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(54) **CAMERA-SPACE HAND MESH PREDICTION WITH DIFFERENTIAL GLOBAL POSITIONING**

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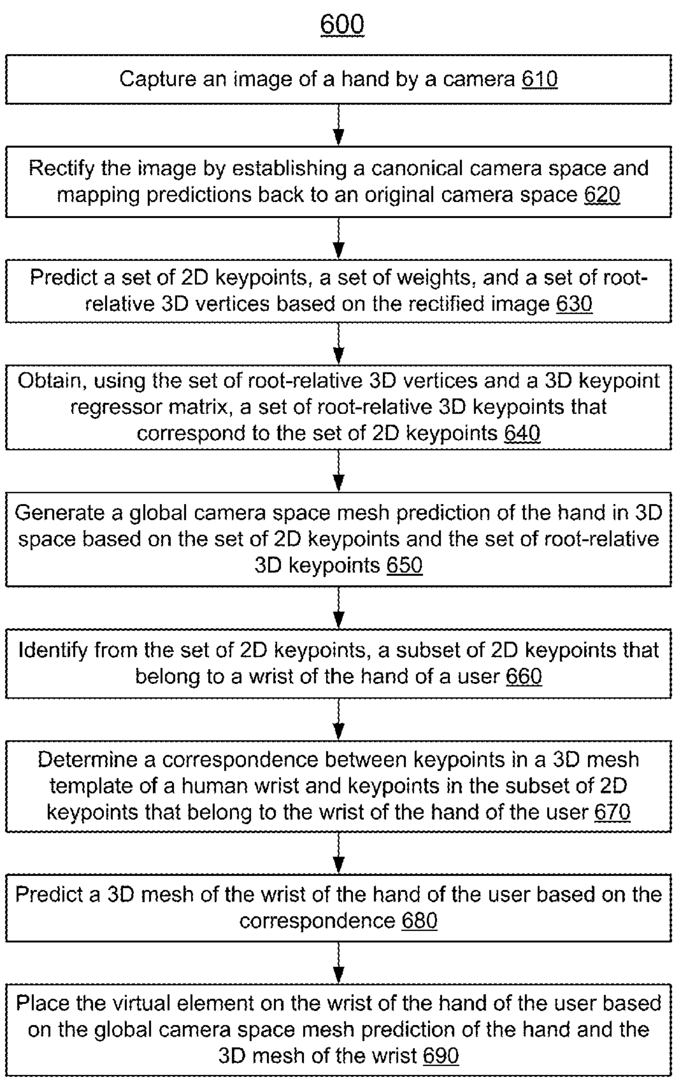
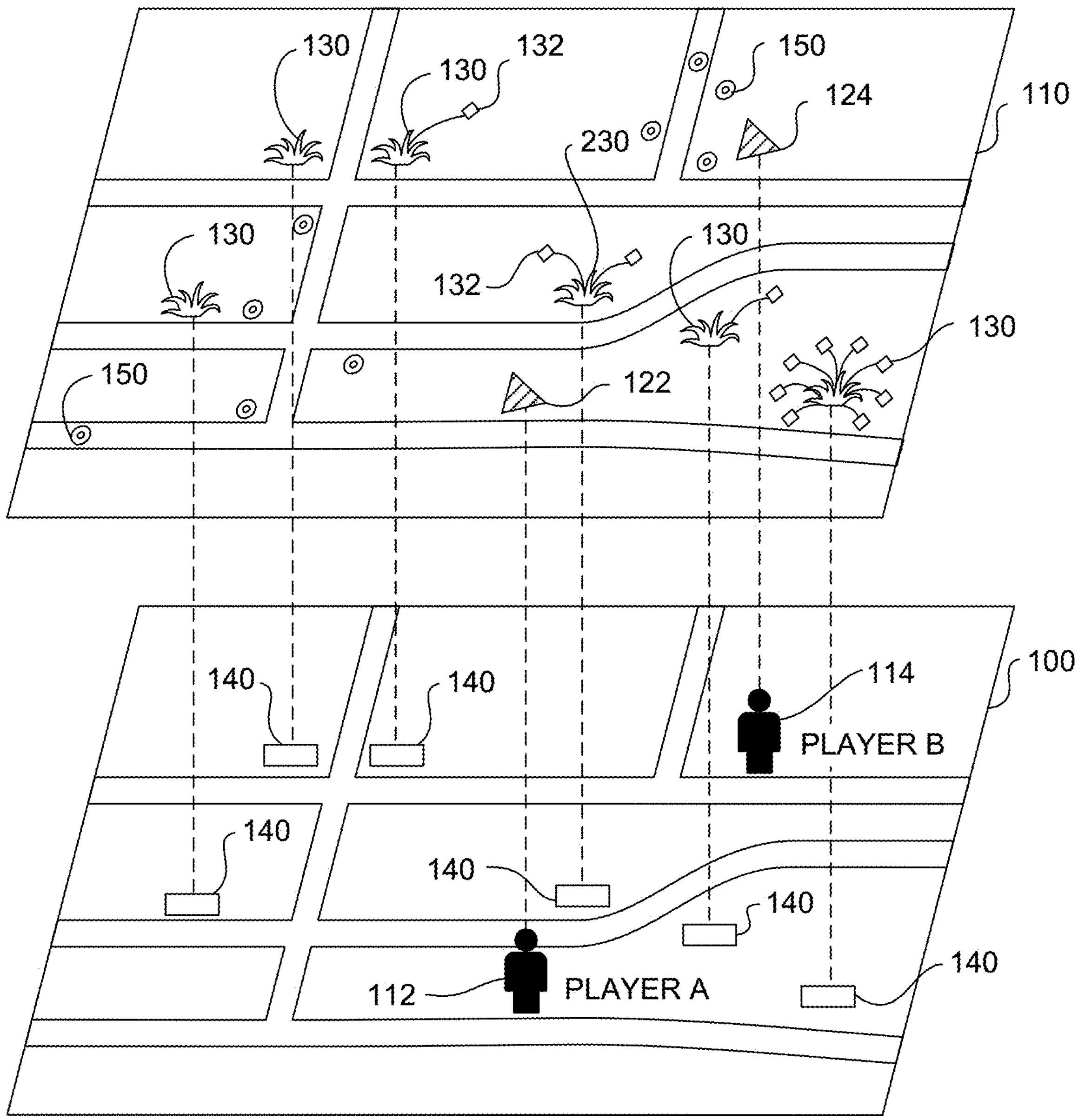
(57) **ABSTRACT**

An image of a hand is captured by a camera. The captured image is rectified by establishing a canonical camera space and mapping predictions back to an original camera space. A set of 2D keypoints, a set of root-relative vertices, and a set of weights are predicted based on the rectified image. Using the set of root-relative vertices, a set of 3D keypoints that correspond to the set of 2D keypoints are obtained. A global camera space hand mesh prediction is generated in 3D space based on the set of 2D keypoints, the set of weights, and the set of 3D keypoints. A virtual element is output in a virtual space based on the generated global camera space hand mesh prediction.





130
132
130
150
124
110
230
130
130
132
130
150
122
140
140
114
100
PLAYER B
140
140
140
140
112
PLAYER A

FIG. 1

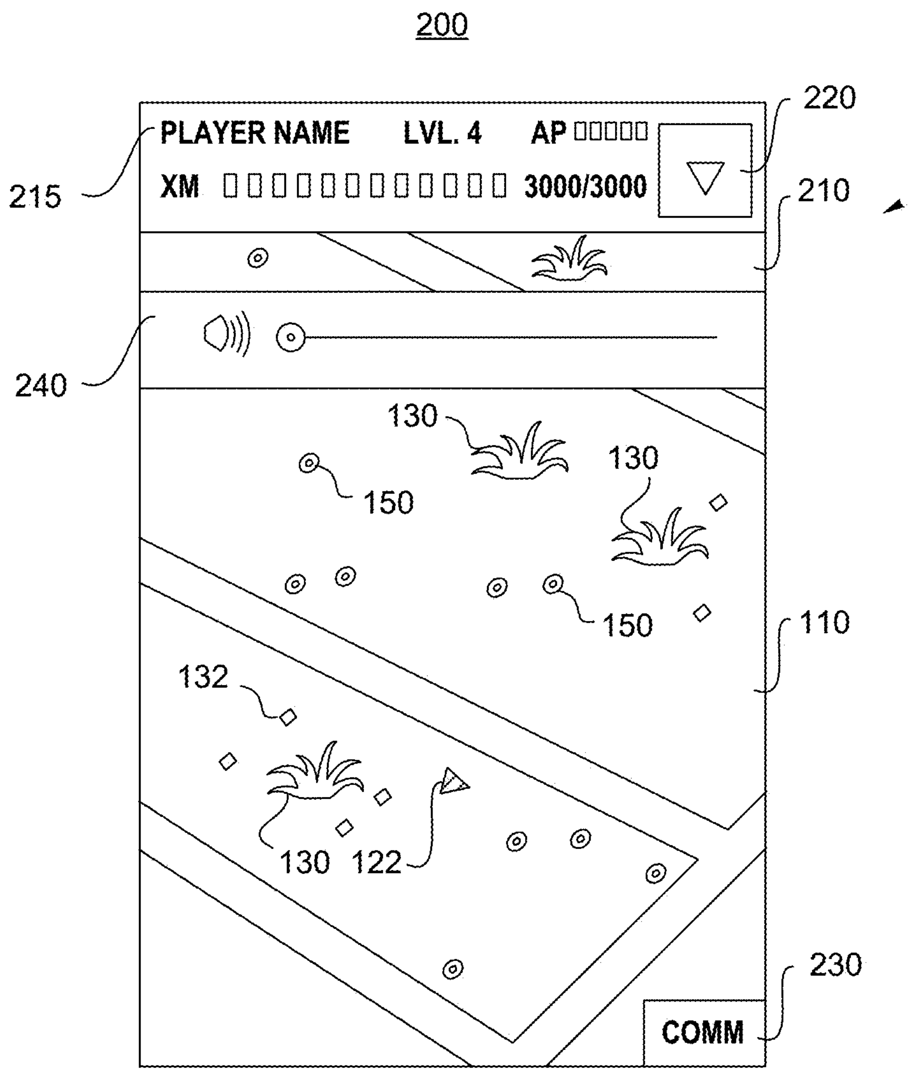

200
PLAYER NAME
LVL. 4
AP
XM
3000/3000
220
215
210
240
130
130
150
150
110
132
130
122
230
COMM

FIG. 2

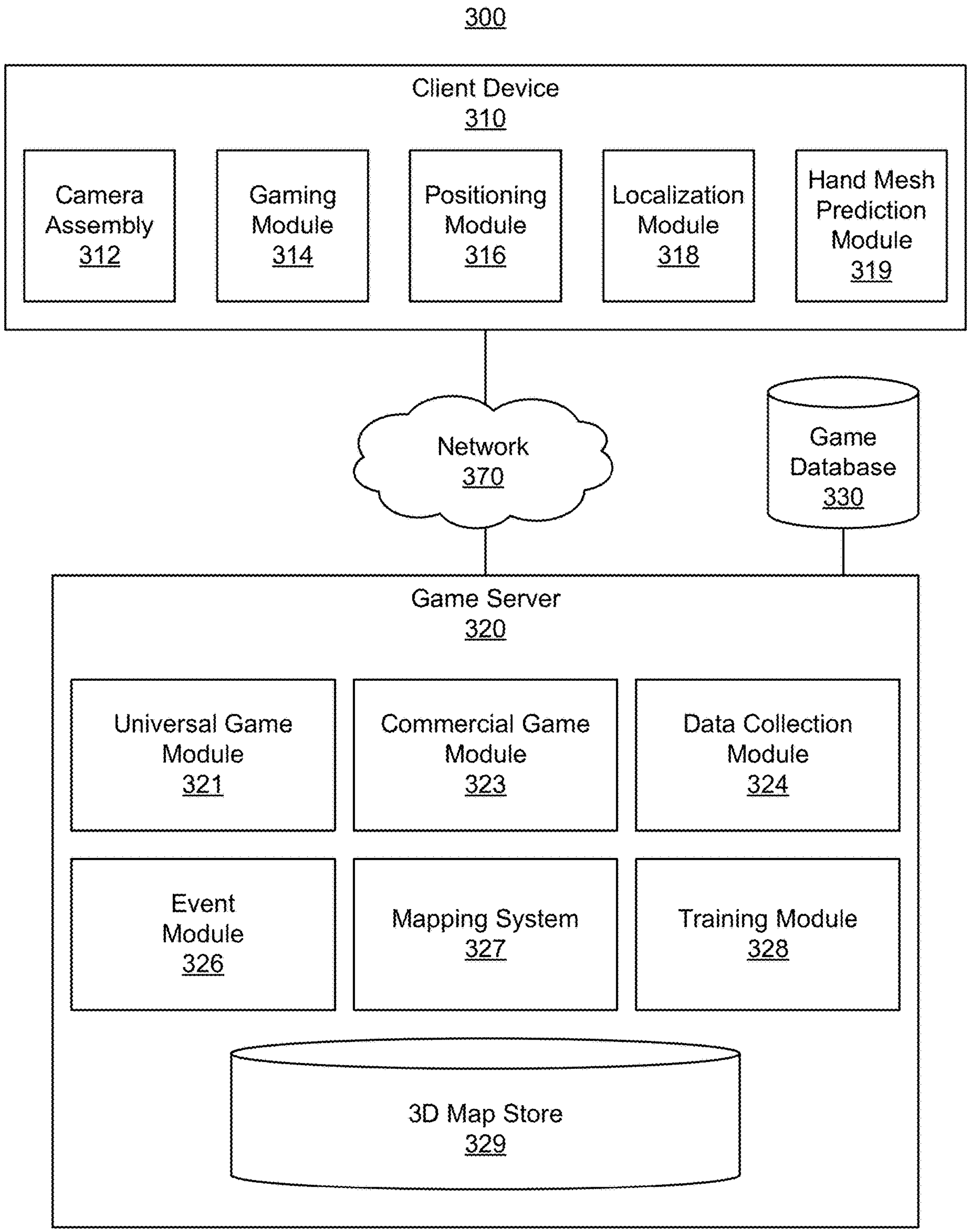

300
Client Device
310
Camera Assembly
312
Gaming Module
314
Positioning Module
316
Localization Module
318
Hand Mesh Prediction Module
319
Network
370
Game Database
330
Game Server
320
Universal Game Module
321
Commercial Game Module
323
Data Collection Module
324
Event Module
326
Mapping System
327
Training Module
328
3D Map Store
329

FIG. 3

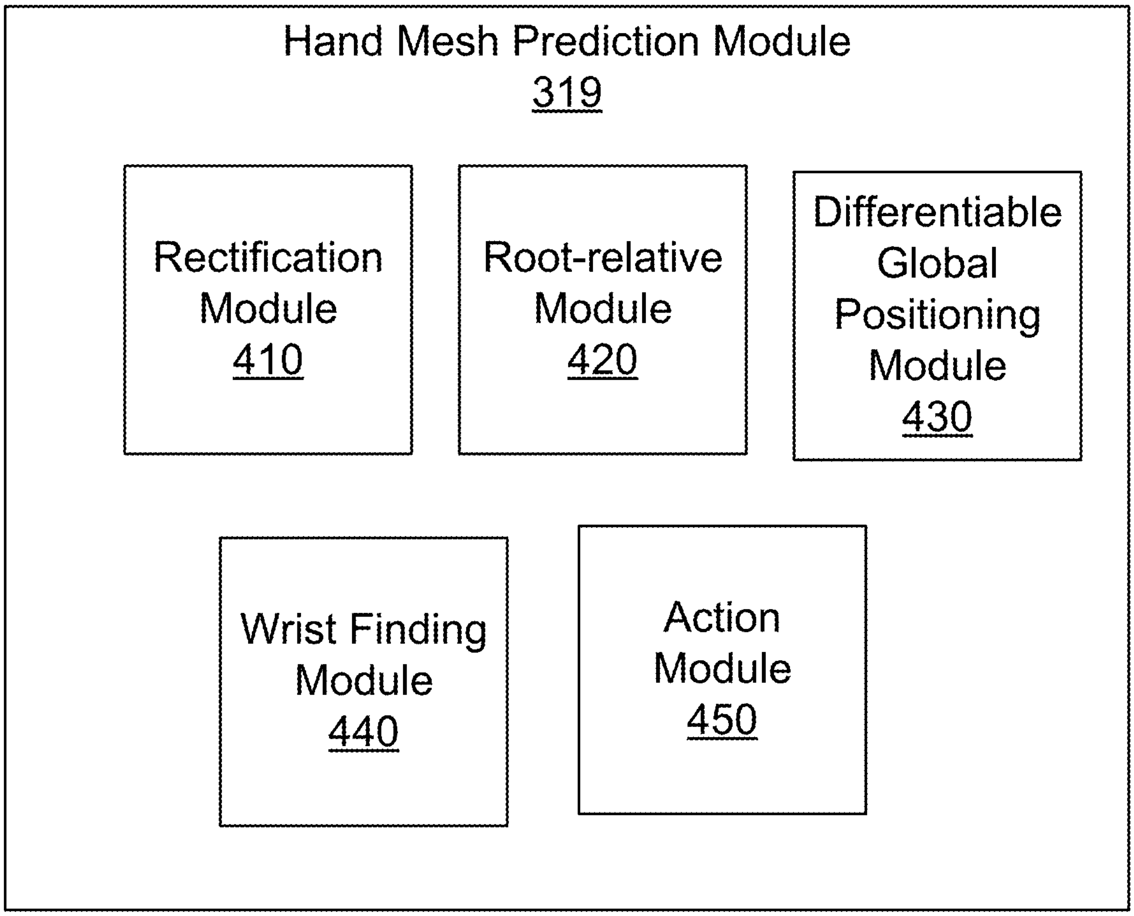
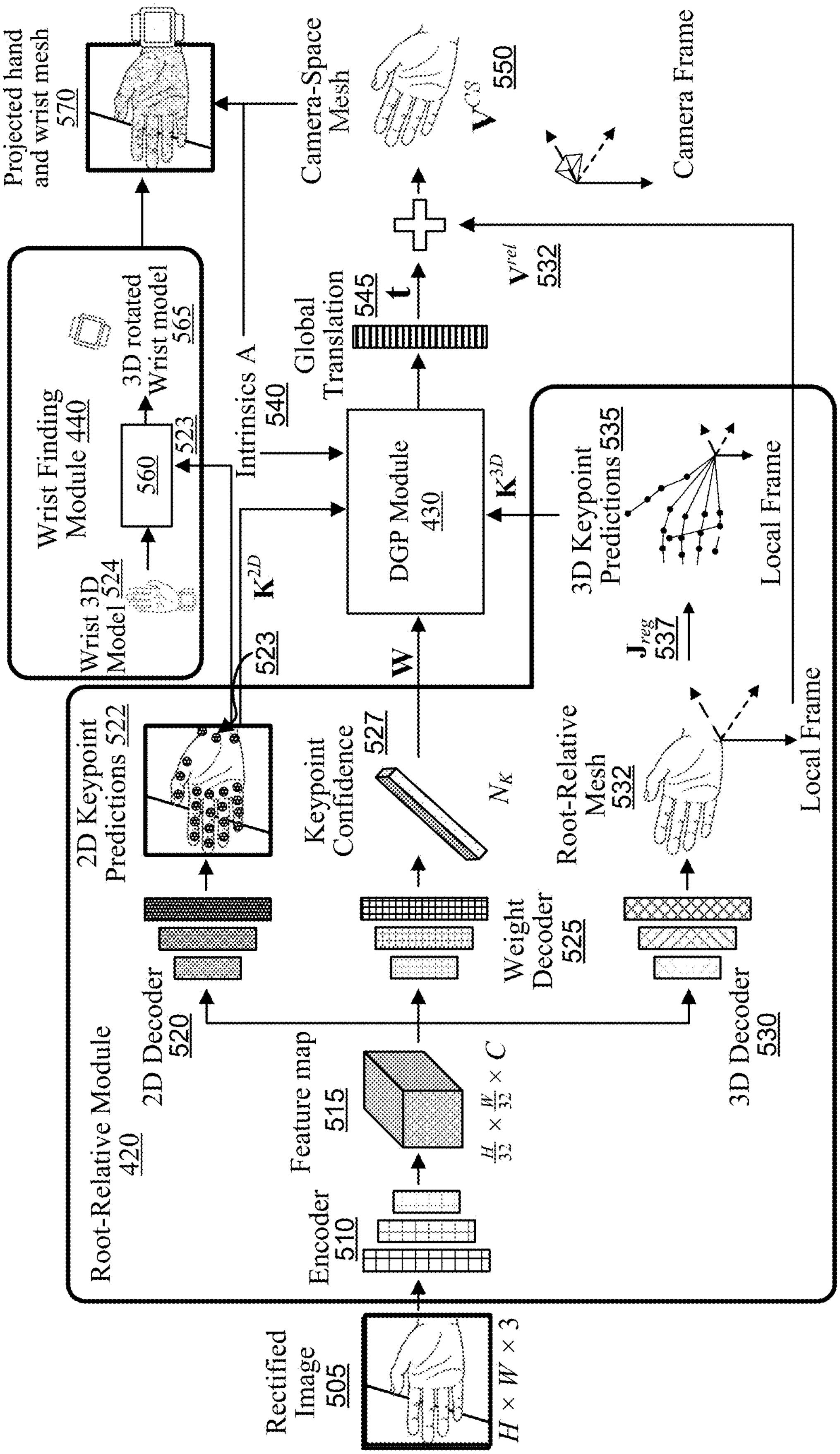

Hand Mesh Prediction Module
319
Rectification Module
410
Root-relative Module
420
Differentiable Global Positioning Module
430
Wrist Finding Module
440
Action Module
450

FIG. 4



Rectified Image 505
$H \times W \times 3$
Root-Relative Module 420
Encoder 510
Feature map 515
$\frac{H}{32} \times \frac{W}{32} \times C$
2D Decoder 520
Weight Decoder 525
3D Decoder 530
2D Keypoint Predictions 522
Keypoint Confidence 527
N_K
Root-Relative Mesh 532
Local Frame
$\mathbf{J}_{reg}$ 537
3D Keypoint Predictions 535
Local Frame
523
$\mathbf{K}^{2D}$
$\mathbf{W}$
DGP Module 430
$\mathbf{K}^{3D}$
Intrinsics A 540
Global Translation 545
$\mathbf{t}$
$\mathbf{V}^{rel}$ 532
Camera-Space Mesh
$\mathbf{V}^{CS}$ 550
Camera Frame
Wrist Finding Module 440
Wrist 3D Model 524
560
523
3D rotated Wrist model 565
Projected hand and wrist mesh 570

FIG. 5

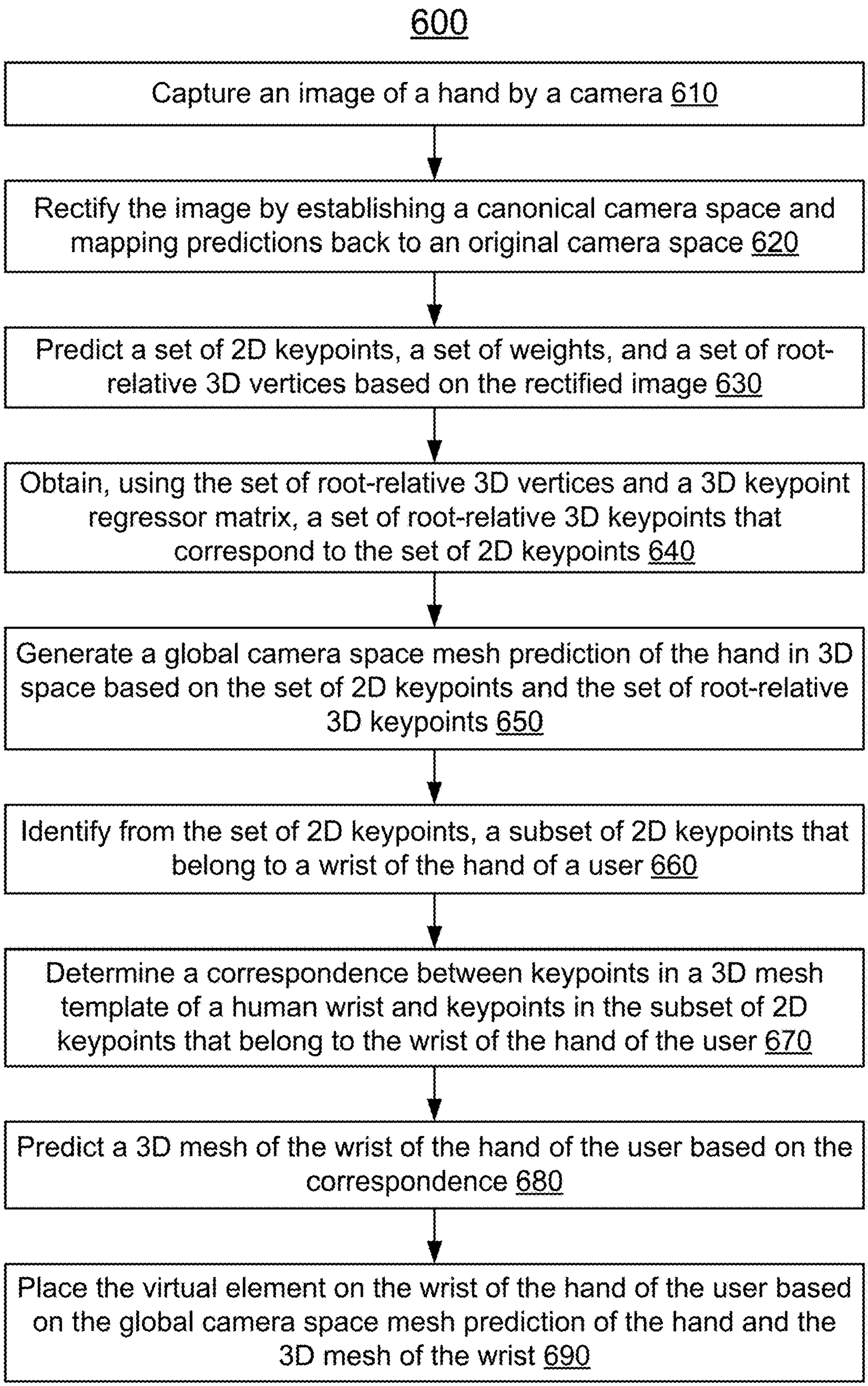

600
Capture an image of a hand by a camera 610
Rectify the image by establishing a canonical camera space and mapping predictions back to an original camera space 620
Predict a set of 2D keypoints, a set of weights, and a set of root-relative 3D vertices based on the rectified image 630
Obtain, using the set of root-relative 3D vertices and a 3D keypoint regressor matrix, a set of root-relative 3D keypoints that correspond to the set of 2D keypoints 640
Generate a global camera space mesh prediction of the hand in 3D space based on the set of 2D keypoints and the set of root-relative 3D keypoints 650
Identify from the set of 2D keypoints, a subset of 2D keypoints that belong to a wrist of the hand of a user 660
Determine a correspondence between keypoints in a 3D mesh template of a human wrist and keypoints in the subset of 2D keypoints that belong to the wrist of the hand of the user 670
Predict a 3D mesh of the wrist of the hand of the user based on the correspondence 680
Place the virtual element on the wrist of the hand of the user based on the global camera space mesh prediction of the hand and the 3D mesh of the wrist 690

FIG. 6

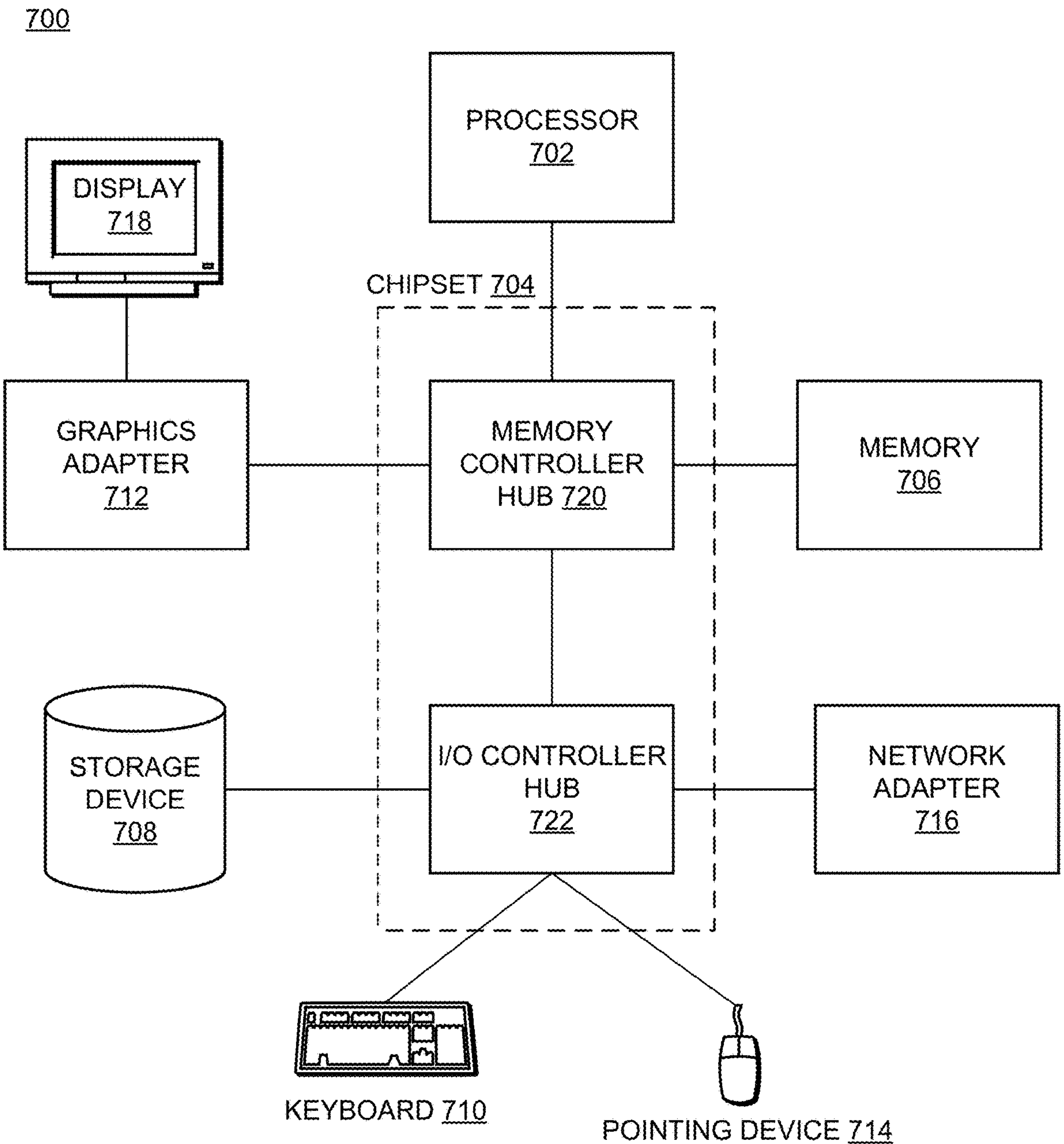

700
PROCESSOR
702
DISPLAY
718
CHIPSET 704
GRAPHICS
ADAPTER
712
MEMORY
CONTROLLER
HUB 720
MEMORY
706
STORAGE
DEVICE
708
I/O CONTROLLER
HUB
722
NETWORK
ADAPTER
716
KEYBOARD 710
POINTING DEVICE 714

FIG. 7

CAMERA-SPACE HAND MESH PREDICTION WITH DIFFERENTIAL GLOBAL POSITIONING

BACKGROUND

1. Technical Field

[0001] The subject matter described relates generally to hand pose estimation, and, in particular, to camera-space 3D hand mesh prediction.

2. Problem

[0002] Predicting 3D hand meshes from single-view RGB images is useful in augmented and virtual reality applications, such as virtual try-on experiences, human digitization, and gaming. While there has been significant progress in recent years, hand mesh prediction remains a challenging problem primarily due to its highly articulated structure, self-occlusions, annotation difficulty, and 2D-to-3D scale and depth ambiguity. Most existing approaches in hand mesh and pose estimation rely on predicting root-relative hand meshes, i.e., 3D hand meshes in coordinates relative to a pre-defined root joint, such as the wrist, as opposed to predicting in a global camera space. Also, the existing techniques typically require large amounts of training data and associated model training that leads to excessive consumption of computing resources including storage requirements, network bandwidth, and processing power.

SUMMARY

[0003] This disclosure pertains to predicting camera-space hand meshes from single RGB images for enabling realistic hand interactions in 3D virtual and augmented worlds. Most conventional approaches in monocular RGB-based camera-space 3D hand mesh and pose estimation follow a two-stage approach: (1) a first stage in which, given a cropped image of the hand, predict meshes in root-relative coordinates, and (2) a second separate and independent stage in which the predicted root-relative coordinates are lifted into camera space, often resulting in the loss of valuable contextual and scale information. To prevent the loss of these cues, techniques disclosed herein look to unify these two stages into an end-to-end solution. This disclosure enables back-propagation from camera space outputs to the rest of the network through a differentiable global positioning (DGP) module. The DGP module enables the backpropagation of gradients directly from camera space outputs to the rest of the network, using a set of 2D-3D correspondences defined by 2D keypoint predictions and root-relative 3D hand mesh predictions. Additionally, this disclosure includes an image rectification module that harmonizes the training dataset and the input image as if they were acquired with the same camera, helping to alleviate the inherent scale-depth ambiguity of the problem.

[0004] In one embodiment, a computer-implemented method according to the present disclosure includes a plurality of steps. The plurality of steps includes a step of accessing an image of a hand captured by a camera, and a step of predicting a set of 2D keypoints and a set of root-relative 3D vertices based on the image. In addition, the steps further include a step of obtaining, using the set of root-relative 3D vertices, a set of root-relative 3D keypoints that correspond to the set of 2D keypoints, and generating a global camera space mesh prediction of the hand in 3D space based on the set of 2D keypoints and the set of root-relative 3D keypoints. Still further, the steps include a step of outputting a virtual element in a virtual space based on the global camera space mesh prediction of the hand.

[0005] In some embodiments, the image is a single RGB image, and the method also includes a step of rectifying the image by establishing a canonical camera space and mapping predictions back to an original camera space, wherein the set of 2D keypoints and the set of root-relative 3D vertices are predicted using the rectified image. The step of rectifying the image may include a step of resizing the image with a ratio that converts camera parameters to an original set of camera parameters.

[0006] In some embodiments, the method also includes a step of predicting a set of weights based on the rectified image, wherein each weight of the set of weights represents a confidence in a prediction of a corresponding keypoint of the set of 2D keypoints, the set of weights accounting for keypoint landmark correspondence inaccuracy due to, for example, occlusion of the hand in the image. The step of obtaining the set of root-relative 3D keypoints that correspond to the set of 2D keypoints may include a step of accessing a 3D keypoint regressor matrix defining keypoint landmarks on the hand as a linear combination of hand mesh vertices; and a step of using the 3D keypoint regressor matrix to obtain the set of root-relative 3D keypoints based on the set of root-relative 3D vertices.

[0007] In some embodiments, the global camera space mesh prediction of the hand is a camera-space vertex prediction that can be projected into 2D using a pinhole camera perspective projection. The method may further include a step of predicting a global translation in camera space based on the set of 2D keypoints, the set of root-relative 3D keypoints, and the set of weights; and a step of generating the global camera space mesh prediction of the hand in 3D space based on the global translation and the set of root-relative 3D vertices.

[0008] In some embodiments, the method may also include a step of identifying from the set of 2D keypoints, a subset of 2D keypoints that belong to a wrist of the hand of a user; a step of determining a correspondence between keypoints in a 3D mesh template of a human wrist and keypoints in the subset of 2D keypoints that belong to the wrist of the hand of the user; and a step of predicting a 3D mesh of the wrist of the hand of the user based on the correspondence. The step of outputting the virtual element in the virtual space based the global camera space mesh prediction of the hand may include a step of placing the virtual element on the wrist of the hand of the user based on the global camera space mesh prediction of the hand and the 3D mesh of the wrist.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** depicts a representation of a virtual world having a geography that parallels the real world, according to one embodiment.

[0010] FIG. **2** depicts an exemplary interface of a parallel reality game, according to one embodiment.

[0011] FIG. **3** is a block diagram of a networked computing environment suitable for camera-space 3D hand mesh prediction, according to one embodiment.

[0012] FIG. **4** is a block diagram of the hand mesh prediction module shown in FIG. **3**, according to one embodiment.

[0013] FIG. **5** illustrates the architecture and image processing pipeline of the hand mesh prediction module shown in FIG. **3**, according to one embodiment.

[0014] FIG. **6** is a flowchart of a process for generating a camera-space 3D mesh of the hand and a wrist, according to one embodiment.

[0015] FIG. **7** illustrates an example computer system suitable for use in the networked computing environment of FIG. **1**, according to one embodiment.

DETAILED DESCRIPTION

[0016] The figures and the following description describe certain embodiments by way of illustration only. One skilled in the art will recognize from the following description that alternative embodiments of the structures and methods may be employed without departing from the principles described. Wherever practicable, similar or like reference numbers are used in the figures to indicate similar or like functionality. Where elements share a common numeral followed by a different letter, this indicates the elements are similar or identical. A reference to the numeral alone generally refers to any one or any combination of such elements, unless the context indicates otherwise.

[0017] Various embodiments are described in the context of a parallel reality game that includes augmented reality content in a virtual world geography that parallels at least a portion of the real-world geography such that player movement and actions in the real-world affect actions in the virtual world. The subject matter described is applicable in other situations where camera-space 3D hand mesh prediction is desirable. In addition, the inherent flexibility of computer-based systems allows for a great variety of possible configurations, combinations, and divisions of tasks and functionality between and among the components of the system.

Example Location-Based Parallel Reality Game

[0018] FIG. **1** is a conceptual diagram of a virtual world **110** that parallels the real world **100**. The virtual world **110** can act as the game board for players of a parallel reality game. As illustrated, the virtual world **110** includes a geography that parallels the geography of the real world **100**. In particular, a range of coordinates defining a geographic area or space in the real world **100** is mapped to a corresponding range of coordinates defining a virtual space in the virtual world **110**. The range of coordinates in the real world **100** can be associated with a town, neighborhood, city, campus, locale, a country, continent, the entire globe, or other geographic area. Each geographic coordinate in the range of geographic coordinates is mapped to a corresponding coordinate in a virtual space in the virtual world **110**.

[0019] A player's position in the virtual world **110** corresponds to the player's position in the real world **100**. For instance, player A located at position **112** in the real world **100** has a corresponding position **122** in the virtual world **110**. Similarly, player B located at position **114** in the real world **100** has a corresponding position **124** in the virtual world **110**. As the players move about in a range of geographic coordinates in the real world **100**, the players also move about in the range of coordinates defining the virtual space in the virtual world **110**. In particular, a positioning system (e.g., a GPS system, a localization system, or both) associated with a mobile computing device carried by the player can be used to track a player's position as the player navigates the range of geographic coordinates in the real world **100**. Data associated with the player's position in the real world **100** is used to update the player's position in the corresponding range of coordinates defining the virtual space in the virtual world **110**. In this manner, players can navigate along a continuous track in the range of coordinates defining the virtual space in the virtual world **110** by simply traveling among the corresponding range of geographic coordinates in the real world **100** without having to check in or periodically update location information at specific discrete locations in the real world **100**.

[0020] The location-based game can include game objectives requiring players to travel to or interact with various virtual elements or virtual objects scattered at various virtual locations in the virtual world **110**. A player can travel to these virtual locations by traveling to the corresponding location of the virtual elements or objects in the real world **100**. For instance, a positioning system can track the position of the player such that as the player navigates the real world **100**, the player also navigates the parallel virtual world **110**. The player can then interact with various virtual elements and objects at the specific location to achieve or perform one or more game objectives.

[0021] A game objective may have players interacting with virtual elements **130** located at various virtual locations in the virtual world **110**. These virtual elements **130** can be linked to landmarks, geographic locations, or objects **140** in the real world **100**. The real-world landmarks or objects **140** can be works of art, monuments, buildings, businesses, libraries, museums, or other suitable real-world landmarks or objects. Interactions include capturing, claiming ownership of, using some virtual item, spending some virtual currency, etc. To capture these virtual elements **130**, a player travels to the landmark or geographic locations **140** linked to the virtual elements **130** in the real world and performs any necessary interactions (as defined by the game's rules) with the virtual elements **130** in the virtual world **110**. For example, player A may have to travel to a landmark **140** in the real world **100** to interact with or capture a virtual element **130** linked with that particular landmark **140**. The interaction with the virtual element **130** can require action in the real world, such as taking a photograph or verifying, obtaining, or capturing other information about the landmark or object **140** associated with the virtual element **130**.

[0022] Game objectives may require that players use one or more virtual items that are collected by the players in the location-based game. For instance, the players may travel the virtual world **110** seeking virtual items **132** (e.g., weapons, creatures, power ups, or other items) that can be useful for completing game objectives. These virtual items **132** can be found or collected by traveling to different locations in the real world **100** or by completing various actions in either the virtual world **110** or the real world **100** (such as interacting with virtual elements **130**, battling non-player characters or other players, or completing quests, etc.). In the example shown in FIG. **1**, a player uses virtual items **132** to capture one or more virtual elements **130**. In particular, a player can deploy virtual items **132** at locations in the virtual world **110** near to or within the virtual elements **130**. Deploying one or more virtual items **132** in this manner can result in the capture of the virtual element **130** for the player or for the team/faction of the player.

[0023] In one particular implementation, a player may have to gather virtual energy as part of the parallel reality game. Virtual energy **150** can be scattered at different locations in the virtual world **110**. A player can collect the virtual energy **150** by traveling to (or within a threshold distance of) the location in the real world **100** that corresponds to the location of the virtual energy in the virtual world **110**. The virtual energy **150** can be used to power virtual items or perform various game objectives in the game. A player that loses all virtual energy **150** may be disconnected from the game or prevented from playing for a certain amount of time or until they have collected additional virtual energy **150**.

[0024] According to aspects of the present disclosure, the parallel reality game can be a massive multi-player location-based game where every participant in the game shares the same virtual world. The players can be divided into separate teams or factions and can work together to achieve one or more game objectives, such as to capture or claim ownership of a virtual element. In this manner, the parallel reality game can intrinsically be a social game that encourages cooperation among players within the game. Players from opposing teams can work against each other (or sometime collaborate to achieve mutual objectives) during the parallel reality game. A player may use virtual items to attack or impede progress of players on opposing teams. In some cases, players are encouraged to congregate at real world locations for cooperative or interactive events in the parallel reality game. In these cases, the game server seeks to ensure players are indeed physically present and not spoofing their locations.

[0025] FIG. **2** depicts one embodiment of a game interface **200** that can be presented (e.g., on a player's smartphone) as part of the interface between the player and the virtual world **110**. The game interface **200** includes a display window **210** that can be used to display the virtual world **110** and various other aspects of the game, such as player position **122** and the locations of virtual elements **130**, virtual items **132**, and virtual energy **150** in the virtual world **110**. The user interface **200** can also display other information, such as game data information, game communications, player information, client location verification instructions and other information associated with the game. For example, the user interface can display player information **215**, such as player name, experience level, and other information. The user interface **200** can include a menu **220** for accessing various game settings and other information associated with the game. The user interface **200** can also include a communications interface **230** that enables communications between the game system and the player and between one or more players of the parallel reality game.

[0026] According to aspects of the present disclosure, a player can interact with the parallel reality game by carrying a client device around in the real world. For instance, a player can play the game by accessing an application associated with the parallel reality game on a smartphone and moving about in the real world with the smartphone. In this regard, it is not necessary for the player to continuously view a visual representation of the virtual world on a display screen in order to play the location-based game. As a result, the user interface **200** can include non-visual elements that allow a user to interact with the game. For instance, the game interface can provide audible notifications to the player when the player is approaching a virtual element or object in the game or when an important event happens in the parallel reality game. In some embodiments, a player can control these audible notifications with audio control **240**. Different types of audible notifications can be provided to the user depending on the type of virtual element or event. The audible notification can increase or decrease in frequency or volume depending on a player's proximity to a virtual element or object. Other non-visual notifications and signals can be provided to the user, such as a vibratory notification or other suitable notifications or signals.

[0027] The parallel reality game can have various features to enhance and encourage game play within the parallel reality game. For instance, players can accumulate a virtual currency or another virtual reward (e.g., virtual tokens, virtual points, virtual material resources, etc.) that can be used throughout the game (e.g., to purchase in-game items, to redeem other items, to craft items, etc.). Players can advance through various levels as the players complete one or more game objectives and gain experience within the game. Players may also be able to obtain enhanced "powers" or virtual items that can be used to complete game objectives within the game.

[0028] Those of ordinary skill in the art, using the disclosures provided, will appreciate that numerous game interface configurations and underlying functionalities are possible. The present disclosure is not intended to be limited to any one particular configuration unless it is explicitly stated to the contrary.

Example Gaming System

[0029] FIG. **3** illustrates one embodiment of a networked computing environment **300**. The networked computing environment **300** uses a client-server architecture, where a game server **320** communicates with a client device **310** over a network **370** to provide a parallel reality game to a player at the client device **310**. The networked computing environment **300** also may include other external systems such as sponsor/advertiser systems or business systems. Although only one client device **310** is shown in FIG. **3**, any number of client devices **310** or other external systems may be connected to the game server **320** over the network **370**. Furthermore, the networked computing environment **300** may contain different or additional elements and functionality may be distributed between the client device **310** and the server **320** in different manners than described below.

[0030] The networked computing environment **300** provides for the interaction of players in a virtual world having a geography that parallels the real world. In particular, a geographic area in the real world can be linked or mapped directly to a corresponding area in the virtual world. A player can move about in the virtual world by moving to various geographic locations in the real world. For instance, a player's position in the real world can be tracked and used to update the player's position in the virtual world. Typically, the player's position in the real world is determined by finding the location of a client device **310** through which the player is interacting with the virtual world and assuming the player is at the same (or approximately the same) location. For example, in various embodiments, the player may interact with a virtual element if the player's location in the real world is within a threshold distance (e.g., ten meters, twenty meters, etc.) of the real-world location that corresponds to the virtual location of the virtual element in the virtual world. For convenience, various embodiments are described with reference to "the player's location" but one of skill in the art will appreciate that such references may refer to the location of the player's client device **310**.

[0031] A client device **310** can be any portable computing device capable for use by a player to interface with the game server **320**. For instance, a client device **310** is preferably a portable wireless device that can be carried by a player, such as a smartphone, portable gaming device, augmented reality (AR) headset, cellular phone, tablet, personal digital assistant (PDA), navigation system, handheld GPS system, or other such device. For some use cases, the client device **310** may be a less-mobile device such as a desktop or a laptop computer. Furthermore, the client device **310** may be a vehicle with a built-in computing device.

[0032] The client device **310** communicates with the game server **320** to provide sensory data of a physical environment. In one embodiment, the client device **310** includes a camera assembly **312**, a gaming module **314**, a positioning module **316**, a localization module **318**, and a hand mesh prediction module **319**. The client device **310** also includes a network interface (not shown) for providing communications over the network **370**. In various embodiments, the client device **310** may include different or additional components, such as additional sensors, display, and software modules, etc.

[0033] The camera assembly **312** includes one or more cameras which can capture image data. The cameras capture image data describing a scene of the environment surrounding the client device **310** with a particular pose (the location and orientation of the camera within the environment). The camera assembly **312** may use a variety of photo sensors with varying color capture ranges and varying capture rates. Similarly, the camera assembly **312** may include cameras with a range of different lenses, such as a wide-angle lens or a telephoto lens. The camera assembly **312** may be configured to capture single images or multiple images as frames of a video. In some embodiments, the camera assembly **312** may capture an image (e.g., live image or through image) of a hand of a user of the client device **310**. The captured image may be processed and input to the hand mesh prediction module **319** to generate and overlay a live 3D mesh of the hand and the wrist of the user to enable different virtual experiences related to augmented reality, virtual reality, mixed reality, parallel reality, and the like. For example, the virtual experiences may include virtual try-on experiences, office work using an AR or mixed-reality headset, gaming, and the like.

[0034] The client device **310** may also include additional sensors for collecting data regarding the environment surrounding the client device, such as movement sensors, accelerometers, gyroscopes, barometers, thermometers, light sensors, microphones, etc. The image data captured by the camera assembly **312** can be appended with metadata describing other information about the image data, such as additional sensory data (e.g., temperature, brightness of environment, air pressure, location, pose etc.) or capture data (e.g., exposure length, shutter speed, focal length, capture time, etc.).

[0035] The gaming module **314** provides a player with an interface to participate in the parallel reality game. The game server **320** transmits game data over the network **370** to the client device **310** for use by the gaming module **314** to provide a local version of the game to a player at locations remote from the game server. In one embodiment, the gaming module **314** presents a user interface on a display of the client device **310** that depicts a virtual world (e.g., renders imagery of the virtual world) and allows a user to interact with the virtual world to perform various game objectives. In some embodiments, the gaming module **314** presents images of the real world (e.g., captured by the camera assembly **312**) augmented with virtual elements from the parallel reality game. In these embodiments, the gaming module **314** may generate or adjust virtual content according to other information received from other components of the client device **310**. For example, the gaming module **314** may adjust a virtual object to be displayed on the user interface according to a depth map of the scene captured in the image data.

[0036] The gaming module **314** can also control various other outputs to allow a player to interact with the game without requiring the player to view a display screen. For instance, the gaming module **314** can control various audio, vibratory, or other notifications that allow the player to play the game without looking at the display screen.

[0037] The positioning module **316** can be any device or circuitry for determining the position of the client device **310**. For example, the positioning module **316** can determine actual or relative position by using a satellite navigation positioning system (e.g., a GPS system, a Galileo positioning system, the Global Navigation satellite system (GLONASS), the BeiDou Satellite Navigation and Positioning system), an inertial navigation system, a dead reckoning system, IP address analysis, triangulation and/or proximity to cellular towers or Wi-Fi hotspots, or other suitable techniques.

[0038] As the player moves around with the client device **310** in the real world, the positioning module **316** tracks the position of the player and provides the player position information to the gaming module **314**. The gaming module **314** updates the player position in the virtual world associated with the game based on the actual position of the player in the real world. Thus, a player can interact with the virtual world simply by carrying or transporting the client device **310** in the real world. In particular, the location of the player in the virtual world can correspond to the location of the player in the real world. The gaming module **314** can provide player position information to the game server **320** over the network **370**. In response, the game server **320** may enact various techniques to verify the location of the client device **310** to prevent cheaters from spoofing their locations. It should be understood that location information associated with a player is utilized only if permission is granted after the player has been notified that location information of the player is to be accessed and how the location information is to be utilized in the context of the game (e.g., to update player position in the virtual world). In addition, any location information associated with players is stored and maintained in a manner to protect player privacy.

[0039] The localization module **318** provides an additional or alternative way to determine the location of the client device **310**. In one embodiment, the localization module **318** receives the location determined for the client device **310** by the positioning module **316** and refines it by determining a pose of one or more cameras of the camera assembly **312**. The localization module **318** may use the location generated by the positioning module **316** to select a 3D map of the environment surrounding the client device **310** and localize against the 3D map. The localization module **318** may obtain the 3D map from local storage or from the game server **320**. The 3D map may be a point cloud, mesh, or any other suitable 3D representation of the environment surrounding the client device **310**. Alternatively, the localization module **318** may determine a location or pose of the client device **310** without reference to a coarse location (such as one provided by a GPS system), such as by determining the relative location of the client device **310** to another device.

[0040] In one embodiment, the localization module **318** applies a trained model to determine the pose of images captured by the camera assembly **312** relative to the 3D map. Thus, the localization model can determine an accurate (e.g., to within a few centimeters and degrees) determination of the position and orientation of the client device **310**. The position of the client device **310** can then be tracked over time using dead reckoning based on sensor readings, periodic re-localization, or a combination of both. Having an accurate pose for the client device **310** may enable the gaming module **314** to present virtual content overlaid on images of the real world (e.g., by displaying virtual elements in conjunction with a real-time feed from the camera assembly **312** on a display) or the real world itself (e.g., by displaying virtual elements on a transparent display of an AR headset) in a manner that gives the impression that the virtual objects are interacting with the real world. For example, a virtual character may hide behind a real tree, a virtual hat may be placed on a real statue, or a virtual creature may run and hide if a real person approaches it too quickly.

[0041] The hand mesh prediction module **319** performs camera space 3D hand mesh predictions based on an image captured by the camera assembly **312**. The 3D hand mesh predicted by the hand mesh prediction module **319** may be provided to the gaming module **314** to enable the gaming module **314** to present virtual content overlaid on a real-world image of a hand of the user of the client device **310** (e.g., by displaying virtual elements in conjunction with a real-time feed that includes a hand from the camera assembly **312** on a display) to enable, e.g., virtual try-on experiences, human digitization, gaming experiences, and office work when using AR or mixed-reality headsets. For example, an image captured by the camera assembly **312** may be a single RGB image. The RGB image may be stored in a memory (e.g., temporary memory, storage disk) of the client device **310**. The stored image may be accessed by the hand mesh prediction module **319** to perform the hand mesh prediction based on the accessed image. One or more processes (e.g., rectification by an image rectification module) may be performed on the accessed image prior to performing the hand mesh prediction. One or more models that form the hand mesh prediction pipeline of the hand mesh prediction module **319** may be trained in advance (e.g., by the training module **328**) and provided to the client device **310** in advance.

[0042] The game server **320** includes one or more computing devices that provide game functionality to the client device **310**. The game server **320** can include or be in communication with a game database **330**. The game database **330** stores game data used in the parallel reality game to be served or provided to the client device **310** over the network **370**.

[0043] The game data stored in the game database **330** can include: (1) data associated with the virtual world in the parallel reality game (e.g., image data used to render the virtual world on a display device, geographic coordinates of locations in the virtual world, etc.); (2) data associated with players of the parallel reality game (e.g., player profiles including but not limited to player information, player experience level, player currency, current player positions in the virtual world/real world, player energy level, player preferences, team information, faction information, etc.); (3) data associated with game objectives (e.g., data associated with current game objectives, status of game objectives, past game objectives, future game objectives, desired game objectives, etc.); (4) data associated with virtual elements in the virtual world (e.g., positions of virtual elements, types of virtual elements, game objectives associated with virtual elements; corresponding actual world position information for virtual elements; behavior of virtual elements, relevance of virtual elements etc.); (5) data associated with real-world objects, landmarks, positions linked to virtual-world elements (e.g., location of real-world objects/landmarks, description of real-world objects/landmarks, relevance of virtual elements linked to real-world objects, etc.); (6) game status (e.g., current number of players, current status of game objectives, player leaderboard, etc.); (7) data associated with player actions/input (e.g., current player positions, past player positions, player moves, player input, player queries, player communications, etc.); or (8) any other data used, related to, or obtained during implementation of the parallel reality game. The game data stored in the game database **330** can be populated either offline or in real time by system administrators or by data received from users (e.g., players), such as from a client device **310** over the network **370**.

[0044] In one embodiment, the game server **320** is configured to receive requests for game data from a client device **310** (for instance via remote procedure calls (RPCs)) and to respond to those requests via the network **370**. The game server **320** can encode game data in one or more data files and provide the data files to the client device **310**. In addition, the game server **320** can be configured to receive game data (e.g., player positions, player actions, player input, etc.) from a client device **310** via the network **370**. The client device **310** can be configured to periodically send player input and other updates to the game server **320**, which the game server uses to update game data in the game database **330** to reflect any and all changed conditions for the game.

[0045] In the embodiment shown in FIG. **3**, the game server **320** includes a universal game module **322**, a commercial game module **323**, a data collection module **324**, an event module **326**, a mapping system **327**, a training module **328**, and a 3D map store **329**. As mentioned above, the game server **320** interacts with a game database **330** that may be part of the game server or accessed remotely (e.g., the game database **330** may be a distributed database accessed via the network **370**). In other embodiments, the game server **320** contains different or additional elements. In addition, the functions may be distributed among the elements in a different manner than described.

[0046] The universal game module **322** hosts an instance of the parallel reality game for a set of players (e.g., all players of the parallel reality game) and acts as the authoritative source for the current status of the parallel reality game for the set of players. As the host, the universal game module **322** generates game content for presentation to players (e.g., via their respective client devices **310**). The universal game module **322** may access the game database **330** to retrieve or store game data when hosting the parallel reality game. The universal game module **322** may also receive game data from client devices **310** (e.g., depth information, player input, player position, player actions, landmark information, etc.) and incorporates the game data received into the overall parallel reality game for the entire set of players of the parallel reality game. The universal game module **322** can also manage the delivery of game data to the client device **310** over the network **370**. In some embodiments, the universal game module **322** also governs security aspects of the interaction of the client device **310** with the parallel reality game, such as securing connections between the client device and the game server **320**, establishing connections between various client devices, or verifying the location of the various client devices **310** to prevent players cheating by spoofing their location.

[0047] The commercial game module **323** can be separate from or a part of the universal game module **322**. The commercial game module **323** can manage the inclusion of various game features within the parallel reality game that are linked with a commercial activity in the real world. For instance, the commercial game module **323** can receive requests from external systems such as sponsors/advertisers, businesses, or other entities over the network **370** to include game features linked with commercial activity in the real world. The commercial game module **323** can then arrange for the inclusion of these game features in the parallel reality game on confirming the linked commercial activity has occurred. For example, if a business pays the provider of the parallel reality game an agreed upon amount, a virtual object identifying the business may appear in the parallel reality game at a virtual location corresponding to a real-world location of the business (e.g., a store or restaurant).

[0048] The data collection module **324** can be separate from or a part of the universal game module **322**. The data collection module **324** can manage the inclusion of various game features within the parallel reality game that are linked with a data collection activity in the real world. For instance, the data collection module **324** can modify game data stored in the game database **330** to include game features linked with data collection activity in the parallel reality game. The data collection module **324** can also analyze data collected by players pursuant to the data collection activity and provide the data for access by various platforms.

[0049] The event module **326** manages player access to events in the parallel reality game. Although the term "event" is used for convenience, it should be appreciated that this term need not refer to a specific event at a specific location or time. Rather, it may refer to any provision of access-controlled game content where one or more access criteria are used to determine whether players may access that content. Such content may be part of a larger parallel reality game that includes game content with less or no access control or may be a stand-alone, access controlled parallel reality game.

[0050] The mapping system **327** generates a 3D map of a geographical region based on a set of images. The 3D map may be a point cloud, polygon mesh, or any other suitable representation of the 3D geometry of the geographical region. The 3D map may include semantic labels providing additional contextual information, such as identifying objects tables, chairs, clocks, lampposts, trees, etc.), materials (concrete, water, brick, grass, etc.), or game properties (e.g., traversable by characters, suitable for certain in-game actions, etc.). In one embodiment, the mapping system **327** stores the 3D map along with any semantic/contextual information in the 3D map store **329**. The 3D map may be stored in the 3D map store **329** in conjunction with location information (e.g., GPS coordinates of the center of the 3D map, a ringfence defining the extent of the 3D map, or the like). Thus, the game server **320** can provide the 3D map to client devices **310** that provide location data indicating they are within or near the geographic area covered by the 3D map.

[0051] The training module **328** trains the one or more models (e.g., neural networks) of the hand mesh prediction module **319** for use by client devices **310**. Although the training module **328** is shown as part of the game server **320** for convenience, the training module **328** may be trained and provided to client devices **310** by another system or systems. For example, a differentiable global positioning model, a wrist finding model, and/or a root-relative model of the hand mesh prediction module **319** may be trained by a development system and incorporated in an application that is downloaded to client devices **310** from an app store.

[0052] The network **370** can be any type of communications network, such as a local area network (e.g., an intranet), wide area network (e.g., the internet), or some combination thereof. The network can also include a direct connection between a client device **310** and the game server **320**. In general, communication between the game server **320** and a client device **310** can be carried via a network interface using any type of wired or wireless connection, using a variety of communication protocols (e.g., TCP/IP, HTTP, SMTP, FTP), encodings or formats (e.g., HTML, XML, JSON), or protection schemes (e.g., VPN, secure HTTP, SSL).

[0053] This disclosure makes reference to servers, databases, software applications, and other computer-based systems, as well as actions taken and information sent to and from such systems. One of ordinary skill in the art will recognize that the inherent flexibility of computer-based systems allows for a great variety of possible configurations, combinations, and divisions of tasks and functionality between and among components. For instance, processes disclosed as being implemented by a server may be implemented using a single server or multiple servers working in combination. Databases and applications may be implemented on a single system or distributed across multiple systems. Distributed components may operate sequentially or in parallel.

[0054] In situations in which the systems and methods disclosed access and analyze personal information about users, or make use of personal information, such as location information, the users may be provided with an opportunity to control whether programs or features collect the information and control whether or how to receive content from the system or other application. No such information or data is collected or used until the user has been provided meaningful notice of what information is to be collected and how the information is used. The information is not collected or used unless the user provides consent, which can be revoked or modified by the user at any time. Thus, the user can have control over how information is collected about the user and used by the application or system. In addition, certain information or data can be treated in one or more ways before it is stored or used, so that personally identifiable information is removed. For example, a user's identity may be treated so that no personally identifiable information can be determined for the user.

[0055] FIG. **4** is a block diagram of the hand mesh prediction module **319** shown in FIG. **3**, according to one embodiment. In the embodiment shown in FIG. **4**, the hand mesh prediction module **319** includes a rectification module **410**, a root-relative module **420**, a differentiable global positioning (DGP) module **430**, and a wrist finding module **440**. In other embodiments, the hand mesh prediction module **319** contains different or additional elements. In addition, the functions may be distributed among the elements in a different manner than described.

[0056] FIG. **5** illustrates the architecture and image processing pipeline of the hand mesh prediction module **319** of FIG. **3**, according to one embodiment. The architecture and image processing pipeline of the hand mesh prediction module **319** illustrated in FIG. **5** is for illustration only. Other embodiments of the hand mesh prediction module **319** may adopt a different architecture and/or image processing pipeline.

[0057] Referring back to FIG. **4**, the rectification module **410** may rectify an image (e.g., single RGB image captured by the camera assembly **312** of the client device **310**) that is input to the image processing pipeline by establishing a canonical camera space and mapping predictions back to an original camera space.

[0058] That is, the rectification module **410** establishes a canonical camera space and transforms the training data into that space. During inference, the rectification module **410** rectifies the image (e.g., an image captured by camera assembly **312** and input to the rectification module **410**) and provides the rectified image to the root-relative module **420** for 3D hand and/or wrist mesh prediction. FIG. **5** illustrates at **505** that an image rectified by the image rectification module **410** is input to the root-relative module **420** for feature extraction and further downstream processing by the image processing pipeline (e.g., predicting a set of 2D keypoints and a set of root-relative 3D vertices using the rectified image). Predictions by the pipeline are mapped back to the original camera space.

[0059] The original set of camera parameters is defined by $\{f, u_0, v_0\}$ where f represents the focal length (we assume $f_x=f_y=f$) and u_0 and v_0 be the principal points. The rectification module **410** may resize the input image I with the ratio

$$\omega_r = \frac{f^c}{f}$$

which converts the camera parameters to $\{f^c, \omega_r u_0, \omega_r v_0\}$. In some embodiments, the rectification module **410** may further rectify the principal point to be the center of the hand crop, resulting in the final canonical intrinsics matrix A defined by $\{f^c, H/2, W/2\}$ where f^c is the canonical focal length and the rectified principal point is the center of the input image. The image rectification step by the rectification module **410** may be performed both during training and testing, and the inverse transformation may be applied to project into the original image during inference.

[0060] Returning to FIG. **4**, the root-relative module **420** predicts a set of 2D keypoints and a set of root-relative 3D vertices based on the image. In some embodiments, the root-relative module **420** may also predict a set of weights based on the rectified image. Each weight of the set of weights may represent a confidence in a prediction of a corresponding keypoint of the set of 2D keypoints. The set of weights may account for keypoint landmark correspondence inaccuracy due to occlusion of the hand in the image.

[0061] For example, as illustrated in the pipeline of FIG. **5**, the root-relative module **420** may take an image **505** $I \in \mathbb{R}^{H\times W\times 3}$ as an input to a convolutional encoder **510** to produce a feature map **515** $F \in \mathbb{R}^{H/32\times W/32\times C}$. The feature map **515** F may then be input to three separate decoder heads: a 2D decoder **520** outputting a set of N_K 2D keypoints K^{2D}, a 3D decoder **530** outputting the root-relative vertices V^{rel}, and a weights decoder **525** outputting a set of confidence weights W.

[0062] That is, as shown in FIG. **5**, starting from a single RGB image **505** $I \in \mathbb{R}^{H\times W\times 3}$, the root-relative module **420** may predict a set of 2D keypoints **522**, that can be joints or other landmarks of the hand input at **505**, $K^{2D}=\{k_i^{2D}\}_{i=1}^{N_K}$, a set of root-relative 3D vertices **532** $V^{rel}=\{v_i^{rel}\}_{i=1}^{N_V}$, and a set of weights **527** $W=\{w_i\}_{i=1}^{N_K}$, that represent the confidence in the predictions of each landmark. As shown in FIG. **5**, the set of 2D keypoints **522** predicted by 2D decoder **520** of the root-relative module **420** may include hand joints or other landmarks such as user wrist keypoints.

[0063] In cases such as occlusion or self-occlusion of parts of the hand, the occluded parts may result in more uncertain keypoint placements at **522** by the 2D decoder **520**. To address this issue, the root-relative module **420** may apply a weighted variant **527** with the weight decoder **525**. That is, the weight decoder **527** determines a confidence score w_i associated with each keypoint correspondence at **522** and constructs a weight matrix by duplicating each weight once and placing them in a diagonal matrix $W=\mathrm{diag}([w_1, w_1, w_2, w_2 \ldots w_{N_K}, w_{N_K}])$.

[0064] Starting from the feature map **515** $F \in \mathbb{R}^{H/32\times W/32\times C}$, the weight decoder **525** may perform a series of 1×1 convolutions to obtain a new feature map $F_W \in \mathbb{R}^{H/32\times W/32\times D}$. The weight decoder **525** may then use the 2D positions provided by K^{2D} **522** in order to grid sample a set of N_K, D-dimensional features **527**, which are concatenated in $D\times N_K$ dimensional latent vector Z_W which is then processed through a set of dense layers with leaky ReLU activations, and the final output is processed through a sigmoid function, forcing the confidence weights to be in [0,1].

[0065] The root-relative module **420** may further obtain, using the set of root-relative 3D vertices **532**, a set of root-relative 3D keypoints **535** that correspond to the set of 2D keypoints **522**. To obtain the set of root-relative 3D keypoints **535**, the root-relative module **420** may access a 3D keypoint regressor matrix **537** defining keypoint landmarks on the hand as a linear combination of hand mesh vertices. The root-relative module **420** may then use the 3D keypoint regressor matrix **537** to obtain the set of root-relative 3D keypoints **535** based on the set of root-relative 3D vertices **532**.

[0066] That is, as shown in FIG. **5**, the root-relative module **420** may obtain $K^{3D}=\{k_i^{3D}\}_{i=1}^{N_K}$ a set of root-relative 3D keypoints **535** on the hand model that correspond to the 2D keypoints K^{2D} **522**. To obtain K^{3D} **535**, the root-relative module **420** may access a 3D keypoint regressor **537** J_{reg}:$V^{rel} \rightarrow K^{3D}$. J_{reg} may be in the form of a matrix, which defines keypoints landmarks on the hand as a linear combination of hand mesh vertices, and may be provided with publicly available mesh models.

[0067] Returning to FIG. **4**, the DGP module **430** may generate a global camera space mesh prediction of the hand in 3D space based on the set of 2D keypoints and the set of root-relative 3D keypoints. That is, as shown in FIG. **5**, the DGP module **430** takes as input K^{3D} **535**, K^{2D} **522**, and camera intrinsics A **540** as input, and outputs the global camera-space translation t **545** in a differentiable manner.

[0068] To obtain the global translation **545** $t=[\tau_X, \tau_y, \tau_z]^T$ in a differentiable way, the DGP module **430** adapts a technique based on Direct Linear Transform (DLT). Firstly, by design K^{3D} **535** and K^{2D} **522** give a set of 2D-3D correspondences $\mathcal{M}=\{(k_i^{3D}, k_i^{2D})\}_{i=1}^{N_K}$, with $k_i^{3D}=[x_i, y_i, z_i]^T$ and $k_i^{2D}=[u_i, v_i]^T$. Additionally, the 3D keypoints K^{3D} **535** are expressed in a frame that shares the same orientation as the camera frame, with only the global root translation missing to map root-relative keypoint coordinates to camera-space coordinates. Assuming a pinhole camera model with intrinsic parameters A **540**, the projection equation is expressed as:

$$d_i\begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} = \Lambda\left[\begin{array}{ccc|c} 1 & 0 & 0 & \tau_x \\ 0 & 1 & 0 & \tau_y \\ 0 & 0 & 1 & \tau_z \end{array}\right]\begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix}, \tag{1}$$

[0069] with d_i the depth value of keypoint i. Expanding and re-arranging, this gives a system of linear equations that can be written in the following form:

$$\begin{bmatrix} -1 & 0 & u_i' \\ 0 & -1 & v_i' \end{bmatrix}\begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = \begin{bmatrix} x_i - z_i u_i' \\ y_i - z_i v_i' \end{bmatrix}, \tag{2}$$

[0070] where

$$\begin{bmatrix} u_i' \\ v_i' \\ 1 \end{bmatrix} = \Lambda^{-1}\begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix}.$$

[0071] Since Equation 2 is obtained considering a single keypoint correspondence, and since we have three unknowns, it is under-constrained. Using all the keypoints in the correspondence set, Equation 2 can be re-written as

$$\begin{bmatrix} -1 & 0 & u_1' \\ 0 & -1 & v_1' \\ & \vdots & \\ 0 & -1 & v_{N_K}' \end{bmatrix} t = \begin{bmatrix} x_1 - z_1 u_1' \\ y_1 - z_1 v_1' \\ \vdots \\ y_{N_K} - z_{N_K} v_{N_K}' \end{bmatrix} \tag{3}$$

[0072] which has the form At=B. To solve for t, the DGP module **430** considers the least-squares solutions $t^*=\arg\min_t\|At-B\|^2$, which can be obtained in closed-form:

$$t^* = (A^T A)^{-1} A^T B. \tag{4}$$

[0073] The DGP module **430** first uses the network outputs to build the matrices A and B, and then uses the linear least-squares solution to solve for the translation. Since all the operations involved are differentiable, the hand mesh prediction module **319** can use this translation to obtain and backpropagate through camera-space vertex predictions, fully incorporating the root-finding task in an end-to-end training pipeline.

[0074] While the above solution allows the hand mesh prediction module **319** to incorporate root finding into an end-to-end differentiable pipeline, it does not provide for any outlier filtering or keypoint selection mechanism that could help filter out more uncertain correspondences. To address this issue, the DGP module **430** uses the weights W **527** in addition to the root-relative 3D keypoints K^{3D} **535** and the 2D keypoints K^{2D} **522**, in order to predict a global translation $t \in \mathbb{R}^3$ in camera-space. That is, the DGP module **430** predicts a global translation in camera space based on the set of 2D keypoints, the set of root-relative 3D keypoints, and the set of weights; and generates the global camera space mesh prediction of the hand in 3D space based on the global translation and the set of root-relative 3D vertices.

[0075] That is, the DGP module **430** generates a weighted least-squares minimisation $t^*=\arg\min_t\|W(At-B)\|^2$, with closed-form solution:

$$t^* = (A^T W^2 A)^{-1} A^T W^2 B. \tag{5}$$

[0076] The global translation **545** predicted as described above by the DGP module **430** can then be used to obtain the camera-space vertex predictions **550** $V^{cs}=\{v_i^{cs}\}_{i=1}^{N_V}$, with

$$v_i^{cs} = v_i^{rel} + t. \tag{6}$$

[0077] That is, using J_{reg} **537**, the root-relative module **420** obtains the root-relative 3D keypoints K^{3D} **535**, forming a set of 2D-3D correspondences $\mathcal{M}$=JV $\{(u_i, v_i, x_i, y_i, z_i)\}_{i=1}^{N_K}$. Using $\mathcal{M}$, the DGP module **430** constructs the matrices A and B, and obtains t **545** using Equations 4 and 5. Finally, as shown in the image processing pipeline in FIG. **5**, t **545**, V^{rel} **532**, and K^{3D} **535** are used to obtain the camera-space vertices V^{cs} **550** and camera-space keypoints, following Equation 6, and use all of the mentioned network outputs to construct training losses.

[0078] The camera-space vertex predictions **550** can finally be used to project the mesh into 2D **570** using a pinhole camera perspective projection. The pipeline shown in FIG. **5**, enables including the global root translation **545** and the resulting mesh projections **570** as part of the neural network training. Incorporating hand root prediction as part of the training this way has the benefit of avoiding the accumulation of errors that can occur when using two independent processes for root-relative predictions and root-finding. Also, the pipeline illustrated in FIG. **5** is agnostic to the particular designs used to obtain the predictions for V^{rel} **532**, K **522**, **535**, and W **527**.

[0079] Returning to FIG. **4**, the wrist finding module **440** may identify from the set of 2D keypoints, a subset of 2D keypoints that belong to a wrist of the hand of a user, and determine a correspondence between keypoints in a 3D mesh template of a human wrist and keypoints in the subset of 2D keypoints that belong to the wrist of the hand of the user. The wrist finding module **440** may predict a 3D mesh of the wrist of the hand of the user based on the correspondence.

[0080] As shown in the pipeline of FIG. **5**, the wrist finding module **440**, may identify from the set of 2D keypoints **522**, a subset of 2D keypoints **523** that belong to a wrist of the hand of a user. The wrist finding module **440** may further take as input, a template wrist 3D model **524** and employ a pose estimation algorithm **560** such as perspective-n-point (PnP) to determine a 3D rotated wrist model **565** of the wrist of the hand image input at **505**. That is, the pose estimation module **560** may determine a correspondence between keypoints in a 3D mesh template of a human wrist **524** and keypoints in the subset of 2D keypoints **523** that belong to the wrist of the hand of the user, and predicting a 3D mesh **565** of the wrist of the hand of the user based on the correspondence.

[0081] The action module **450** of FIG. **4** outputs a virtual element in a virtual space based on the global camera space mesh prediction of the hand **550** and/or the wrist **565**, as shown in FIG. **5**. For example, the action module **450** places the virtual element on the wrist of the hand of the user (as shown at **570** in FIG. **5**) based on the global camera space mesh prediction **550** of the hand and the 3D mesh of the wrist **565**. In the example shown in FIG. **5** at **570**, the action module **450** enables a virtual try-on experience for the user by rendering a watch based on the predicted global camera space mesh of the hand **550** and the 3D rotated wrist model **565**. The user manipulating their hand and wrist will cause the rendered watch to be accurately re-rendered in real-time based on the functionality provided by the hand mesh prediction module **319**, thereby enabling the user to fully appreciate a look and feel of the watch as if they were trying it on in the real world.

Example Methods

[0082] FIG. **6** is a flowchart of a process **600** for generating a camera-space 3D mesh of the hand and a wrist, according to one embodiment. The steps of FIG. **6** are illustrated from the perspective of the client device **310** performing the method **600**. However, some or all of the steps may be performed by other entities or components. In addition, some embodiments may perform the steps in parallel, perform the steps in different orders, not perform all of the steps, perform different steps, or perform additional steps.

[0083] In the embodiment shown, the method **600** begins when the client device **310** captures **610** an image (e.g., RBG image) of a hand by a camera (e.g., the camera assembly **312**). The client device **310** may rectify **620** (e.g., with the rectification module **410** in FIG. **4**; rectified image **505** in FIG. **5**) the image captured at block **610** by establishing a canonical camera space and mapping predictions back to an original camera space.

[0084] The client device **310** may predict **630** (e.g., using the root-relative module **420** in FIG. **4**) a set of 2D keypoints (e.g., 2D keypoint predictions **522** in FIG. **5**), a set of weights (e.g., keypoint confidence **527** in FIG. **5**), and a set of root-relative 3D vertices (e.g., root-relative mesh **532** in FIG. **5**) based on the rectified image (e.g., image **505** in FIG. **5**).

[0085] The client device **310** may obtain 640 (e.g., using the root-relative module **420** in FIG. **4**), using the set of root-relative 3D vertices (e.g., root-relative mesh **532** in FIG. **5**) and a 3D keypoint regressor matrix (e.g., J_{reg} **537** in FIG. **5**), a set of root-relative 3D keypoints (e.g., 3D keypoint predictions **535** in FIG. **5**) that correspond to the set of 2D keypoints (e.g., 2D keypoint predictions **522** in FIG. **5**).

[0086] The client device **310** may generate **650** (e.g., using DGP module **430**) a global camera space mesh prediction (e.g., camera-space mesh **550** in FIG. **5**) of the hand in 3D space based on the set of 2D keypoints and the set of root-relative 3D keypoints. The client device **310** may identify **660** (e.g., using wrist finding module **440**) from the set of 2D keypoints (e.g., 2D keypoint predictions **522** in FIG. **5**), a subset of 2D keypoints (e.g., subset keypoints **523** in FIG. **5**) that belong to a wrist of the hand of a user.

[0087] The client device **310** may determine **670** (e.g., using pose estimation module **560** in FIG. **5**) a correspondence between keypoints in a 3D mesh template (e.g., wrist 3D model **524** in FIG. **5**) of a human wrist and keypoints in the subset of 2D keypoints (e.g., subset keypoints **523** in FIG. **5**) that belong to the wrist of the hand of the user.

[0088] The client device **310** may predict **680** a 3D mesh (e.g., 3D rotated wrist model **656** in FIG. **5**) of the wrist of the hand of the user based on the correspondence. The client device **310** may place **690** (e.g., using action module **450**) a virtual element (e.g., watch shown at **570** in FIG. **5**) on the wrist of the hand of the user based on the global camera space mesh prediction of the hand (e.g., camera-space mesh **550** in FIG. **5**) and the 3D mesh of the wrist (e.g., 3D rotated wrist model **656** in FIG. **5**).

Example Computing System

[0089] FIG. **7** is a block diagram of an example computer **700** suitable for use as a client device **310** or game server **320**. The example computer **700** includes at least one processor **702** coupled to a chipset **704**. References to a processor (or any other component of the computer **700**) should be understood to refer to any one such component or combination of such components working cooperatively to provide the described functionality. The chipset **704** includes a memory controller hub **720** and an input/output (I/O) controller hub **722**. A memory **706** and a graphics adapter **712** are coupled to the memory controller hub **720**, and a display **718** is coupled to the graphics adapter **712**. A storage device **708**, keyboard **710**, pointing device **714**, and network adapter **716** are coupled to the I/O controller hub **722**. Other embodiments of the computer **700** have different architectures.

[0090] In the embodiment shown in FIG. **7**, the storage device **708** is a non-transitory computer-readable storage medium such as a hard drive, compact disk read-only memory (CD-ROM), DVD, or a solid-state memory device. The memory **706** holds instructions and data used by the processor **702**. The pointing device **714** is a mouse, track ball, touch-screen, or other type of pointing device, and may be used in combination with the keyboard **710** (which may be an on-screen keyboard) to input data into the computer system **700**. The graphics adapter **712** displays images and other information on the display **718**. The network adapter

716 couples the computer system **700** to one or more computer networks, such as network **370**.

[0091] The types of computers used by the entities of FIGS. **3** and **4** can vary depending upon the embodiment and the processing power required by the entity. For example, the game server **320** might include multiple blade servers working together to provide the functionality described. Furthermore, the computers can lack some of the components described above, such as keyboards **710**, graphics adapters **712**, and displays **718**.

Additional Considerations

[0092] Some portions of above description describe the embodiments in terms of algorithmic processes or operations. These algorithmic descriptions and representations are commonly used by those skilled in the computing arts to convey the substance of their work effectively to others skilled in the art. These operations, while described functionally, computationally, or logically, are understood to be implemented by computer programs comprising instructions for execution by a processor or equivalent electrical circuits, microcode, or the like. Furthermore, it has also proven convenient at times, to refer to these arrangements of functional operations as modules, without loss of generality.

[0093] Any reference to "one embodiment" or "an embodiment" means that a particular element, feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment. Similarly, use of "a" or "an" preceding an element or component is done merely for convenience. This description should be understood to mean that one or more of the elements or components are present unless it is obvious that it is meant otherwise.

[0094] Where values are described as "approximate" or "substantially" (or their derivatives), such values should be construed as accurate+/−10% unless another meaning is apparent from the context. From example, "approximately ten" should be understood to mean "in a range from nine to eleven."

[0095] The terms "comprises," "comprising," "includes," "including," "has," "having" or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article, or apparatus that comprises a list of elements is not necessarily limited to only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus. Further, unless expressly stated to the contrary, "or" refers to an inclusive or and not to an exclusive or. For example, a condition A or B is satisfied by any one of the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B are true (or present).

[0096] Upon reading this disclosure, those of skill in the art will appreciate still additional alternative structural and functional designs for a system and a process for providing the described functionality. Thus, while particular embodiments and applications have been illustrated and described, it is to be understood that the described subject matter is not limited to the precise construction and components disclosed. The scope of protection should be limited only by the following claims.

What is claimed is:

1. A computer-implemented method comprising:
- accessing an image of a hand captured by a camera;
- predicting a set of 2D keypoints and a set of root-relative 3D vertices based on the image;
- obtaining, using the set of root-relative 3D vertices, a set of root-relative 3D keypoints that correspond to the set of 2D keypoints;
- generating a global camera space mesh prediction of the hand in 3D space based on the set of 2D keypoints and the set of root-relative 3D keypoints; and
- outputting a virtual element in a virtual space based on the global camera space mesh prediction of the hand.

2. The computer-implemented method of claim **1**, wherein the image is a single RGB image, and wherein the method further comprises:
- rectifying the image by establishing a canonical camera space and mapping predictions back to an original camera space, wherein the set of 2D keypoints and the set of root-relative 3D vertices are predicted using the rectified image.

3. The computer-implemented method of claim **2**, wherein rectifying the image comprises:
- resizing the image with a ratio that converts camera parameters to an original set of camera parameters.

4. The computer-implemented method of claim **2**, further comprising:
- predicting a set of weights based on the rectified image, wherein each weight of the set of weights represents a confidence in a prediction of a corresponding keypoint of the set of 2D keypoints, the set of weights accounting for keypoint landmark correspondence inaccuracy due to occlusion of the hand in the image.

5. The computer-implemented method of claim **4**, wherein obtaining the set of root-relative 3D keypoints that correspond to the set of 2D keypoints comprises:
- accessing a 3D keypoint regressor matrix defining keypoint landmarks on the hand as a linear combination of hand mesh vertices; and
- using the 3D keypoint regressor matrix to obtain the set of root-relative 3D keypoints based on the set of root-relative 3D vertices.

6. The computer-implemented method of claim **5**, wherein the global camera space mesh prediction of the hand is a camera-space vertex prediction that can be projected into 2D using a pinhole camera perspective projection, and wherein the method further comprises:
- predicting a global translation in camera space based on the set of 2D keypoints, the set of root-relative 3D keypoints, and the set of weights; and
- generating the global camera space mesh prediction of the hand in 3D space based on the global translation and the set of root-relative 3D vertices.

7. The computer-implemented method of claim **1**, further comprising:
- identifying from the set of 2D keypoints, a subset of 2D keypoints that belong to a wrist of the hand of a user;
- determining a correspondence between keypoints in a 3D mesh template of a human wrist and keypoints in the subset of 2D keypoints that belong to the wrist of the hand of the user; and
- predicting a 3D mesh of the wrist of the hand of the user based on the correspondence.

8. The computer-implemented method of claim **7**, wherein outputting the virtual element in the virtual space based the global camera space mesh prediction of the hand comprises:

placing the virtual element on the wrist of the hand of the user based on the global camera space mesh prediction of the hand and the 3D mesh of the wrist.

9. A non-transitory computer-readable medium storing instructions that, when executed by a computing system, cause the computing system to perform operations comprising:

accessing an image of a hand captured by a camera;

predicting a set of 2D keypoints and a set of root-relative 3D vertices based on the image;

obtaining, using the set of root-relative 3D vertices, a set of root-relative 3D keypoints that correspond to the set of 2D keypoints;

generating a global camera space mesh prediction of the hand in 3D space based on the set of 2D keypoints and the set of root-relative 3D keypoints; and

outputting a virtual element in a virtual space based on the global camera space mesh prediction of the hand.

10. The non-transitory computer-readable medium of claim **9**, wherein the image is a single RGB image, and wherein the operations further comprise:

rectifying the image by establishing a canonical camera space and mapping predictions back to an original camera space, wherein the set of 2D keypoints and the set of root-relative 3D vertices are predicted using the rectified image.

11. The non-transitory computer-readable medium of claim **10**, wherein rectifying the image comprises:

resizing the image with a ratio that converts camera parameters to an original set of camera parameters.

12. The non-transitory computer-readable medium of claim **10**, wherein the operations further comprise:

predicting a set of weights based on the rectified image, wherein each weight of the set of weights represents a confidence in a prediction of a corresponding keypoint of the set of 2D keypoints, the set of weights accounting for keypoint landmark correspondence inaccuracy due to occlusion of the hand in the image.

13. The non-transitory computer-readable medium of claim **12**, wherein obtaining the set of root-relative 3D keypoints that correspond to the set of 2D keypoints comprises:

accessing a 3D keypoint regressor matrix defining keypoint landmarks on the hand as a linear combination of hand mesh vertices; and

using the 3D keypoint regressor matrix to obtain the set of root-relative 3D keypoints based on the set of root-relative 3D vertices.

14. The non-transitory computer-readable medium of claim **13**, wherein the global camera space mesh prediction of the hand is a camera-space vertex prediction that can be projected into 2D using a pinhole camera perspective projection, and wherein the operations further comprise:

predicting a global translation in camera space based on the set of 2D keypoints, the set of root-relative 3D keypoints, and the set of weights; and

generating the global camera space mesh prediction of the hand in 3D space based on the global translation and the set of root-relative 3D vertices.

15. The non-transitory computer-readable medium of claim **9**, wherein the operations further comprise:

identifying from the set of 2D keypoints, a subset of 2D keypoints that belong to a wrist of the hand of a user;

determining a correspondence between keypoints in a 3D mesh template of a human wrist to keypoints in the subset of 2D keypoints that belong to the wrist of the hand of the user; and

predicting a 3D mesh of the wrist of the hand of the user based on the correspondence.

16. The non-transitory computer-readable medium of claim **15**, wherein outputting the virtual element in the virtual space based the global camera space mesh prediction of the hand comprises:

placing the virtual element on the wrist of the hand of the user based on the global camera space mesh prediction of the hand and the 3D mesh of the wrist.

17. A client device for predicting a hand mesh, the client device comprising:

a display;

a camera;

one or more processors; and

memory storing instructions that, when executed by the one or more processors, cause the one or more processors to perform operations comprising:

accessing an image of a hand captured by the camera;

predicting a set of 2D keypoints and a set of root-relative 3D vertices based on the image;

obtaining, using the set of root-relative 3D vertices, a set of root-relative 3D keypoints that correspond to the set of 2D keypoints;

generating a global camera space mesh prediction of the hand in 3D space based on the set of 2D keypoints and the set of root-relative 3D keypoints; and

displaying, on the display, a virtual element in a virtual space based on the global camera space mesh prediction of the hand.

18. The client device of claim **17**, wherein the operations further comprise:

identifying from the set of 2D keypoints, a subset of 2D keypoints that belong to a wrist of the hand of a user;

determining a correspondence between keypoints in a 3D mesh template of a human wrist to keypoints in the subset of 2D keypoints that belong to the wrist of the hand of the user; and

predicting a 3D mesh of the wrist of the hand of the user based on the correspondence.

19. The client device of claim **18**, wherein outputting the virtual element in the virtual space based the global camera space mesh prediction of the hand comprises:

placing the virtual element on the wrist of the hand of the user based on the global camera space mesh prediction of the hand and based on the 3D mesh of the wrist.

20. The client device of claim **17**, wherein the image is a single RGB image, and wherein the operations further comprise:

rectifying the image by establishing a canonical camera space and mapping predictions back to an original camera space, wherein the set of 2D keypoints and the set of root-relative 3D vertices are predicted using the rectified image.

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