406** to the ungripped state **408** if the user **200** simply lets go of or throws the device **100** in space, allowing the tracking device **100** to freefall or otherwise move. Similarly, the tracking device **100** transitions from the stationary state **402** to the ungripped state **408** if the user **200** knocks over the device **100** while it is at rest, without first securely gripping the tracking device **100**.

(42) In the ungripped state **408**, therefore, the tracking device **100** is in motion. The ungripped state **408** is a transitory state, in that the tracking device **100** cannot remain in the ungripped state **408** indefinitely. Rather, from the ungripped state **408** the tracking device **100** will soon (or at least eventually) transition to the gripped state **404** or the stationary state **402**. The tracking device **100** transitions from the ungripped state **408** to the gripped state **404** if the user **200** securely grips the device **100**, and transitions to the stationary state **402** if the tracking device **100** instead stops moving and is not securely grasped by the user **200**.

(43) FIG. **5**A shows an example process **500** by which the tracking device **100** transitions from the stationary state **402** through the gripped state **404** to the anchored state **406**. The parts of the process **500** in the left column are performed by the tracking device **100**, the parts in the middle column are performed by the computing device **302**, and the parts in the right column are performed by the camera device **204**. The camera device **204** continually captures and sends images to the computing device (**502**), which receives the captured images (**504**). The images are of the area in front of the user **200**, and may include either hand **201** of the user **200**, and/or the tracking device **100**.

(44) From the stationary state **402**, the tracking device **100** transitions to the gripped state **404** in

which the user **200** has securely gripped the device **100** with his or her hand **201**. The grip sensor **106** of the tracking device **100** detects entry of the device **100** into the gripped state **404** (**506**), and the transceiver **110** of the tracking device **100** responsively sends a notification to the computing device **302** that the device **100** has entered the gripped state **404** (**508**). The computing device **302** receives this notification (**510**), and therefore the devices **100** and **302** are in sync as to the current state of the device **100**.

(45) Responsive to entry of the tracking device **100** entering the gripped state **404**, the transceiver **110** also starts sending to the computing device **302** orientation data that is indicative of the orientation of the device **100** in the tracking device space as captured by the inertial movement sensor **108** (**512**). The computing device **302** thus receives the orientation data (**514**). The computing device **302** then determines, or calculates, the orientation of the hand **201** of the user **200** in which the tracking device **100** is securely gripped, in hand tracking space, from the images captured by the camera device **204** (**516**). The computing device **302** also determines, or calculates, the orientation of the tracking device **100** in tracking device space from the orientation data received from the device **100** (**518**).

(46) The calculated orientation of the user **200**'s hand **201** in hand tracking space corresponds to the calculated orientation of the tracking device **100** in tracking device space, since the user **200** is securely gripping the device **100** in his or her hand **201**. Therefore, the computing device **302** generates a transformation matrix that anchors the tracking device space to the hand tracking space based on these orientations (**520**). The transformation matrix specifically maps the orientation of the tracking device **100** in tracking device space to the orientation of the user **200**'s hand **201** in hand tracking space to map the tracking device space to the hand tracking space. For example, singular value decomposition (SVD) can be used to map the orientation of the tracking device **100** to the orientation of the user **200**'s hand **201** to anchor the tracking device space to the hand tracking space.

(47) As a result of generation of the transformation matrix, the tracking device **100** is considered to have entered the anchored state **406**. That is, in the anchored state the tracking device space is anchored to the hand tracking space. Therefore, since generation of the transformation matrix anchors the tracking device space to the hand tracking space, such generation causes the tracking device **100** to enter the anchored state **406**. Unlike entry of the tracking device **100** into the gripped state **404**, the ungripped state **408**, and the stationary state **402**, which the device **100** may itself detect, the computing device **302** causes (and thus in effect detects) entry of the tracking device **100** into the anchored state **406**.

(48) The computing device **302** sends a notification to the tracking device **100** that the device **100** has entered the anchored state **406** (**522**). The transceiver **110** of the tracking device **100** receives this notification (**524**), so that both the device **100** and the computing device **302** are in sync with respect to the current state of the tracking device **100**. While in the anchored state **406**, the transceiver **110** continues to send orientation data indicative of the orientation of the tracking device **100** in tracking device space, as captured by the inertial measurement sensor **108** (**526**), which the computing device **302** receives (**528**).

(49) As the computing device **302** receives orientation data from the tracking device **100** that is indicative of the device **100**'s orientation in tracking device space, the device **302** can apply (e.g., multiply) the previously generated transformation matrix to the orientation data to transform the tracking device **100**'s orientation from the tracking device space to the hand tracking space (**530**). The computing device **302** may then perform an action based on the orientation of the tracking device **100** as has been transformed into hand tracking space (**532**). As has been noted, for instance, the images displayed by the display device **304** may be adjusted or modified in correspondence with the transformed orientation of the tracking device **100**. For example, a virtual object corresponding to the tracking device **100** may have its orientation modified in the displayed images in correspondence with the transformed orientation of the device **100**.

(50) The transformation matrix that is generated in part **520** and is applied to orientation data indicative of the orientation of the tracking device **100** in tracking device space is specific to the current entry of the device **100** into the anchored state **406**. That is, when the tracking device **100** transitions from the anchored state **406** to a different state (e.g., the stationary state **402** or the ungripped state **408**), the generated transformation matrix is not valid if the device **100** subsequently reenters the anchored state **406**. Rather, each time the tracking device **100** enters the anchored state **406**, the transformation matrix has to be recalculated. This is because the orientation of the tracking device **100** vis-à-vis the orientation of the user **200**'s hand **201** can differ each time the user **200** securely grips the device **100** and causes the tracking device **100** to enter the gripped state **404**.

(51) FIG. **5**B shows an example process **540** by which the tracking device **100** transitions from the anchored state **406** to the ungripped state **408**. The parts of the process **540** in the left column are performed by the tracking device **100**, and the parts in the right column are performed by the computing device **302**. From the anchored state **406**, the tracking device **100** transitions to the ungripped state **408** in which the user **200** is no longer securely gripping the device **100** and the tracking device **100** is in motion. For example, the user may no longer be holding the tracking device **100** at all, or may still be holding the device **100** but not be securely gripping the tracking device **100**.

(52) The grip sensor **106** of the tracking device **100** detects entry of the device **100** into the ungripped state **408** (**542**), and the transceiver **110** of the tracking device **100** responsively sends a notification to the computing device **302** that the device **100** has entered the ungripped state **408** (**542**), which the computing device **302** correspondingly receives (**546**). The devices **100** and **302** are therefore in sync as to the current state of the tracking device **100**. The transceiver **110** may continue sending to the computing device **302** orientation data indicative of the tracking device's **100** orientation in tracking device space as captured by the inertial measurement sensor **108** (**548**). The computing device **302** thus may continue receiving this orientation data (**550**).

(53) Because the tracking device **100** is no longer in the anchored state **406**, the tracking device space is no longer anchored to the hand tracking space. Therefore, the previously generated transformation matrix can no longer be applied to the orientation data to transform the orientation of the tracking device **100** from tracking device space to hand tracking space. As noted, though, the tracking device **100** may still continue sending this orientation data to the computing device **302**, such as in an implementation in which the computing device **302** (as opposed to the tracking device **100**) detects transition of the device **100** from the ungripped state **408** to the stationary state **402**. For example, when the orientation data received from the tracking device **100** indicates that the orientation of the device **100** has stabilized, the computing device **302** can conclude and thus detect that the tracking device **100** is at rest and therefore has entered the stationary state **402**.

(54) FIG. **5**C shows an example process **560** by which the tracking device **100** transitions from the ungripped state **408** back to the stationary state **402**. The parts of the process **560** in the left column are performed by the tracking device **100**, and the parts in the right column are performed by the computing device **302**. From the ungripped state **408** in which the user **200** is not securely gripping the tracking device **100** and the device **100** is in motion, the tracking device **100** transitions to the stationary state **402** at which the device **100** is no longer in motion and thus at rest.

(55) In the example, the inertial measurement sensor **108** of the tracking device **100** detects entry of the device **100** into the stationary state **402** (**562**), such as by the sensor **108** determining that the orientation data indicative of the orientation of the tracking device **100** in tracking device space has stabilized. The transceiver **110** of the tracking device **100** correspondingly sends a notification to the computing device **302** that the device **100** has entered the stationary state **402** (**564**), which the device **302** receives (**568**). However, in another implementation, the computing device **302** may instead detect entry of the tracking device **100** into the stationary state **402**, as has been described, in which case the computing device **302** sends a notification to the tracking device **100**, which the

transceiver **110** receives. In either case, the devices **100** and **302** are in sync as to the current state of the tracking device **100**.

(56) Upon detection of entry of the tracking device **100** in the stationary state **402**, the transceiver **110** stops sending orientation data indicative of the orientation of the device **100** in tracking device space to the computing device **302** (**566**). The inertial measurement sensor **108** may similarly stop capturing the orientation data, or it may continue capturing the data with the transceiver **110** just not sending the captured data. In either case, the computing device **302** no longer receives orientation data from the tracking device **100** indicative of the device **100**'s orientation in tracking device space (**570**).

(57) Upon detection of entry of the tracking device **100** in the stationary state **402**, the computing device **302** also determines the orientation of the tracking device **100** in hand tracking space from the images captured by the camera device **204** (**572**). Specifically, the computing device **302** can identify which fiducial marks **104** of the tracking device **100** appear in the captured images (**574**), and calculate the orientation of the tracking device **100** based on which of the fiducial marks **104** have been identified and based on known information regarding the locations of these marks **104** on the device **100** (**576**). For example, the positions of the identified fiducial marks **104** relative to one another, the pattern of these marks **104**, and so on, within the captured images can be compared to their known positions relative to one another on the tracking device **100** and/or to their known pattern on the device **100** to calculate the orientation of the tracking device **100** in hand tracking space.

(58) The orientation of the tracking device **100** is calculated in hand tracking space, as opposed to tracking device space, because the orientation is calculated from images captured by the camera device **204** and not from orientation data captured by the inertial measurement sensor **108** of the device **100**. That is, whereas the orientation data captured by the tracking device **100** is indicative of the orientation of the device **100** in tracking device space, the images captured by the camera device **204** are indicative of orientation in hand tracking space. The same camera device **204** used to track and thus determine the orientation of the user **200**'s hand **201** in hand tracking space is therefore leveraged to track and determine the orientation of the tracking device **100** when the device **100** has entered the stationary state **402**.

(59) FIG. **5D** shows an example process **580** by which the tracking device **100** transitions from the ungripped state **408** to the gripped state **404**. The process **580** is performed by the tracking device **100**. From the ungripped state **408** in which the user **200** is not securely gripping the tracking device **100** but the device **100** is in motion, the tracking device **100** transitions to the gripped state **404** in which the user **200** is securely gripping the device **100** in his or her hand **201**. The grip sensor **106** of the tracking device **100** detects entry of the device **100** into the gripped state **404** (**582**). The process **580** then continues at part **508** of FIG. **5A**, such that the tracking device **100** ultimately reenters the anchored state **406** (i.e., with the computing device **302** redetermining both the orientation of the user **200**'s hand **201** and the orientation of the tracking device **100**, and reanchoring tracking device space to hand tracking space by regenerating the transformation matrix).

(60) FIG. **5E** shows an example process **586** by which the tracking device **100** transitions from the stationary state **402** to the ungripped state **408**. The process **586** is performed by the tracking device **100**. From the stationary state **402** in which the tracking device **100** is at rest, the device **100** transitions to the ungripped state **408** in which the tracking device **100** is in motion but is either not gripped by the user **200** or if gripped is insecurely gripped by the user **200**.

(61) In the example, the inertial measurement sensor **108** of the tracking device **100** may detect entry into the ungripped state **408** from the stationary state **402** (**588**). For example, the inertial measurement sensor **108** may detect that the tracking device **100** is no longer stationary, with the grip sensor **106** detecting that the device **100** is not securely gripped by the user **200**. The process **586** then continues at part **544** of FIG. **5B**, with transmission of a corresponding notification to the

computing device **302**.

(62) In another implementation, however, the computing device **302** may detect transition of the tracking device **100** from the stationary state **402** to the ungripped state **408** if the device **302** is still receiving orientation data from the device **100** indicative of the tracking device **100**'s orientation. That is, the computing device **302**, instead of the tracking device **100**, may detect that the captured orientation data indicates that the device **100**'s orientation is no longer stable and is changing over time. In this case, the computing device **302** may send a corresponding notification to the tracking device **100**.

(63) FIG. **5F** shows an example process **592** by which the tracking device **100** transitions from the anchored state **406** to the stationary state **402**. The process **592** is performed by the tracking device **100**. From the anchored state **406** in which the user **200** is securely gripping the tracking device **100** and in which the tracking device space has been anchored to the hand tracking space, the device **100** transitions to the stationary state **402** in which the user **200** is either not gripping the tracking device **100** or is not securely gripping the device **100**, and the tracking device **100** is at rest.

(64) In the example, the tracking device **100** detects entry of the tracking device **100** into the stationary state **402** from the anchored state **406** (**594**). For instance, the inertial measurement sensor **108** of the tracking device **100** can detect that the device **100** is not in motion and the grip sensor **106** of the tracking device **100** can detect that the user **200** is either not gripping the device **100** at all or is not securely gripping the device **100**. The process **592** then continues at part **564** of FIG. **5C**, with transmission of a corresponding notification to the computing device **302**.

(65) In another implementation, however, the computing device **302** may detect transition of the tracking device **100** from the anchored state **406** to the stationary state **402**. While the tracking device **100** is in the anchored state **406**, the computing device **302** receives orientation data captured by the inertial measurement sensor **108** of the device **100**. The computing device **302** can therefore detect from this captured orientation data that the tracking device **100** is at rest. If the computing device **302** also receives a notification that the user **200** is no longer securely gripping the tracking device **100**, as detected by the grip sensor **106** of the device **100**, the computing device **302** can conclude that the tracking device **100** has entered the anchored state. In this case, the computing device **302** may send a corresponding notification to the tracking device **100**.

(66) FIG. **6** shows an example method **600**. The method **600** includes receiving, by a computing device **302** from a tracking device **100**, a notification that the tracking device has entered a gripped state **404** in which a user has securely gripped the tracking device with a hand **201** of the user **200** (**602**). The method **600** includes responsively receiving, by the computing device **302** from the tracking device **100**, orientation data indicative of an orientation of the tracking device **100** in a tracking device space (**604**).

(67) The method **600** includes determining, by the computing device **302**, an orientation of the hand **201** of the user **200** in a hand tracking space from captured image data of the hand of the user and the tracking device **100** (**606**). The method **600** includes generating, by the computing device **302**, a transformation matrix to anchor the tracking device space to the hand tracking space (**608**). The tracking device therefore resultantly enters an anchored state **406**.

(68) FIG. **7** shows an example non-transitory computer-readable data storage medium **700** storing program code **702** executable by a tracking device **100** to perform processing. The processing includes detecting, using a grip sensor **106** of the tracking device **100**, that the tracking device **100** has entered a gripped state **404** in which a user **200** has securely gripped the tracking device **100** with a hand **201** of the user **200** (**704**). The processing includes responsively sending to a computing device **302** a notification that the tracking device **100** has entered the gripped state **404** (**706**), and orientation data captured by an inertial measurement sensor **108** of the tracking device **100** and indicative of an orientation of the tracking device **100** in a tracking device space (**708**). The processing includes receiving from the computing device **302** a notification that the tracking

device **100** has entered an anchored state **406** in which the tracking device space has been anchored to a hand tracking space of the hand **201** of the user **200** (**710**).

(69) Techniques have been described for anchoring tracking device space to hand tracking space. A tracking device is employed that can detect when a user has securely gripped the device and that can capture orientation data indicative of the device's orientation in tracking device space. Upon the tracking device detecting that it has entered a gripped state, a computing device determines the orientation of the user's hand in which the tracking device has been securely gripped, in hand tracking space, from captured images. The computing device determines the orientation of the tracking device in tracking device space from the captured orientation data, and generates a transformation matrix mapping the determined orientation of the tracking device to the determined orientation of the user's hand to anchor tracking device space to hand tracking space. The techniques thus leverage the images already being captured by a camera device for hand tracking, and as a result the tracking device can be more cost effectively produced since it may include just a grip sensor, an inertial measurement sensor, and a transceiver in terms of the tracking device's primary if not only electronics.

Claims

1. A method comprising: receiving, by a computing device from a tracking device, a notification that the tracking device has entered a gripped state in which a user has securely gripped the tracking device with a hand of the user; responsive to receiving the notification that the tracking device has entered the gripped state: receiving, by the computing device from the tracking device, orientation data indicative of an orientation of the tracking device in a tracking device space; determining, by the computing device, an orientation of the hand of the user in a hand tracking space from captured image data of the hand of the user and the tracking device; generating, by the computing device, a transformation matrix to anchor the tracking device space to the hand tracking space, the tracking device resultantly entering an anchored state; receiving, by the computing device from the tracking device, a notification that the tracking device has entered, from the anchored state, a stationary state in which the user is not securely gripping the tracking device with the hand of the user and the tracking device is at rest, the computing device no longer receiving from the tracking device the orientation data indicative of the orientation of the tracking device in the tracking device space; and determining, by the computing device, the orientation of the tracking device in the hand tracking space from the captured image data without using the transformation matrix.

2. The method of claim 1, further comprising, while the tracking device remains in the anchored state: continuing to receive, by the computing device from the tracking device, the orientation data indicative of the orientation of the tracking device in the tracking device space; applying, by the computing device, the transformation matrix to the orientation data to transform the orientation of the tracking device into the hand tracking space; and performing, by the computing device, an action based on the orientation of the tracking device as transformed into the hand tracking space.

3. The method of claim 1, further comprising: receiving, by the computing device from the tracking device, a notification that the tracking device has entered, from the anchored state, an ungripped state in which the user is not securely gripping the tracking device with the hand of the user and the tracking device is in motion; and responsive to receiving the notification that the tracking device has entered, from the anchored state, the ungripped state: continuing to receive, by the computing device from the tracking device, the orientation data indicative of the orientation of the tracking device in the tracking device space.

4. The method of claim 3, wherein determining the orientation of the tracking device in the hand tracking space from the captured image data comprises: identifying fiducial marks on the tracking device within the captured image data; and calculating the orientation of the tracking device in the

hand tracking space based on the identified fiducial marks and known information regarding locations of the fiducial marks on the tracking device.

5. The method of claim 3, further comprising: receiving, by the computing device from the tracking device, a notification that the tracking device has entered, from the ungripped state, the gripped state; responsive to receiving the notification that the tracking device has entered, from the ungripped state, the gripped state: continuing to receive, by the computing device from the tracking device, the orientation data indicative of the orientation of the tracking device in the tracking device space; redetermining, by the computing device, the orientation of the hand of the user in the hand tracking space from the captured image data; and regenerating, by the computing device, the transformation matrix to reanchor the tracking device space to the hand tracking space, the tracking device resultantly reentering the anchored state.

6. The method of claim 1, further comprising: sending, by the computing device to the hand tracking device, a notification that the tracking device has entered the anchored state; and continuously receiving, by the computing device from a camera device, the captured image data of the hand of the user and the tracking device.

7. The method of claim 1, further comprising, by the computing device, modifying an extended reality (XR) environment in which the user is participating based on the orientation of the hand of the user and the orientation of the tracking device in either the hand tracking space or the tracking device space.

8. A non-transitory computer-readable data storage medium storing program code executable by a tracking device to perform processing comprising: detecting, using a grip sensor of the tracking device, that the tracking device has entered a gripped state in which a user has securely gripped the tracking device with a hand of the user; responsive to detecting that the tracking device has entered the gripped state: sending to a computing device a notification that the tracking device has entered the gripped state; responsive to sending to the computing device the notification: starting to send to the computing device orientation data captured by an inertial measurement sensor of the tracking device and indicative of an orientation of the tracking device in a tracking device space; and receiving from the computing device a notification that the tracking device has entered an anchored state in which the tracking device space has been anchored to a hand tracking space of the hand of the user.

9. The non-transitory computer-readable data storage medium of claim 8, wherein the processing further comprises: detecting, using the grip sensor, that the tracking device has entered, from the anchored state, an ungripped state in which the user is not securely gripping the tracking device with the hand of the user and the tracking device is in motion; responsive to detecting that the tracking device has entered, from the anchored state, the ungripped state: sending to the computing device a notification that the tracking device has entered, from the anchored state, the ungripped state; continuing to send to the computing device the orientation data captured by the inertial measurement sensor of the tracking device and indicative of the orientation of the tracking device in the tracking device space; detecting, using the inertial measurement sensor, that the tracking device has entered, from the ungripped state, a stationary state in which the user is not securely gripping the tracking device with the hand of the user and the tracking device is at rest; responsive to detecting that the tracking device has entered, from the ungripped state, the stationary state: sending to the computing device a notification that the tracking device has entered the stationary state; and no longer sending to the computing device any orientation data captured by the inertial measurement sensor and indicative of the orientation of the tracking device in the tracking device space.

10. The non-transitory computer-readable data storage medium of claim 8, wherein the processing further comprises: detecting, using the grip sensor, that the tracking device has entered, from the anchored state, an ungripped state in which the user is not securely gripping the tracking device with the hand of the user and the tracking device is in motion; responsive to detecting that the

tracking device has entered, from the anchored state, the ungripped state: sending to the computing device a notification that the tracking device has entered, from the anchored state, the ungripped state; continuing to send to the computing device the orientation data captured by the inertial measurement sensor of the tracking device and indicative of the orientation of the tracking device in the tracking device space; detecting, using the grip sensor, that the tracking device has entered, from the ungripped state, the gripped state; responsive to detecting that the tracking device has entered, from the ungripped state, the gripped state: sending to the computing device a notification that the tracking device has entered, from the ungripped state, the gripped state; continuing to send to the computing device the orientation data captured by the inertial measurement sensor of the tracking device and indicative of the orientation of the tracking device in the tracking device space; and receiving from the computing device a notification that the tracking device has reentered the anchored state.

11. The non-transitory computer-readable data storage medium of claim 8, wherein the processing further comprises: detecting, using the grip sensor and the inertial measurement sensor, that the tracking device has entered, from the anchored state, a stationary state in which the user is not securely gripping the tracking device with the hand of the user and the tracking device is at rest; responsive to detecting that the tracking device has entered, from the anchored state, the stationary state: sending to the computing device a notification that the tracking device has entered, from the anchored state, the stationary state; and no longer sending to the computing device any orientation data captured by the inertial measurement sensor and indicative of the orientation of the tracking device in the tracking device space.

12. A tracking device comprising: an enclosure having a geometric shape corresponding to one or multiple poses at which the tracking device is in a stationary state in which a user is not securely gripping the tracking device with a hand of the user and the tracking device is at rest; a plurality of fiducial marks on the enclosure, a number of the fiducial marks and locations of the fiducial marks on the enclosure sufficient to permit calculation of an orientation of the tracking device in a hand tracking space from captured image data of the tracking device, taking into account the poses to which the geometric shape of the enclosure corresponds at which the tracking device is in the stationary state; a grip sensor exposed at the enclosure to detect secure gripping of the tracking device such that the tracking device is in a gripped state; and a transceiver to, responsive to the grip sensor detecting that the tracking device is in the gripped state: send a notification that the tracking device has entered the gripped state, and start sending orientation data indicative of an orientation of the tracking device in a tracking device space.

13. The tracking device of claim 12, further comprising: an inertial measurement sensor within the enclosure to detect the orientation data indicative of the orientation of the tracking device in the tracking device space while the tracking device is in the gripped state or is in an ungripped state in which the user is not securely gripping the tracking device with the hand of the user and the tracking device is in motion.

14. The tracking device of claim 12, wherein the transceiver is to send a notification that the tracking device is in the stationary state, the gripped state, or the ungripped state, to send the orientation data, and to receive a notification that the tracking device is in an anchored state in which the tracking device space has been anchored to a hand tracking space of the hand of the user.

15. The tracking device of claim 12, wherein the transceiver is to: send a notification that the tracking device has entered, from an anchored state in which the tracking device space has been anchored to a hand tracking space of the hand of the user, an ungripped state in which the user is not securely gripping the tracking device with the hand of the user and the tracking device is in motion; and responsive to sending the notification that the tracking device has entered, from the anchored state, the ungripped state: continue to send the orientation data indicative of the orientation of the tracking device in the tracking device space.

16. The tracking device of claim 15, wherein: the grip sensor is to detect that the tracking device

has entered, from the ungripped state, a stationary state in which the user is not securely gripping the tracking device with the hand of the user and the tracking device is at rest, and the transceiver is to, in response to the grip sensor detecting that the tracking device has entered, from the ungripped state, the stationary state: stop sending the orientation data indicative of the orientation of the tracking device in the tracking device space.

17. The tracking device of claim 15, wherein: the grip sensor is to detect that the tracking device has entered, from the ungripped state, the gripped state, and the transceiver is to, in response to the grip sensor detecting that the tracking device has entered, from the ungripped state, the gripped state: continue to send the orientation data indicative of the orientation of the tracking device in the tracking device space.

18. The tracking device of claim 17, wherein the transceiver is to, in response to continuing to send the orientation data indicative of the orientation data of the tracking device in the tracking space: receive a notification that the tracking device has reentered the anchored state.

19. The tracking device of claim 12, wherein the transceiver is to: send a notification that the tracking device has entered, from an anchored state in which the tracking device space has been anchored to a hand tracking space of the hand of the user, a stationary state in which the user is not securely gripping the tracking device with the hand of the user and the tracking device is at rest; and responsive to sending the notification that the tracking device has entered, from the anchored state, the stationary state: no longer transmit the orientation data indicative of the orientation of the tracking device in the tracking device space.

20. The tracking device of claim 12, wherein the tracking device is a handheld controller of an extended reality (XR) environment.