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(54) **MOTION MIRRORING SYSTEM THAT INCORPORATES VIRTUAL ENVIRONMENT CONSTRAINTS**

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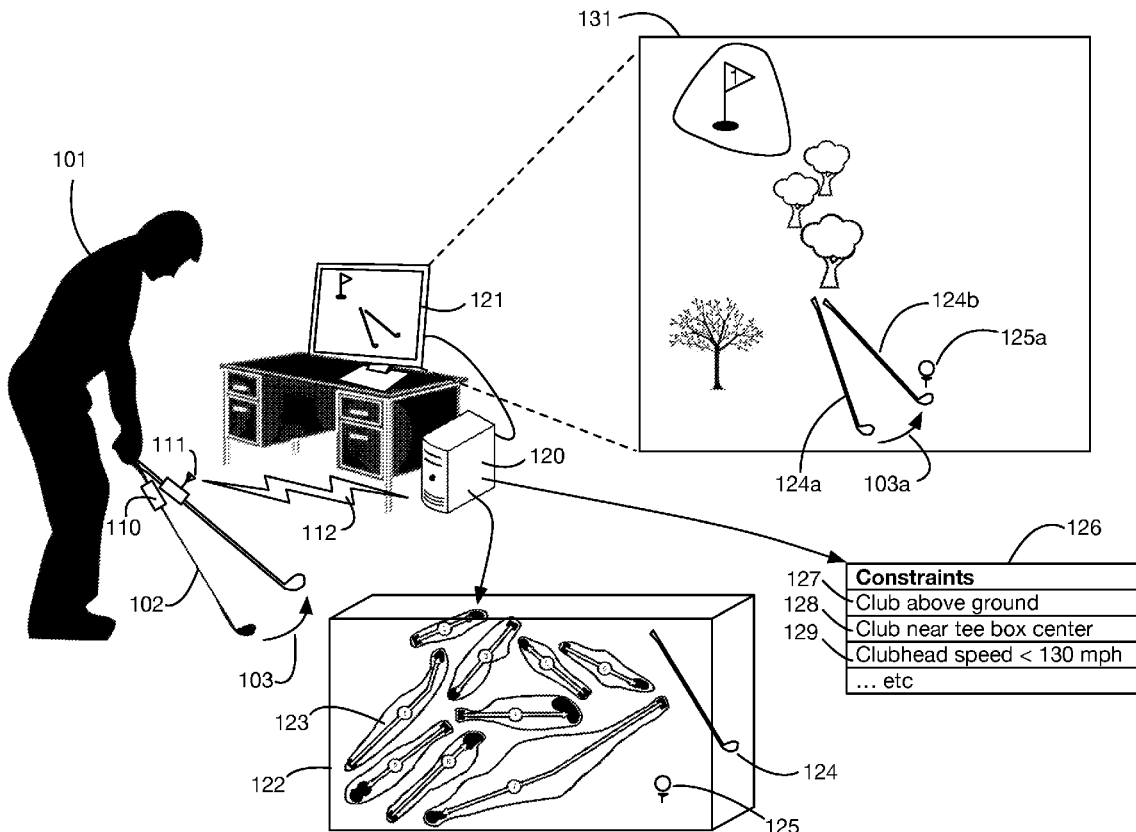
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(57) **ABSTRACT**

A system that mirrors motion of a physical object by displaying a virtual object moving in a virtual environment. The mirroring display may be used for example for feedback, coaching, or for playing virtual games. Motion of the physical object is measured by motion sensors that may for example include an accelerometer, a gyroscope, and a magnetometer. Sensor data is transmitted to a computer that calculates the position and orientation of the physical object and generates a corresponding position and orientation of the virtual object. The computer may correct or adjust the calculations using sensor data redundancies. The virtual environment may include constraints on the position, orientation, or motion of the virtual object. These constraints may be used to compensate for accumulating errors in position and orientation. The system may for example use proportional error feedback to adjust position and orientation based on sensor redundancies and virtual environment constraints.

FIG. 1

Constraints

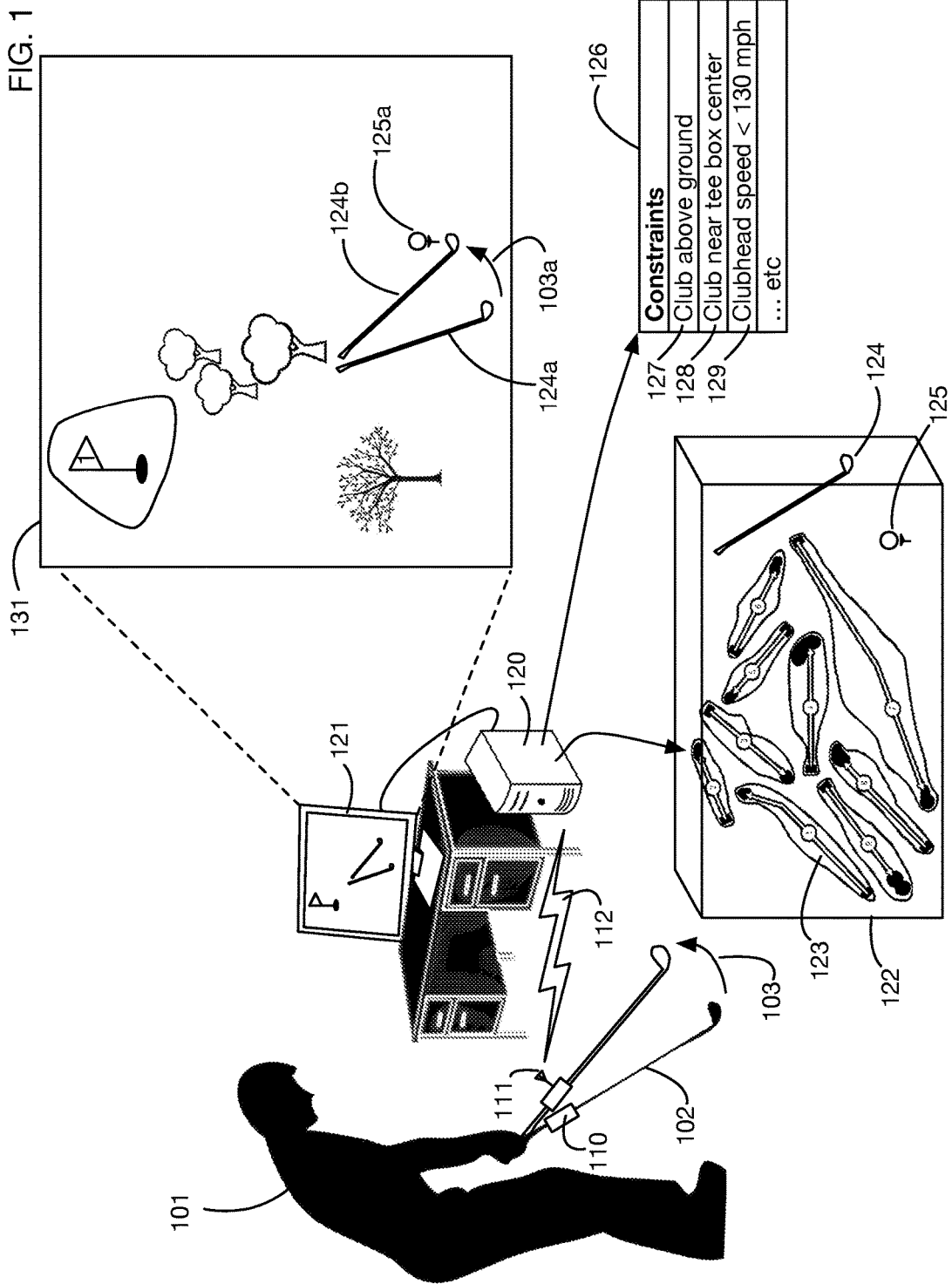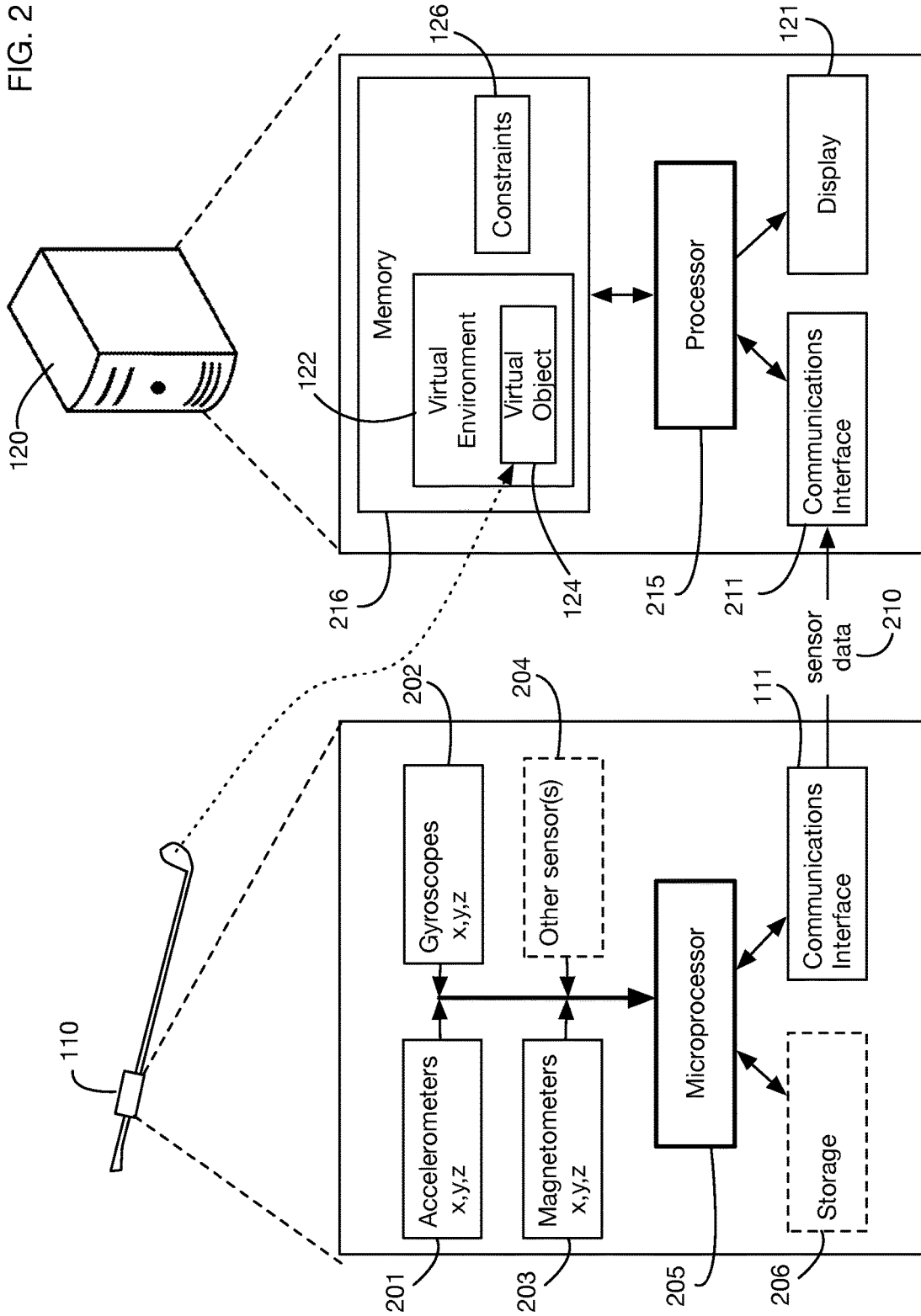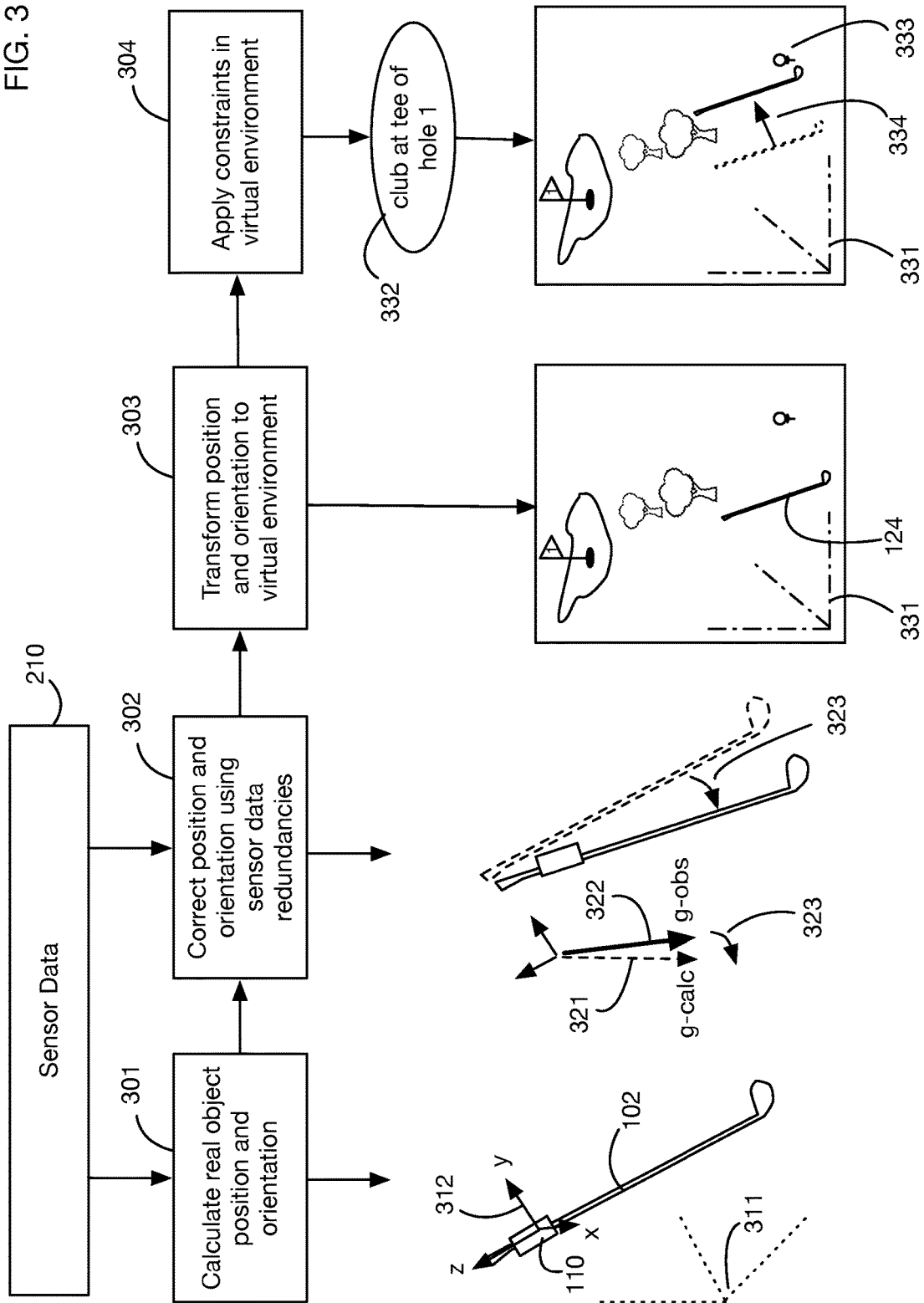| 127 | Club above ground |
128	Club near tee box center
129	Clubhead speed < 130 mph
	... etc

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

Initial Position and Orientation

Calculated Position and Orientation

Sensors

ω, a, m

∫∫

601

602

704

Apply constraint: club above ground

710

711

712

713

postion error

e

714

+

-
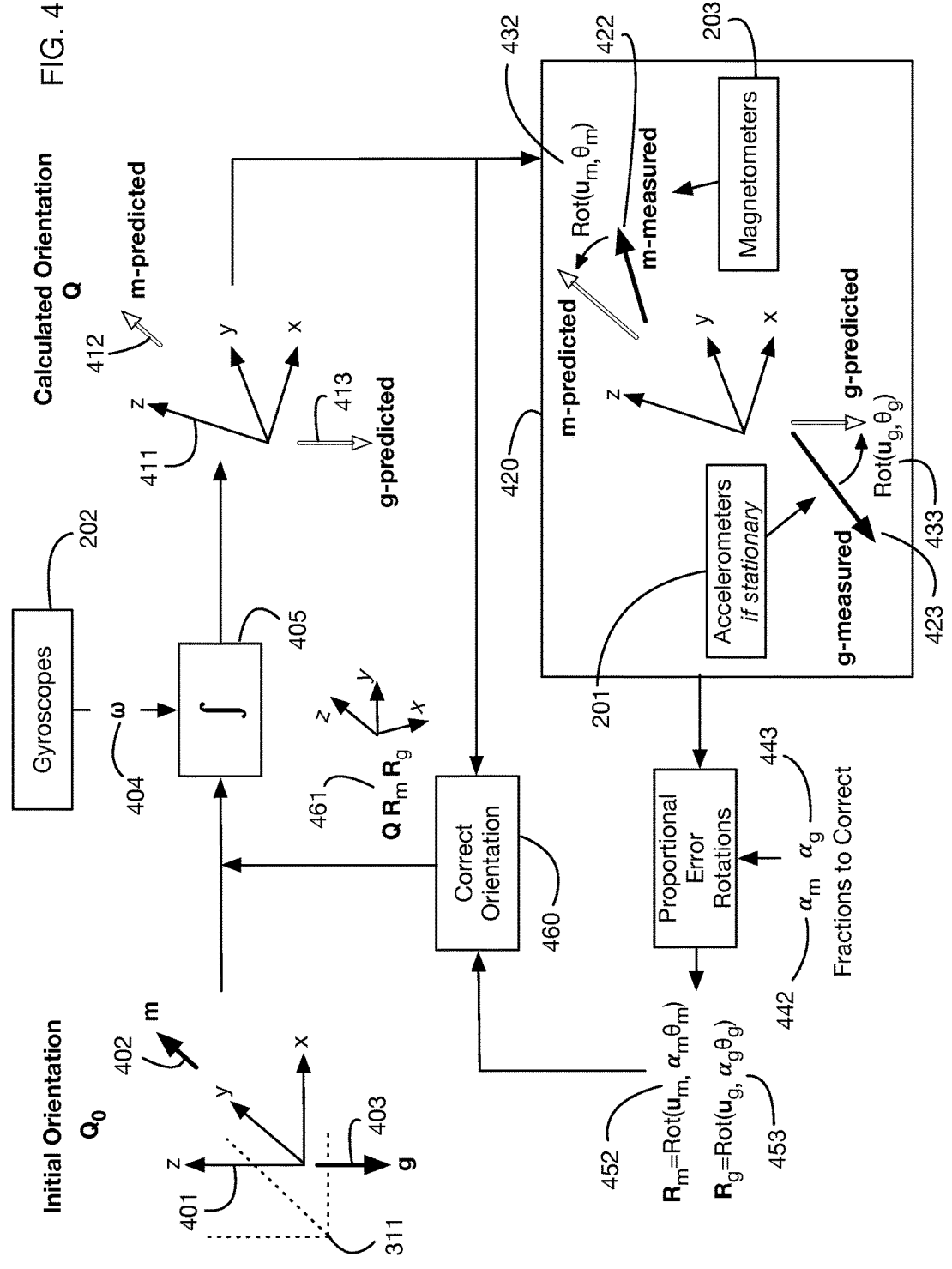
FIG. 8

MOTION MIRRORING SYSTEM THAT INCORPORATES VIRTUAL ENVIRONMENT CONSTRAINTS

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] One or more embodiments setting forth the ideas described throughout this disclosure pertain to the field of motion capture sensors and displaying motion data in a virtual reality environment. More particularly, but not by way of limitation, one or more aspects of the invention enable a system that mirrors the motion of a real object with motion of a virtual object in a virtual environment, and that applies constraints defined in the virtual environment to the motion of the virtual object.

Description of the Related Art

[0002] Motion capture sensors and systems for analyzing motion data are known in the art, but these systems typically provide delayed analysis or playback after events occur. For example, there are systems that analyze the swing of a golf club using motion sensors attached to the club; these systems wait until a swing signature is detected, and then analyze the sensor data to reconstruct and diagnose the swing. Existing motion analysis systems do not provide real-time mirroring of the motion of an object such as a golf club with a display of a virtual club in a virtual environment. Such a mirroring system may provide valuable feedback to a user, who can observe the motion of the object from various angles while it is occurring. Observations of the motion in real-time may also be valuable for coaching and teaching. Real-time mirroring of the motion of an object may also provide the ability to use the object to control a virtual reality game; for example, a user may swing a real golf club to play a virtual round of golf on a virtual golf course. While there are virtual reality systems that provide gaming experiences, these systems typically require specialized game controllers. There are no known systems that use real sporting equipment as game controllers for virtual games for the associated sports, by attaching motion sensors to these real objects.

[0003] Real-time, continuous mirroring of the motion of an object in a virtual environment presents additional challenges since sensor data inaccuracies can accumulate over time. These challenges are less acute for systems that perform after the fact analysis of events, but they are critical for long-term motion mirroring. There are no known systems that address these accumulating errors by using combinations of redundant sensor data and constraints on the motion of virtual objects in a virtual environment.

[0004] For at least the limitations described above there is a need for a motion mirroring system that incorporates virtual environment constraints.
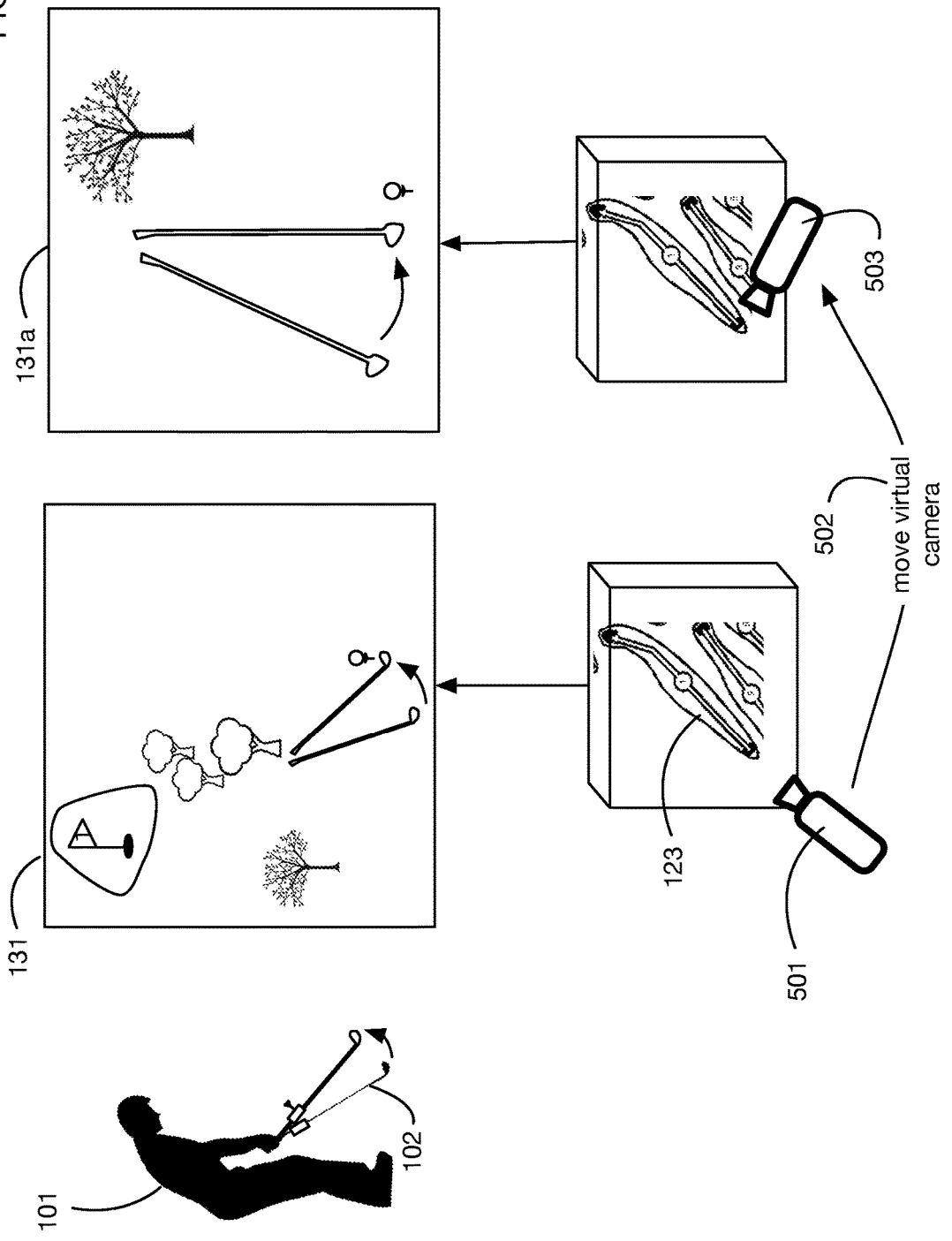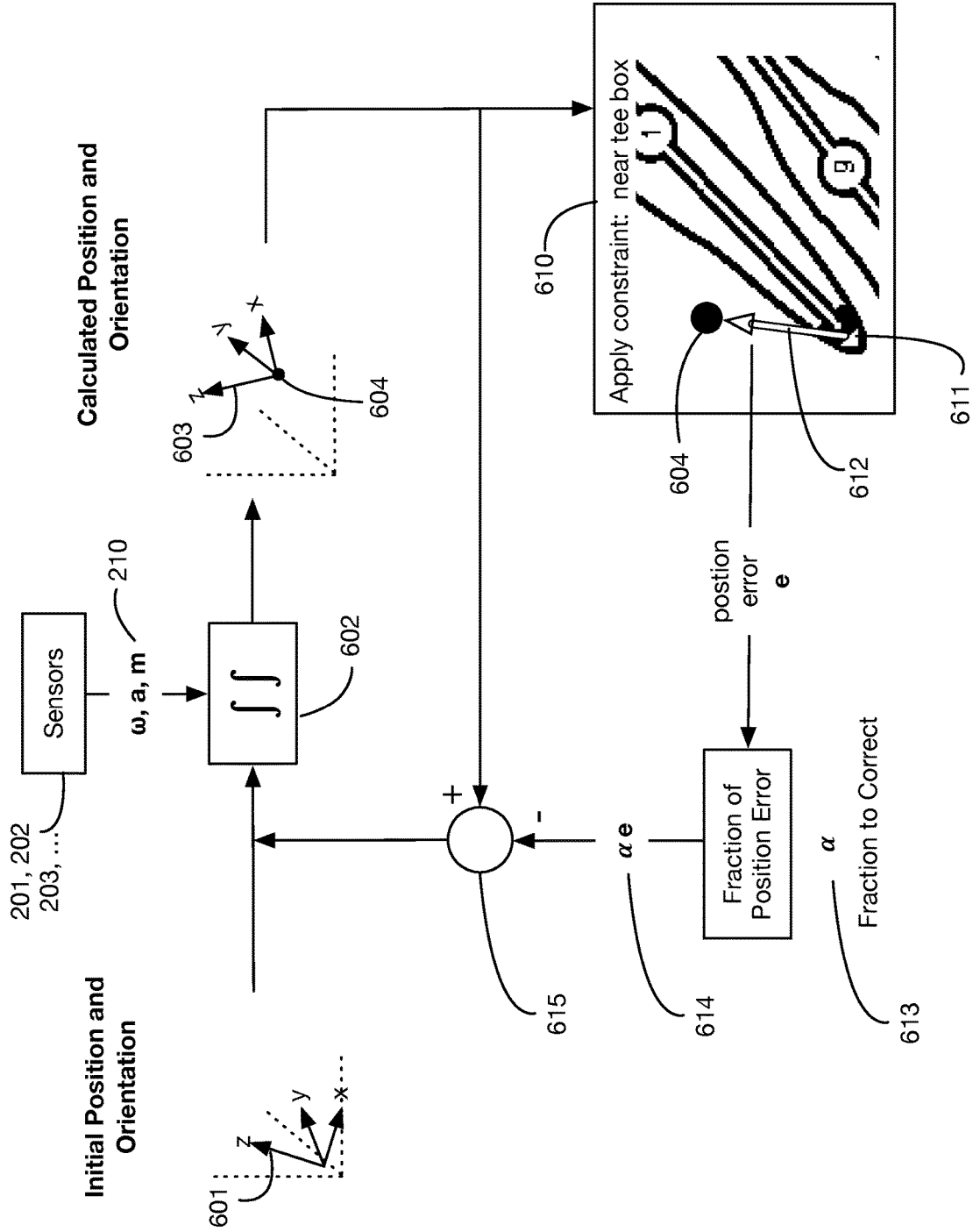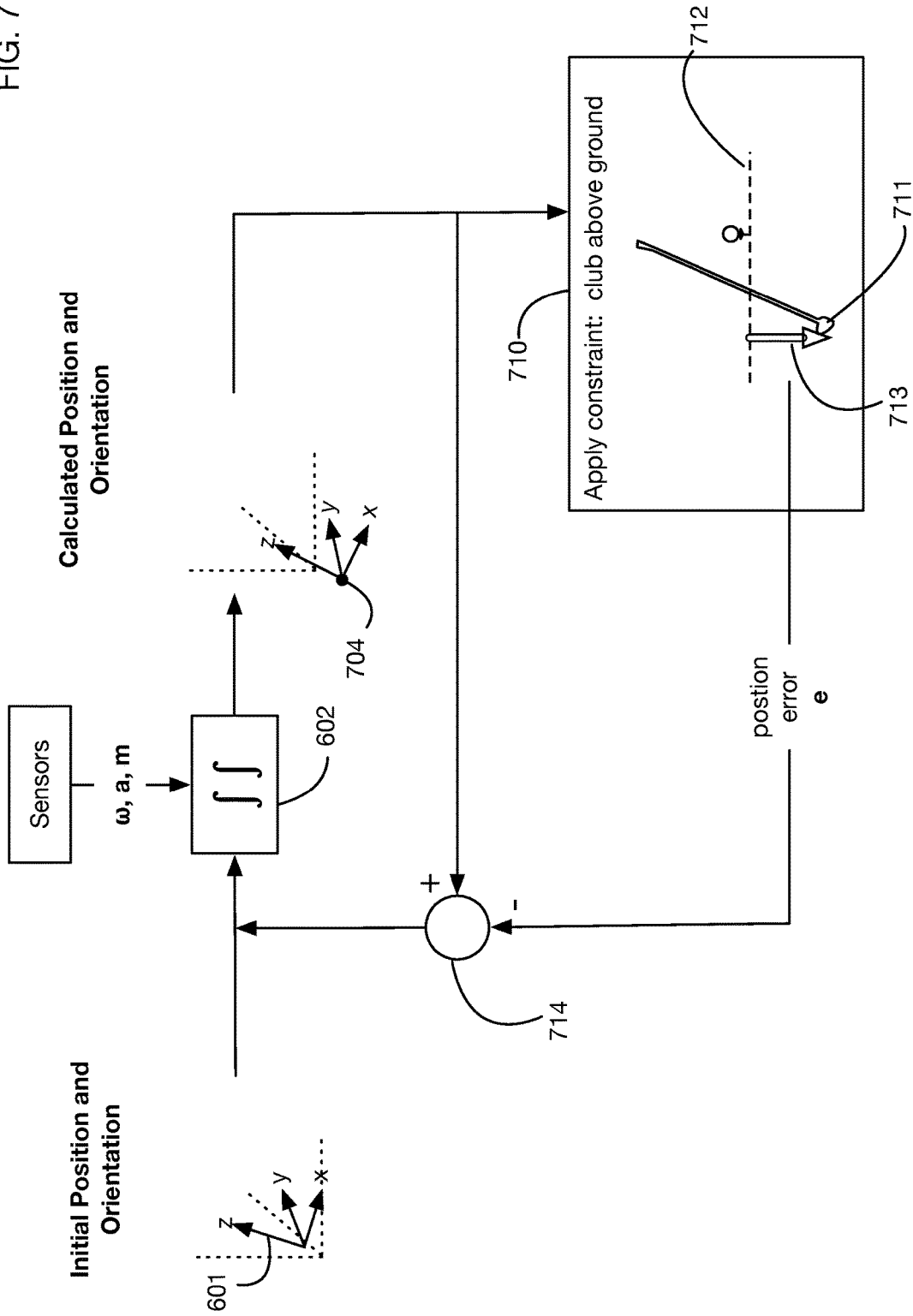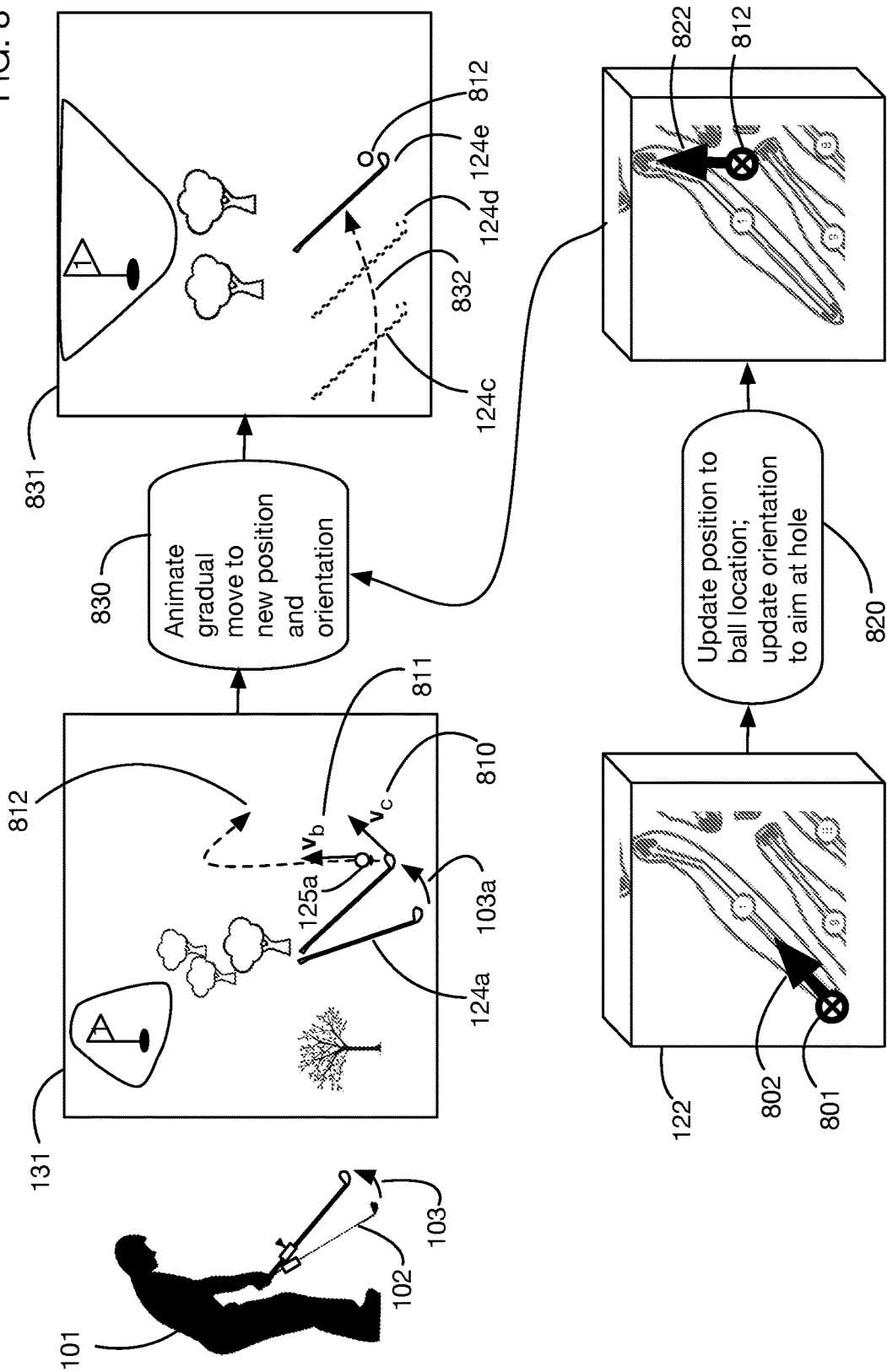
BRIEF SUMMARY OF THE INVENTION

[0005] Embodiments of the invention enable a motion mirroring system that generates and animates a virtual object in response to motion of a physical object equipped with motion sensors. The virtual object motion may take into account constraints defined for the virtual environment, such as for example regions the virtual object should remain in or remain near. The mirroring of physical object motion on a virtual environment display may be used for example for coaching or training, for playing virtual reality games, or for continuous feedback to a user.

[0006] One or more embodiments of the system may include a motion capture element (or several such elements) that may be coupled to a moveable, physical object. The motion capture element may include one or more sensors, a microprocessor to collect and transmit sensor data, and a communication interface for transmission of the data. The communication interface may be wireless, wired, or a combination thereof. Sensors may for example capture data related to any or all of the moveable object's position, orientation, linear velocity, linear acceleration, angular velocity, or angular acceleration. Sensors may capture additional or alternate data such as for example pressure, temperature, stress, strain, or shock.

[0007] The system may also include a computer that receives sensor data over another communication interface. The computer may be any device or combination of devices that can receive and process data, including for example, without limitation, a desktop computer, a laptop computer, a notebook computer, a tablet computer, a server, a mobile phone, a smart phone, a smart watch, smart glasses, a virtual reality headset, a microprocessor, or a network of any of these devices. In one or more embodiments the computer and the microprocessor of the motion capture element may coincide. The computer may access a memory (which may be local or remote, or a combination thereof) that contains a virtual environment state. The virtual environment state may define a virtual environment that includes a virtual object that represents the physical moveable object. The memory may also include one or more constraints on the position, orientation, or other characteristics of the virtual object in the virtual environment. For example, without limitation, constraints may specify regions of the virtual environment space that the virtual object must remain in or near, or regions that it may not be in.

[0008] The computer may receive sensor data from the motion capture element, and may then calculate from the data the position and orientation of the moveable object in the real environment. Because these calculations may result in errors, including potentially accumulating errors over time, the computer may apply one or more corrections to the position and orientation, for example using redundancies in the sensor data. The computer may then transform the position and orientation of the moveable object into a position and orientation of the virtual object in the virtual environment. Rules and algorithms for this transformation may depend on the nature and purpose of the virtual environment; for example, in a virtual game, the transformations may place the virtual object in an appropriate location based on the state of the game. The computer may check whether the transformed position and orientation of the virtual object satisfy the constraints associated with the virtual environment. If they do not, the computer may apply corrections or additional transformations to enforce the constraints. The computer may then generate one or more images of the virtual environment and the virtual object, and transmit these images to a display for viewing. The calculations, corrections, transformation, and image generation may occur in real time or almost real time, so that motions of the physical object result in immediate or almost immediate corresponding motions of the virtual object on the display. For example, delays between motion of the physical object

2

and corresponding mirrored motion of the virtual object on a display may be on the order of less than a half a second, or in some cases on the order of tens of milliseconds or less.

[0009] A moveable object tracked by a motion capture element may for example be a piece of equipment, an article of clothing, or a body part of a person. In one or more embodiments a piece of equipment may be a piece of sporting equipment used in a sports activity, such as for example, without limitation, equipment used in golf, tennis, badminton, racquetball, table tennis, squash, baseball, softball, cricket, hockey, field hockey, croquet, football, rugby, Australian rules football, soccer, volleyball, water polo, polo, basketball, lacrosse, billiards, horseshoes, shuffleboard, handball, bocce, bowling, dodgeball, kick ball, track and field events, curling, martial arts, boxing, archery, pistol shooting, rifle shooting, ice skating, gymnastics, surfing, skateboarding, snowboarding, skiing, windsurfing, roller blading, bicycling, or racing. The virtual environment in one or more embodiments may be a virtual game for an associated sports activity, with the virtual object representing a piece of equipment for that virtual game. For example, in a golf application, the moveable object may be a golf club, and the virtual environment may represent a virtual golf course in which the user plays a virtual round of golf; as the user moves the physical golf club, corresponding mirrored motions may be displayed by the system for the virtual golf club in the virtual golf course.

[0010] In one or more embodiments, sensors in a motion capture element may include one or more of accelerometers, rate gyroscopes, or magnetometers. These sensors may have any number of axes; for example, without limitation, 3-axis sensors may be used for applications that track motion in all directions. These sensors are illustrative; one or more embodiments may use any type or types of sensors to track any aspect of an object's position, orientation, motion, or other characteristics.

[0011] In one or more embodiments, the sensor data may include redundant information that may be used to improve or correct calculations of the moveable object's position or orientation. For example, one or more embodiments may obtain redundant orientation information using three techniques: integration of angular velocity data from a gyroscope, measurement of the object's orientation relative to the Earth's magnetic field from a magnetometer, and measurement of the object's orientation relative to the Earth's gravitational field from an accelerometer (during periods of time when the object is substantially stationary, for example). One or more embodiments may for example use the first calculation (integration of angular velocity) to obtain an initial estimate of an object's orientation, and may then apply corrections based on differences between predicted gravity and magnetic field vectors and values measured from an accelerometer and a magnetometer, respectively.

[0012] For example, without limitation, one or more embodiments may apply corrections by calculating a magnetic rotational error between the predicted magnetic field vector based on angular velocity integration and the measured magnetic field vector, and by calculating a gravitational rotational error between the predicted gravitational field vector based on angular velocity integration and the measured gravitational field vector. One or more embodiments may then apply a fraction of either or both of the

magnetic rotational error and the gravitational rotational error to the calculated orientation, to form a corrected orientation.

[0013] In one or more embodiments an image of the virtual object in the virtual environment may be formed by a virtual camera that can be positioned and oriented in the virtual environment. Users or the system may be able to modify or configure the position and orientation of this virtual camera, for example to show the motion of the object from different perspectives.

[0014] In one or more embodiments, constraints on the position, orientation, motion, or other characteristics of the virtual object in the virtual environment may for example describe or define regions of the virtual environment that the virtual object must remain in or remain near. Constraints may describe regions of the virtual environment that the virtual object must not be in or must not be near. Constraints may describe or define virtual barriers that the virtual object may not pass through. For example, without limitation, the virtual environment may define a ground surface that a virtual object must remain above and must not pass through. Constraints may for example describe or define maximum or minimum values for any function of an object's motion, position, or orientation; for example, constraints may limit the virtual object's maximum or minimum speed, acceleration, angular velocity, or angular acceleration. Constraints may describe or define limits on allowable orientations of a virtual object, for example by requiring that the virtual object must be facing in a particular direction or must not face in certain directions.

[0015] In one or more embodiments the motion mirroring system may be used for example to play a virtual game, where a user moves a physical object to control movement of a corresponding virtual piece of equipment in the virtual game. For example, the system may mirror motion of a physical golf club to move a virtual golf club that is used to play a game that simulates a round of golf on a virtual golf course. One or more embodiments that execute games may include one or more virtual game pieces in the virtual environment, such as for example a golf ball in a virtual golf game. In some games a virtual object (such as for example a virtual golf club) may be used to strike a virtual game piece (such as for example a virtual golf ball). The system may calculate the initial velocity of a virtual game piece (as well as other characteristics such as spin) by simulating the impact of the virtual object with the virtual game piece. For example, the initial velocity of a virtual golf ball may be calculated based on the velocity of a virtual golf club when it impacts the virtual golf ball. The velocity of the virtual object at impact may in turn be calculated based on the motion of the physical object corresponding to the virtual object.

[0016] In one or more embodiments the system may relocate the virtual object to a new location in response to events that occur in a virtual game or a virtual simulation. This relocation may occur automatically or in response to user input. For example, in an embodiment that mirrors the motion of a golf club to play a virtual golf game, the system may move the virtual golf club to the new location of the virtual golf ball after a shot, or to the start of a new hole once a previous hole is complete. In one or more embodiments the system may move the virtual object gradually from one position to a new position to avoid discontinuous jumps in the displayed position of the virtual object. In one or more

embodiments the system may update the orientation of a virtual object to a new orientation in response to events that occur in a virtual game or a virtual simulation. For example, in a virtual golf game the system may automatically update the aim direction of a club to aim at the hole when the position of the virtual club changes to a new location where the ball lands or at the start of a new hole. As with changes in position, the system may change the orientation of the virtual object gradually to avoid discontinuous jumps in the displayed orientation of the virtual object.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] The above and other aspects, features and advantages of the ideas conveyed through this disclosure will be more apparent from the following more particular description thereof, presented in conjunction with the following drawings wherein:

[0018] FIG. 1 illustrates an embodiment of a motion mirroring system that uses a motion sensor attached to a golf club; motion of the club is mirrored on a display that shows a virtual golf club moving in a virtual environment.

[0019] FIG. 2 shows an architectural block diagram of one or more embodiments of the system, including components of a motion sensor and of a computer that generates the virtual motion that mirrors the motion sensor data.

[0020] FIG. 3 shows a flow chart of an embodiment that applies both sensor data redundancies and virtual environment constraints to transform sensor data into the position and orientation of a virtual object.

[0021] FIG. 4 illustrates an embodiment of the system that applies proportional error correction to orientation errors derived from redundant data obtained from a gyroscope combined with an accelerometer and a magnetometer.

[0022] FIG. 5 illustrates an embodiment that supports changing the position and orientation of a virtual camera that generates a display of a virtual object in a virtual environment.

[0023] FIG. 6 illustrates an embodiment of the system that applies proportional error correction to position errors derived from position constraints in the virtual environment.

[0024] FIG. 7 illustrates an embodiment that applies a position constraint on a virtual object limiting it to a specific region of space, specifically to an above ground region.

[0025] FIG. 8 shows an embodiment of a golf club mirroring system that calculates a ball trajectory from a virtual strike of a ball, and that then animates motion of a virtual golf club to the new position and orientation for a subsequent shot.

DETAILED DESCRIPTION OF THE INVENTION

[0026] A motion mirroring system that incorporates virtual environment constraints will now be described. In the following exemplary description numerous specific details are set forth in order to provide a more thorough understanding of the ideas described throughout this specification. It will be apparent, however, to an artisan of ordinary skill that embodiments of ideas described herein may be practiced without incorporating all aspects of the specific details described herein. In other instances, specific aspects well known to those of ordinary skill in the art have not been described in detail so as not to obscure the disclosure. Readers should note that although examples of the innova-

tive concepts are set forth throughout this disclosure, the claims, and the full scope of any equivalents, are what define the invention.

[0027] FIG. 1 shows an illustrative embodiment of the system that mirrors the motion of a golf club by displaying a virtual golf club whose motion is synchronized to the motion of the real golf club. User 101 is moving real golf club 102, which has an attached motion capture element 110 that measures motion of the club. One or more embodiments may mirror the motion of any object or objects, including for example, without limitation, pieces of equipment, articles of clothing, wearable objects, objects that are carried or held, objects that are thrown or caught, objects that are hit or struck, vehicles, objects that are driven or ridden, or parts of a user's body. Pieces of equipment may include for example, without limitation, equipment used in sports activities such as golf, tennis, badminton, racquetball, table tennis, squash, baseball, softball, cricket, hockey, field hockey, croquet, football, rugby, Australian rules football, soccer, volleyball, water polo, polo, basketball, lacrosse, billiards, horseshoes, shuffleboard, handball, bocce, bowling, dodgeball, kick ball, track and field events, curling, martial arts, boxing, archery, pistol shooting, rifle shooting, ice skating, gymnastics, surfing, skateboarding, snowboarding, skiing, windsurfing, roller blading, bicycling, and racing.

[0028] Motion capture element 110 measures one or more aspects of the position or orientation (or both) of object 102, or of changes thereto such as linear velocity, linear acceleration, angular velocity, or angular acceleration. Motion capture elements may use any sensing or measuring technologies to measure any physical quantity or quantities; these technologies may include but are not limited to inertial sensing technologies such as accelerometers and gyroscopes. Motion capture elements may include additional devices that may be physically separate from the motion capture element itself, such as transmitters or receivers (such as for example a GPS satellite) or cameras that observe the motion capture element. Any device or combination of devices that provides data that can be used to determine the motion of an object such as golf club 102 is in keeping with the spirit of the invention.

[0029] Motion capture element 110 collects motion data reflecting the motion 103 of the golf club, and transmits this data using communication interface 111 to a receiving computer 120 for analysis and display. In this illustrative example, communication interface 111 is a wireless transmitter. For example, transmitter 111 may send data over wireless channel 112 which may be for example, without limitation, a Bluetooth or Bluetooth Low Energy channel, an 802.11 channel, a cellular network, or any other wireless channel or network. One or more embodiments may use wired connections between motion capture element 110 and computer 120 instead of or in addition to wireless connections such as 112. One or more embodiments may use any desired media, networks, and protocols to transmit data.

[0030] Computer 120 receives sensor data from motion capture element 110 using a corresponding communication interface integrated into or accessible to the computer. Computer 120 may be any device or combination of devices that can receive and process the sensor data. For example, without limitation, computer 120 may include a desktop computer, a laptop computer, a notebook computer, a tablet computer, a server, a mobile phone, a smart phone, a smart watch, smart glasses, a virtual reality headset, a micropro-

cessor, or a network of any of these devices. In one or more embodiments the computer may be part of or collocated with the motion capture element **110**. The computer processes the sensor data received over channel **112** to analyze the motion of the object **102**. The computer **120** accesses one or more memory or storage devices that contain a description **122** of a virtual environment. This memory or storage may be local, remote, or a combination thereof. The virtual environment **122** may for example include a description of terrain or surroundings such as a golf course, including a virtual golf hole **123**. The virtual environment may also include a description of one or more virtual objects in the environment, such as virtual golf club **124** and virtual golf ball **125**. In particular, one of these virtual objects may correspond to the real object **102** that is being moved. In the embodiment shown in FIG. **1**, virtual golf club **124** in virtual environment **122** corresponds to and represents real golf club **102**. While the virtual object **124** may represent real object **102**, in one or more embodiments the size, shape, color, texture, materials, and appearance of the virtual object may not be identical to that of the real object. Computer **120** moves virtual object **124** in the virtual environment to mirror the motion **103** of physical object **102**. The computer transmits one or more images to a display such as monitor **121** to show the mirrored motion in the virtual environment. For example, image **131** shown on display **121** shows an initial position and orientation **124**_a_ of virtual golf club **124**. When user **101** makes real movement **103** of club **102**, the system mirrors this motion with virtual motion **103**_a_ of virtual club **124** from position and orientation **124**_a_ to position and orientation **124**_b_. The virtual club **124** is also positioned near virtual golf ball **125** which is located at position **125**_a_, corresponding for example to a tee box of virtual hole **123**. In one or more embodiments computer **120** modifies and updates the state of the virtual environment **122** in any desired manner based on data from motion capture element **110**, or based on any other inputs for example from user **101** or from other users or systems.

[0031] In mirroring the motion such as **103** of a real object **102** in a virtual environment, one or more embodiments may apply one or more constraints on the motion. For example, in the embodiment of FIG. **1** the memory or storage of computer **120** also contains constraints **126** on the motion of the virtual golf club **124**. These constraints may for example specify defined regions for the position of the virtual club, or limits on the club's orientation or motion. As an example, constraints **126** contain a constraint **127** that virtual club must be entirely above the ground, reflecting a physics-based constraint in the virtual environment. One or more embodiments may have similar constraints that prevent a virtual object from passing through a physical barrier or surface, such as a wall. In one or more embodiments these constraints may be used to transform the real position and orientation of a real object into a corresponding position and orientation of a virtual object. For example, constraint **128** places the position of the virtual club near the tee box of the virtual hole (such as **123**) currently being played in the virtual environment. One or more embodiments may impose physical limits on characteristics of the motion, position, or orientation of a virtual object, such as the maximum speed constraint **129**. Maximum or minimum constraints may be applied to any characteristic, including for example, without limitation, height, speed, velocity component in any direction, acceleration, angular velocity, or angular acceleration.

Constraints may also be used to correct accumulated errors in the calculated position or orientation of an object, resulting for example from drift in inertial navigation, as discussed further below.

[0032] FIG. **2** shows a block diagram of the motion capture element and computer components of one or more embodiments. Motion capture element **110** may include a microprocessor **205** that coordinates obtaining and transmitting sensor data. Sensors may include for example accelerometers **201**, rate gyroscopes **202**, magnetometers **203**, or other sensors **204** as desired. Any type or types of sensors may be used to provide information on position, orientation, or motion. In one or more embodiments the accelerometers, gyroscopes, magnetometers, or other sensors may have any number of axes. 3-axis configurations for example may be used to measure motion or orientation in any direction. In embodiments with motion constrained to fewer dimensions, fewer than three axes may be sufficient or appropriate.

[0033] Motion capture element **110** may have an optional storage device or devices **206**. For example, in one or more embodiments sensor data may be buffered or recorded before transmission to a computer. Use of storage for buffering or recording is optional; one or more embodiments may transmit sensor data directly as soon as it is received, without buffering or recording the data. In one or more embodiments the microprocessor **205** may process data from sensors such as **201**, **202**, **203**, and **204** prior to transmitting (or storing) the data. For example, without limitation, data may be compressed, filtered, integrated, rescaled, resampled, or transformed in any desired manner by the microprocessor **205**. Sensor data **210** (or a transformed version of this data) is transmitted via communications interface **111** to computer **120**.

[0034] Computer **120** may include a processor (or multiple processors) **215**. The processor may access sensor data **210** received on communications interface **211**. It may also access memory device or devices **216**, which may contain for example the description and state of a virtual environment **122**, including a virtual object **124** that may represent a real object being moved. The memory device may also contain constraints **126** on the position, orientation, or motion of the virtual object, or more generally any constraints on the state of the virtual environment. The memory device or devices may be local to computer **120**, remote to the computer and accessed for example via a network connection, or any combination thereof. The processor **215** may update the state of the virtual environment **122** using sensor data **210**, apply constraints **126**, and generate images that are transmitted to display **121**. Display **121** may be local to computer **120** or remote. One or more embodiments may include multiple displays, potentially showing for example different views of virtual environment **122**. In one or more embodiments display **121** may be a stereographic display or any type of 3D display technology. In one or more embodiments the display or displays **121** may be integrated into a headset or into glasses or goggles.

[0035] FIG. **3** shows an illustrative sequence of steps that may be used in one or more embodiments to transform sensor data into a position and orientation of a virtual object. Sensor data **210** is received and is first used in step **301** to calculate the current position and orientation of the real object to which the motion capture element may be coupled. The specific calculations yielding position and orientation depend upon the type of sensor data **210** that is available. As

a non-limiting example, if sensor data includes accelerometer and gyroscope information, inertial navigation algorithms known in the art may be applied to calculate position and orientation over time from the acceleration and angular velocity data. The result of calculations 301 defines the position and orientation 312 of the motion capture element 110 in coordinate system 311 that is fixed to the real environment in which object 102 moves. The position and orientation of object 102 (or any part thereof) may then be determined, for example using rigid body transformations known in the art.

[0036] In one or more embodiments, an initial calculation 301 of object position and orientation 312 may be subject to various errors. For example, as is known in the art, in inertial navigation using accelerometer and gyro data, calculated position and orientation may drift over time from their true values. One or more embodiments may therefore apply a step 302 to correct position and orientation using one or more redundancies in the sensor data 210. The specific corrections depend on the type of sensor data 210 and on the specific redundancies in the data. For example, continuing the inertial navigation example, an accelerometer and a gyroscope contain redundant information about the orientation of an object, since the gyroscope angular velocity can be integrated to form orientation, and the accelerometer can also provide a tilt reading when the object is stationary. In the embodiment illustrated in FIG. 3, the gravity vector predicted based on gyroscope integration is 321, but the observed gravity vector obtained from the accelerometer (assuming a stationary object) is vector 322. The rotational difference 323 between these values can be applied as a correction to the object orientation.

[0037] After corrections 302, step 303 may transform the position and orientation of the real object into the virtual environment. This transformation may depend for example on the state of the virtual environment. For example, in the golf example from FIG. 1, the virtual club 124 is positioned at various holes in the virtual golf course throughout the course of a virtual round. The transformation from real club position to virtual position therefore depends on which virtual hole the user is playing at that point in time. As a user advances to another hole, the position of the virtual club changes, without requiring the real user to move the physical golf club to a new location. Transformation 303 results in a position and orientation for virtual object 124 relative to a virtual environment coordinate system 331.

[0038] After transformation 303 to the virtual environment, one or more embodiments may perform step 304 to apply one or more constraints to the position, orientation, motion, or other characteristics of the virtual object. For example, constraint 332 may require that the virtual club 124 be located at or near the tee of the first hole (or more generally located at or near the ball's current position). Because of accumulated errors such as inertial drift (which may not be fully corrected by step 302), the position of the virtual club may need to be adjusted with a shift 334 to place it near the ball position 333, for example. Other constraints such as those illustrated in FIG. 1 may also be applied to the virtual object.

[0039] FIG. 4 shows an illustrative embodiment that performs correction step 302 for orientation errors using sensor data redundancy in motion capture data from a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer. The approach shown in FIG. 4 is illustrative; one or

more embodiments may use any technique to perform error correction using any type of sensor data redundancy. For simplicity, the example illustrated in FIG. 4 begins with the initial orientation 401 (Q_o) of the motion capture element aligned with the coordinate system 311 of the real environment. In this reference frame, the Earth gravity vector 403 (g) points in the negative z direction, and for simplicity we illustrate the Earth's magnetic field vector 402 (m) pointing in the positive y direction. (The actual direction of the magnetic field vector depends on various factors including the latitude and longitude of the system.) Starting with this initial orientation 401, the system calculates updates to the orientation by integrating the angular velocity 404 (ω) obtained from a 3-axis gyroscope 202. Using integration 405, an updated orientation 411 is calculated after each sensor data sample. (Integration of angular velocity to form orientation updates is known in the art, for example by integrating the differential equation

$$\frac{dQ}{dt} = \omega^x Q,$$

where Q is the orientation matrix and ω^x is the cross product matrix formed from the angular velocity ω.) Given the calculated orientation 411, predicted values can be estimated for the magnetic field vector 412 and the gravity vector 413. This prediction presumes that the orientation of the magnetic vector 412 in the fixed reference frame 311 is the same as its initial orientation 402, and that therefore the change in the magnetic vector measured in the sensor reference frame 411 is due only to the change in orientation. Similarly, the prediction presumes that that the orientation of the gravity vector 413 in the fixed reference frame 311 is the same as its initial orientation 403, and that therefore the change in the gravity vector measured in the sensor reference frame 411 is due only to the change in orientation.

[0040] Calculations 420 then use redundant sensor data to compare the predicted magnetic vector 412 and predicted gravity vector 413 to measured quantities. The measured magnetic vector 422 may for example be obtained from magnetometers 203. The measured gravity vector 423 may for example be obtained from accelerometers 201, provided that the system is stationary or substantially stationary (or not accelerating) when the measurement is made. In one or more embodiments the system may for example determine whether the system is sufficiently stationary to use the gravity vector measurement by testing the magnitude of the angular velocity; a low angular velocity may suggest that the system may be stationary. In one or more embodiments the system may for example also or alternatively determine whether the system is sufficiently stationary by testing the magnitude of the acceleration vector; an acceleration magnitude approximately equal to g (gravity acceleration) may suggest that the system may be stationary. By comparing the predicted and measured vectors, rotations 432 and 433 can be calculated that rotate the measured values into the predicted values. (For example, an axis for each of these rotations can be determined by taking the cross product of the predicted and measured vectors.) These rotations 432 and 433 represent the errors between the calculated orientation and the actual orientation.

[0041] In one or more embodiments one or both of the error rotations 432 and 433 may be applied to the current

orientation with proportional scaling factors to shift the calculated orientation gradually towards the measured orientation. Applying only a portion of the error rotations to the orientation at each update cycle (or at selected update cycles) may for example provide a more robust solution when the measured gravity and magnetic vectors are also subject to possible errors. Fractions **442** and **443**, respectively, are applied to rotations **432** and **433**, yielding proportional error rotations **452** and **453** respectively. In this illustrative example the proportionality factors **442** and **443** are applied to the rotation angles (θ_m and θ_g), and the rotation axes (u_m and u_g) of rotations **432** and **433** are preserved. The rotations **452** and **453** are then applied in step **460** to the orientation **411**, yielding a corrected orientation **461**. In one or more embodiments one or both of the corrections **452** and **453** may be applied at every sensor sample. In one or more embodiments one or both of the corrections may be applied periodically but not at every sensor sample, for example at every tenth sample. In one or more embodiments one or both of the corrections may be applied when the angular magnitude of the error rotations **432** or **433** exceed a threshold.

[0042] After possible correction using redundant sensor data, the position and orientation of a real object may be transformed to the virtual environment to form an image of a virtual object. In one or more embodiments the user or the system may be able to configure or modify the position and orientation in the virtual environment of a virtual camera that generates this image. FIG. **5** illustrates an embodiment with this capability. As in FIG. **1**, user **101** moves real golf club **102**, and this motion is mirrored on a display of a virtual golf club in a virtual environment. Image **131** shows the virtual golf club and the virtual environment from the perspective of a virtual camera **501**, which in this example is positioned and oriented to be behind the golfer looking down the fairway of the virtual hole **123**. The user (or the system, or another user) makes modification **502** to move the virtual camera to new position and orientation **503**, which is to the right of the golfer. This new camera position and orientation results in modified image **131a** of the virtual environment and of the virtual golf club. In one or more embodiments camera position and orientation may be configurable by a user. In one or more embodiments the system may generate changing virtual camera position and orientation to show the virtual environment from different angles as the motion is mirrored. In one or more embodiments the system may select an optimal virtual camera position and orientation, based for example on the motion of the real object.

[0043] As discussed with respect to FIG. **3**, step **304** may apply one or more constraints in the virtual environment to modify, transform, or correct the position or orientation of a virtual object in the virtual environment. In one or more embodiments these constraints may be applied for example to compensate for accumulating errors in position or orientation, due for example to drift in inertial navigation algorithms. These constraints may be applied instead of or in addition to the corrections using redundant sensor data as discussed for example with respect to FIG. **4**. FIG. **6** illustrates an embodiment that measures the position and orientation of a real object using inertial sensors **201**, **202**, and **203**. Sensor data **201** is integrated **602**, starting from initial position and orientation **601**, yielding updated position **604** and updated orientation **603**. As is known in the art,

integration of inertial sensor data over time can result in significant drift from the true position of the measured object. In one or more embodiments constraints in the virtual environment may be applied to compensate for this drift. In the example of FIG. **6**, the desired position of the virtual object (in this case a virtual golf club) is in or near the tee box of a virtual hole. This constraint is applied in step **610** to calculate a position error **612** between the constrained position **611** (near the tee box) and the calculated position **604** after transformation to the virtual environment. In this illustrative example, a proportionality fraction **613** is applied to the position error **612**, yielding a correction **614** that is added in step **615** to the calculated position **604**. This continuous or periodic proportional error correction may compensate for the inertial drift and may prevent the virtual position of the virtual object from drifting away from the constrained region.

[0044] Virtual environment constraints may also ensure that the position and orientation of a virtual object do not violate physical laws or the required configurations imposed by the virtual environment. FIG. **7** shows a variation of the example of FIG. **6**, where the constraint applied in step **710** is that the virtual golf club must be entirely above the ground. This constraint expresses the physical law for the virtual environment that two solid objects cannot pass through one another. As described in FIG. **6**, the calculated position **704** of the object may drift over time, including in this example drifting to place the golf club below ground. Constraint **710** is applied to calculate a position error **713** between the calculated vertical position of the golf clubhead **711** and the horizontal ground plane **712**. In contrast to the example of FIG. **6**, in this example the entire position error **713** is subtracted immediately from the calculated position **714**, reflecting the absolute constraint **710**. In this case a gradual move of the virtual golf club to place it above the ground may not be appropriate; instead the constraint is enforced immediately when the error is detected. One or more embodiments may use different approaches for different constraints: some constraints may be enforced rigidly and immediately, while others may for example result in gradual corrections over time using proportional error correction or similar approaches.

[0045] In one or more embodiments the position or orientation of a virtual object may be determined fully or partially by the state of the virtual environment at a point in time. For example, in embodiments that mirror motion to play a virtual game, the state of the game may affect the placement of the virtual object in the virtual environment. FIG. **8** illustrates an embodiment that mirrors motion of real golf club **102** to play a virtual round of golf in virtual environment **122**. In this embodiment the position and orientation of the golf club change as the player advances through the course. For example, initially the virtual golf club is positioned at position **801** at the tee of the first hole, and is oriented in direction **802** facing down the first fairway. As the user executes motions such as motion **103** of the real club, virtual motions such as **103a** are generated in the virtual environment. In this example, a virtual swing such as **103a** is detected by the system and is interpreted as a strike of a virtual golf ball **125a**. The system calculates the initial velocity **811** of the ball **125a** based on the velocity **810** of the virtual club as it contacts the ball. This initial ball velocity **811** is then used to calculate the trajectory of the ball **125a**, and to calculate the position **812** at which the ball lands after

the shot. Techniques for predicting the trajectory of objects such as golf balls given initial conditions such as initial velocity (and potentially initial angular velocity or other characteristics as well) are known in the art.

[0046] After the virtual environment updates the position of the virtual ball **125***a* to its new position **812**, the system may automatically update the position and orientation of the virtual golf club to reflect the new ball position. For example, the system executes update process **820** to move the virtual club position from **801** to **812**, where the virtual ball landed after the shot. In addition, the system may automatically update the virtual club orientation to aim in the direction facing the hole from the new position, for example updating the aim vector of the club from **802** to **822**. These updates to the position and orientation of the virtual club may occur automatically, even if the user **101** does not execute a specific motion of the real club **102** to make the changes. Subsequent motion of the club **102** may then be interpreted relative to the updated position **812** and updated orientation **822**.

[0047] In one or more embodiments the system may perform a gradual, continuous update of the position and orientation of a virtual object, so that the viewer of the display does not observe a discontinuous jump. For example, in FIG. **8**, the system executes animation process **830** to continuously shift the virtual club to the new position **812**. In updated image **831** shown on the display, the virtual golf club moves continuously through trajectory **832**, shifting gradually from position **124***c* to **124***d* and finally to position **124***e* adjacent to the updated ball position **812**. Similarly, the orientation and aim direction of the club may be gradually and continuously modified to result in the new aim direction **822**.

[0048] While the ideas herein disclosed has been described by means of specific embodiments and applications thereof, numerous modifications and variations could be made thereto by those skilled in the art without departing from the scope of the invention set forth in the claims.

What is claimed is:

1. A motion mirroring system that incorporates virtual environment constraints, comprising

a motion capture element configured to couple with a moveable object located in a real environment, wherein said motion capture element comprises

a sensor configured to capture one or more values associated with an orientation, position, velocity, acceleration, angular velocity, and angular acceleration of said motion capture element;

a first communication interface;

a microprocessor coupled with said sensor and said first communication interface, wherein said microprocessor is configured to

collect data that comprises said one or more values from said sensor;

transmit said data via said first communication interface;

a computer that comprises

a display;

a memory that contains

a virtual environment state comprising a position and orientation of a virtual object in a virtual environment, wherein said virtual object represents said moveable object in said virtual environment;

one or more constraints on said position and orientation of said virtual object in said virtual environment;

a second communication interface configured to communicate with said first communication interface to obtain said data;

wherein said computer is configured to

receive said data via said second communication interface;

calculate a position and orientation of said moveable object in said real environment from said data;

apply one or more corrections to said position and orientation of said moveable object in said real environment based on one or more redundancies in said data;

transform said position and orientation of said moveable object in said real environment into said position and orientation of said virtual object in said virtual environment;

determine whether said position and orientation of said virtual object in said virtual environment satisfies said one or more constraints;

when said position and orientation of said virtual object in said virtual environment does not satisfy one or more of said one or more constraints, modify said position and orientation of said virtual object in said virtual environment to satisfy said one or more constraints;

display said virtual environment and said virtual object on said display.

2. The system of claim **1**, wherein said moveable object is one or more of a piece of equipment, an article of clothing, or a body part of a person.

3. The system of claim **1**, wherein said sensor comprises a 3-axis accelerometer, a 3-axis rate gyroscope, and a 3-axis magnetometer.

4. The system of claim **3**, wherein said redundancies in said data comprise

a calculation of said orientation of said moveable object in said real environment by integration of angular velocity data from said 3-axis rate gyroscope;

a measurement of said orientation of said moveable object in said real environment relative to an Earth magnetic field from said 3-axis magnetometer;

a measurement of said orientation of said moveable object in said real environment relative to an Earth gravitational field from said 3-axis accelerometer, when said data indicates that said moveable object is substantially stationary.

5. The system of claim **4**, wherein

said calculate a position and orientation of said moveable object in said real environment from said data comprises said integration of angular velocity data from said 3-axis rate gyroscope;

said apply one or more corrections to said position and orientation of said moveable object in said real environment comprises one or more of

calculate a first rotational error between

a predicted magnetic field vector based on said integration of angular velocity data, and

a measured magnetic field vector from said 3-axis magnetometer;

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apply a first fraction of said first rotational error to said orientation of said moveable object in said real environment;

calculate a second rotational error between
a predicted gravitational field vector based on said integration of angular velocity data, and
a measured gravitational field vector from said 3-axis accelerometer;

apply a second fraction of said second rotational error to said orientation of said moveable object in said real environment.

6. The system of claim 1, wherein

said virtual environment comprises a virtual camera that forms an image of said virtual environment;

said display said virtual environment and said virtual object on said display transmits said image of said virtual environment to said display;

a position and orientation of said virtual camera in said virtual environment is modifiable by a user.

7. The system of claim 1, wherein a change in said position and orientation of said moveable object in said real environment results in a corresponding change within a predefined time period of said position and orientation of said virtual object in said virtual environment shown on said display.

8. The system of claim 1, wherein said one or more constraints comprise a region in said virtual environment that said virtual object must be located within.

9. The system of claim 1, wherein said one or more constraints comprise a location in said virtual environment that said virtual object must be located near.

10. The system of claim 9, wherein said modify said position and orientation of said virtual object in said virtual environment to satisfy said one or more constraints comprises

calculate an error vector between said position of said virtual object in said virtual environment and said location;

add a fraction of said error vector to said position of said virtual object in said virtual environment.

11. The system of claim 1, wherein said one or more constraints comprise one or more of a maximum speed, a minimum speed, a maximum acceleration, a minimum acceleration, a maximum angular velocity, a minimum angular velocity, a maximum angular acceleration, and a minimum angular acceleration of said virtual object.

12. The system of claim 1, wherein said one or more constraints comprise one or more virtual barriers that said virtual object cannot pass through.

13. The system of claim 12, wherein said one or more virtual barriers comprise a ground surface.

14. The system of claim 1, wherein

said moveable object is a piece of sporting equipment used in a sports activity;

said virtual environment is a virtual game for said sports activity;

said virtual object in said virtual environment is a representation of said piece of sporting equipment.

15. The system of claim 14, wherein said sports activity is one or more of golf, tennis, badminton, racquetball, table tennis, squash, baseball, softball, cricket, hockey, field hockey, croquet, football, rugby, Australian rules football, soccer, volleyball, water polo, polo, basketball, lacrosse, billiards, horseshoes, shuffleboard, handball, bocce, bowling, dodgeball, kick ball, track and field events, curling, martial arts, boxing, archery, pistol shooting, rifle shooting, ice skating, gymnastics, surfing, skateboarding, snowboarding, skiing, windsurfing, roller blading, bicycling, and racing.

16. The system of claim 14, wherein

said virtual object is used to contact and launch a virtual game piece in said virtual game;

said computer calculates a launch velocity of said game piece based on a motion of said virtual object at a time of impact between said virtual object and said virtual game piece.

17. The system of claim 14, wherein said computer relocates said virtual object to a new position in said virtual environment in response to one or more events in said virtual game.

18. The system of claim 17, wherein said relocates said virtual object to a new position occurs gradually to prevent a user from observing a discontinuous change in position on said display.

19. The system of claim 17, wherein

said virtual game is a virtual golf game;

said virtual object is a virtual golf club;

said relocates said virtual object to a new position comprises moves said virtual golf club to a location of a virtual golf ball after a shot, or to a starting position for a new hole after completion of a previous hole.

20. The system of claim 19, wherein said moves said virtual golf club further comprises modifies an orientation of said virtual golf club to aim at a hole from said new position.

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