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(54) **SMART GLASSES SYSTEMS FOR
HEARABLE CONVERSATIONS**

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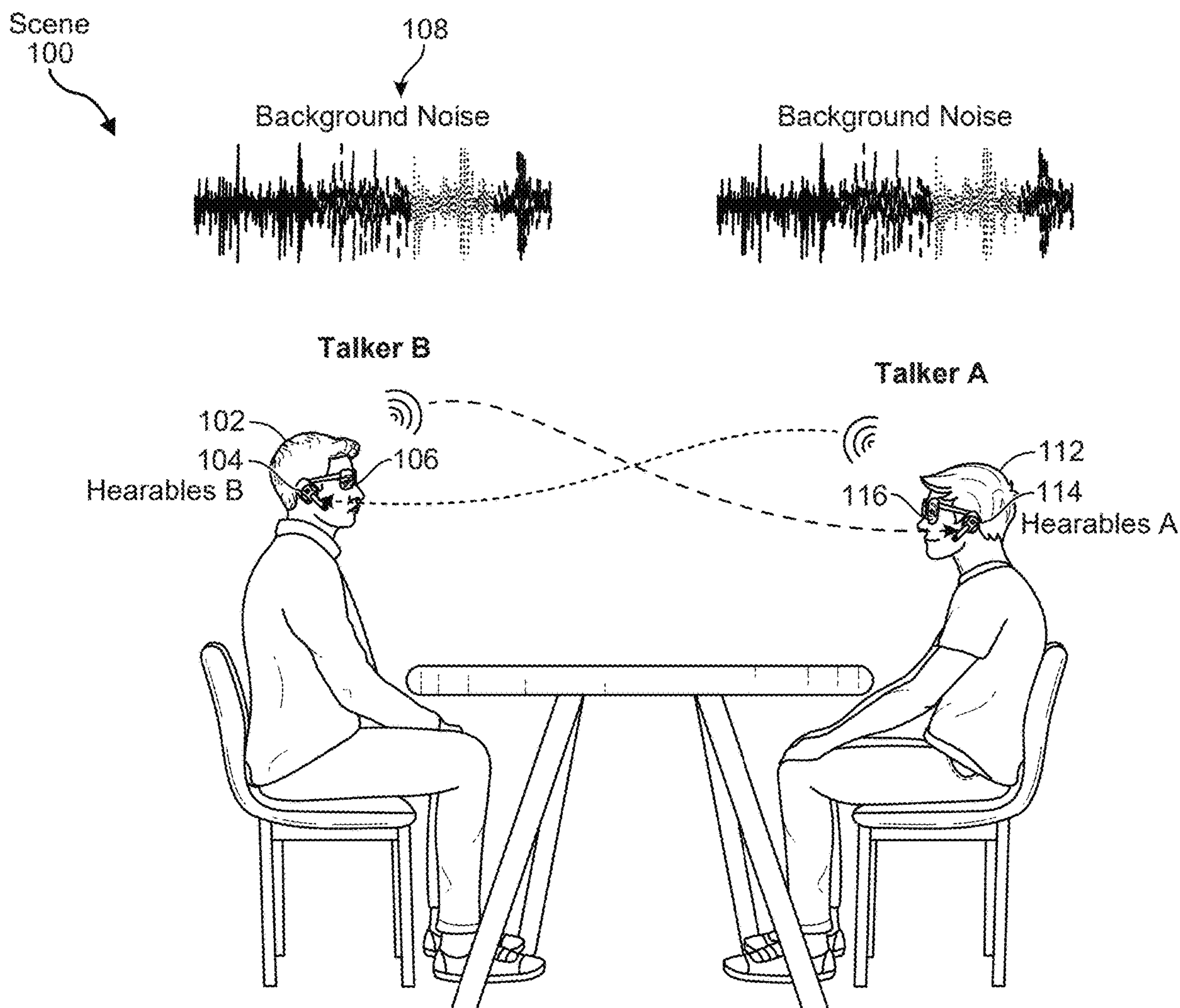
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(57) **ABSTRACT**

A method is provided in which at least one processor of smart glasses belonging to a first user establishes a wireless communication link with a wearable audio device of a second user. The smart glasses detect voice audio from the first user using at least one microphone and transmit the voice audio to the wearable audio device via the wireless communication link. Various other aspects are also disclosed.



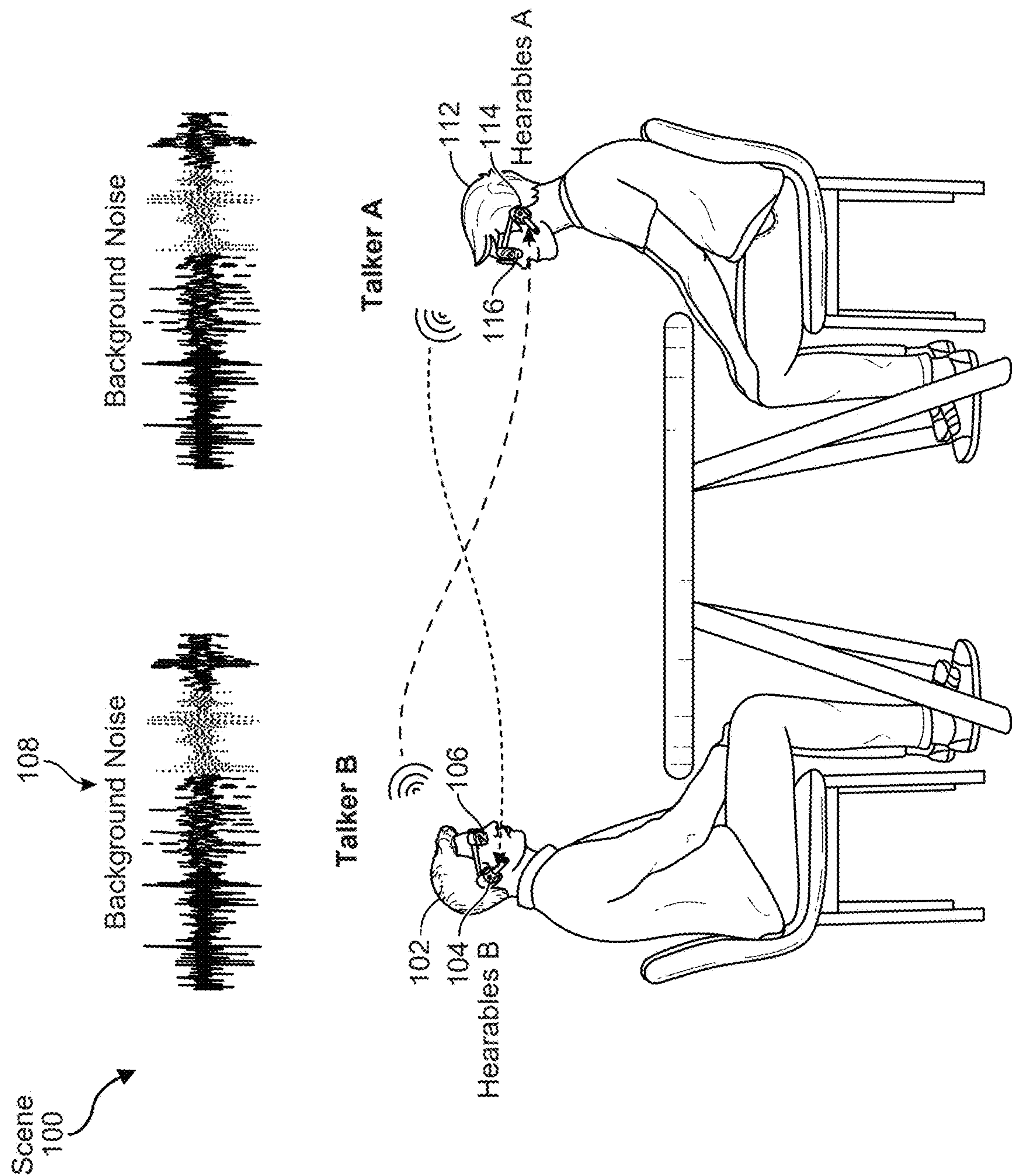


FIG. 1

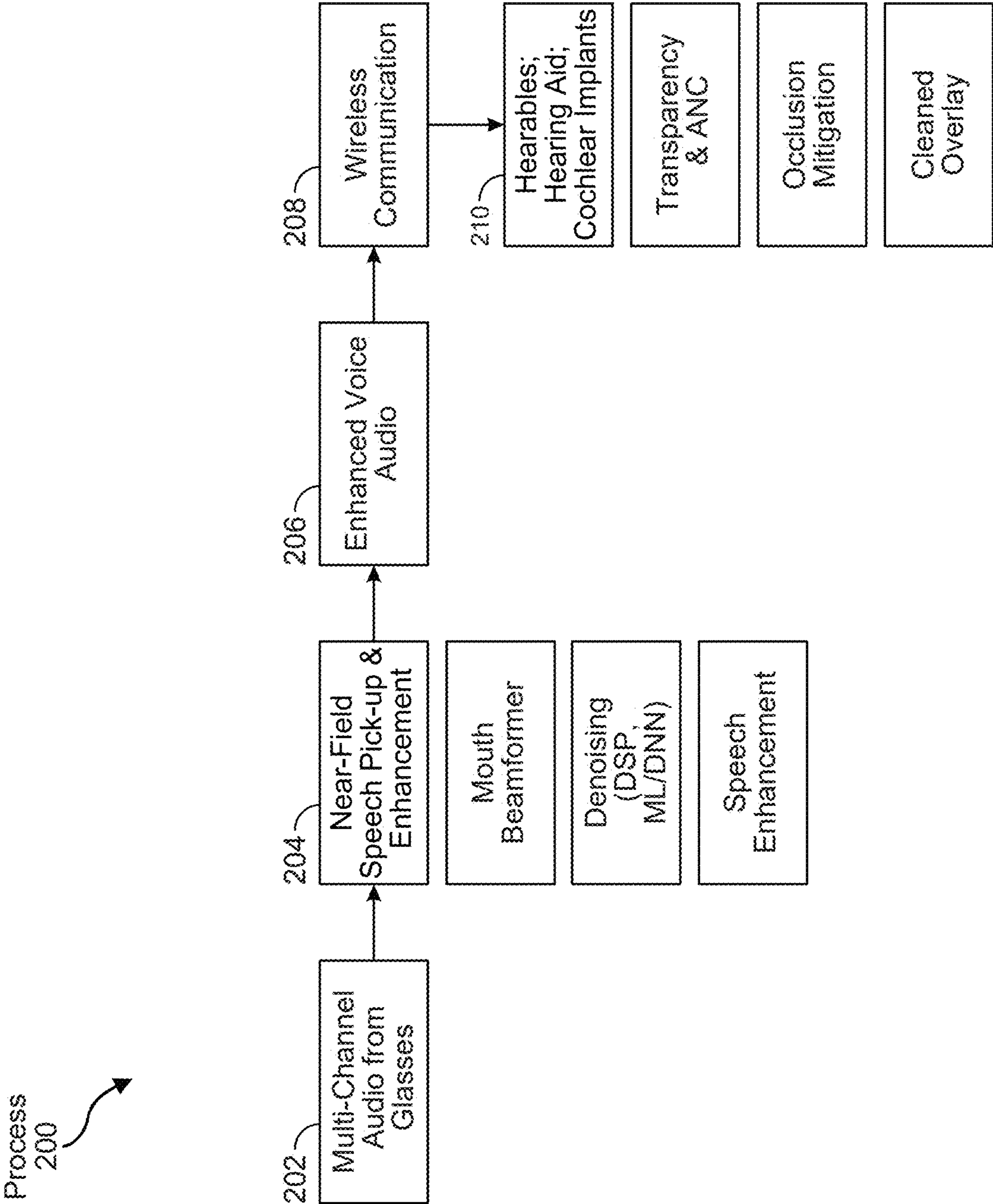
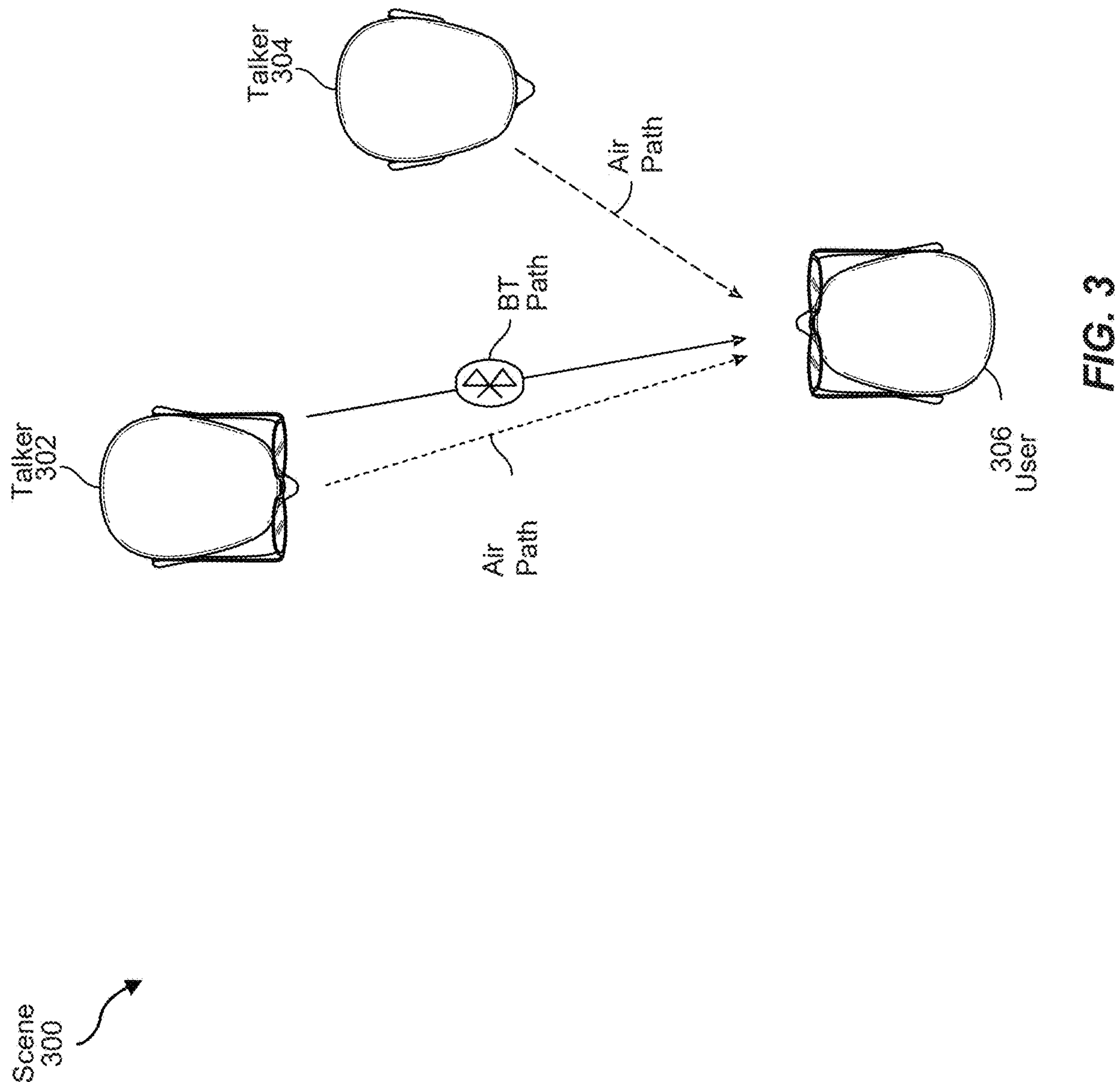


FIG. 2



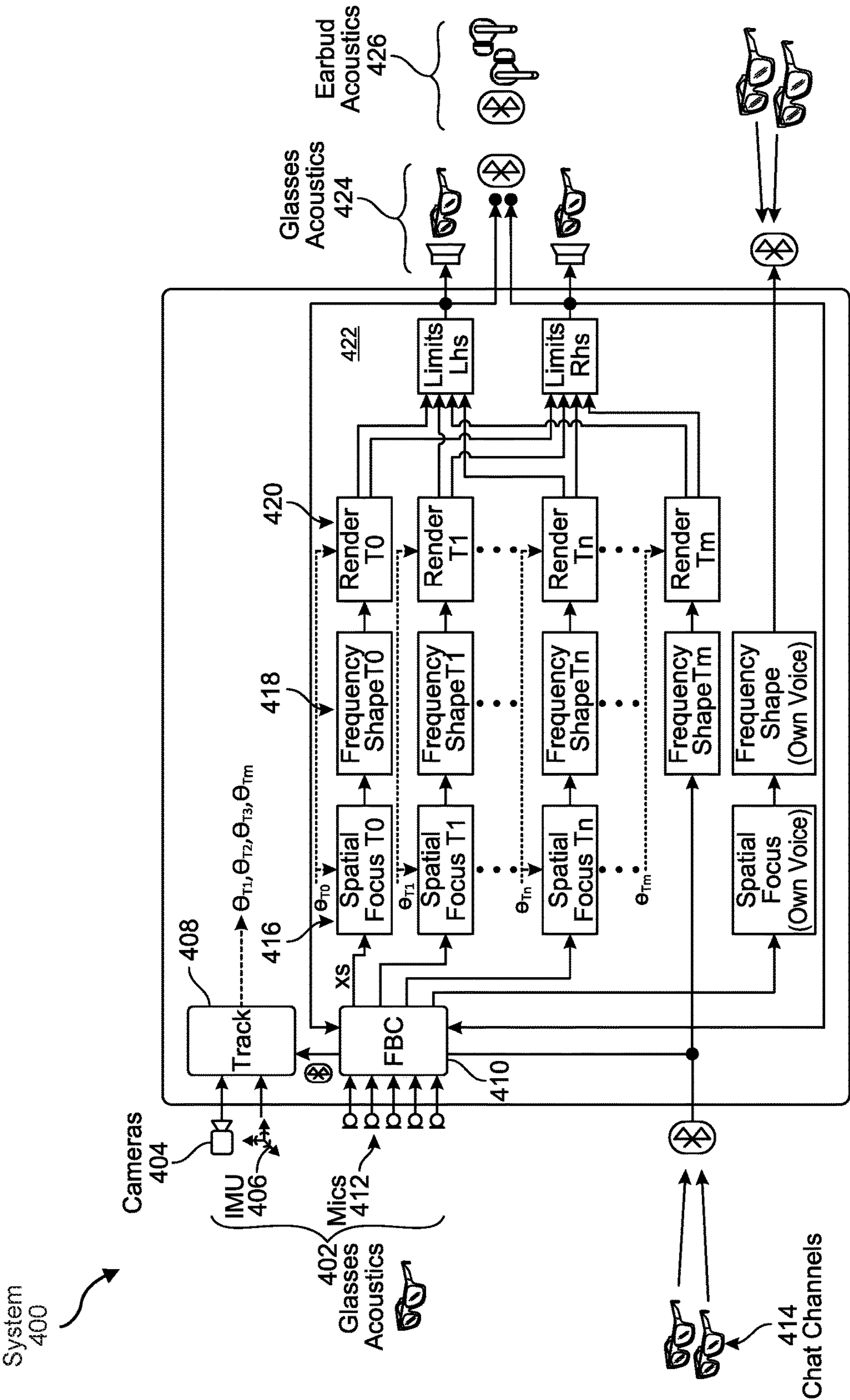


FIG. 4

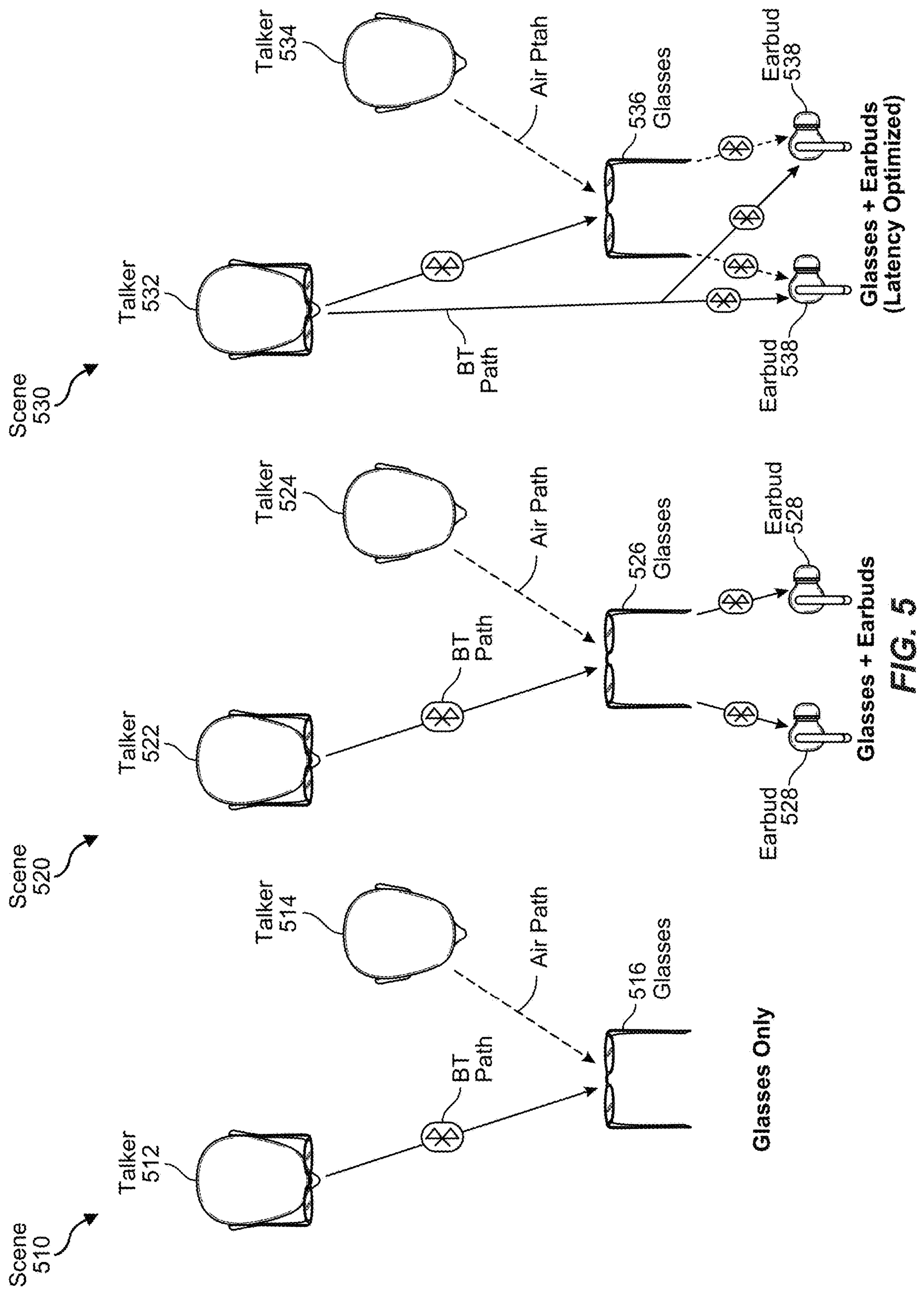


FIG. 5

Method
600

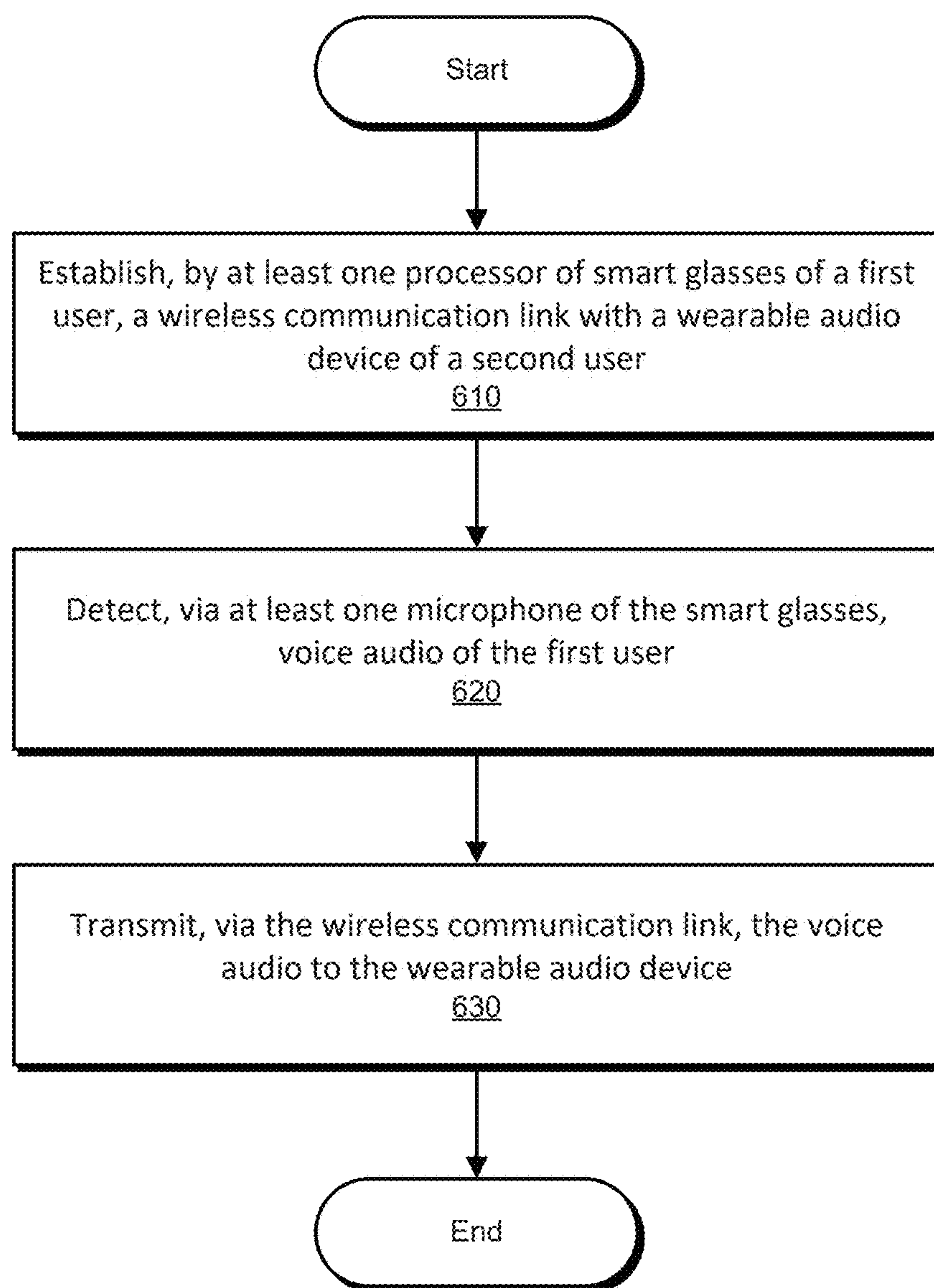


FIG. 6

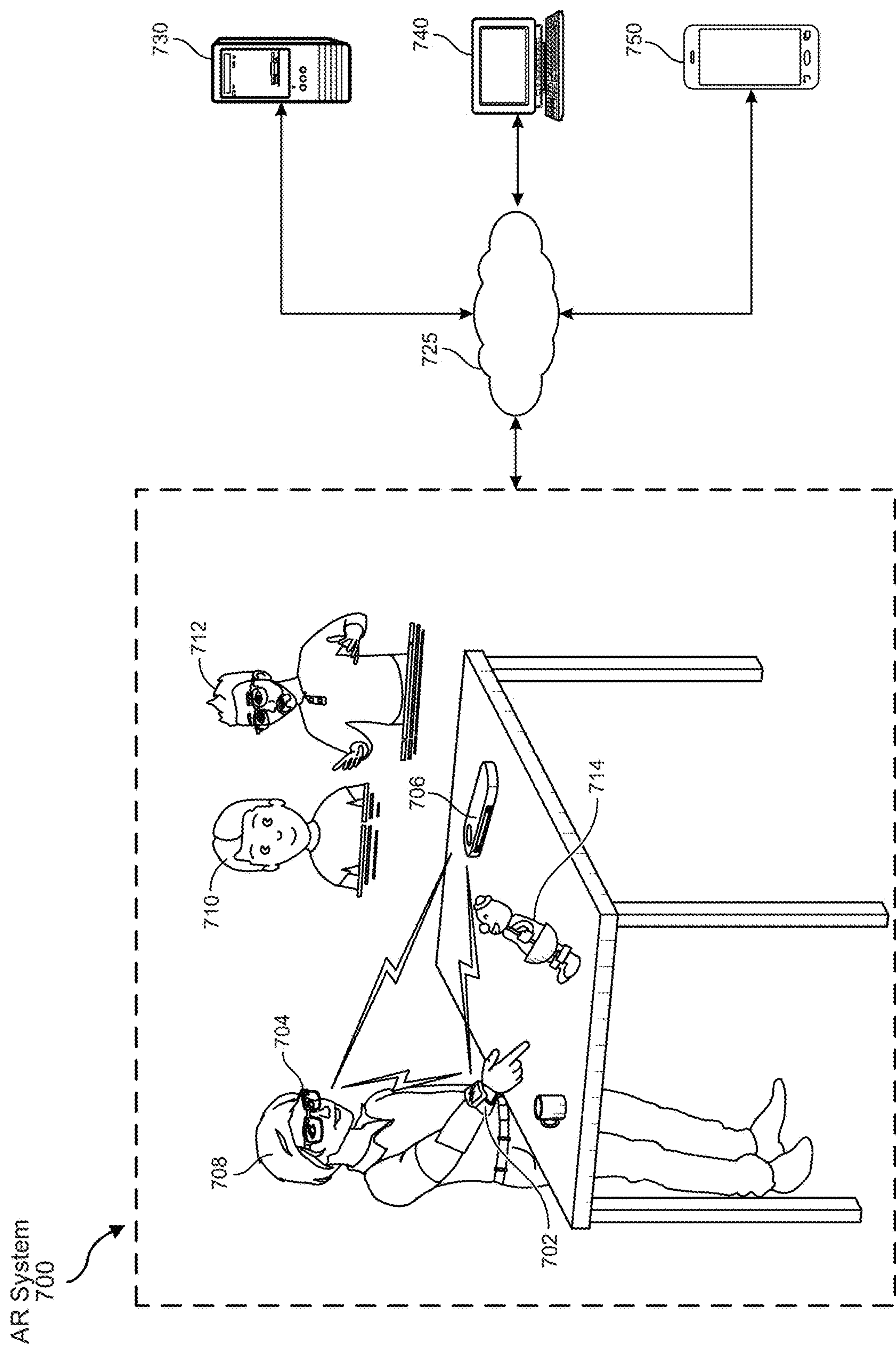


FIG. 7

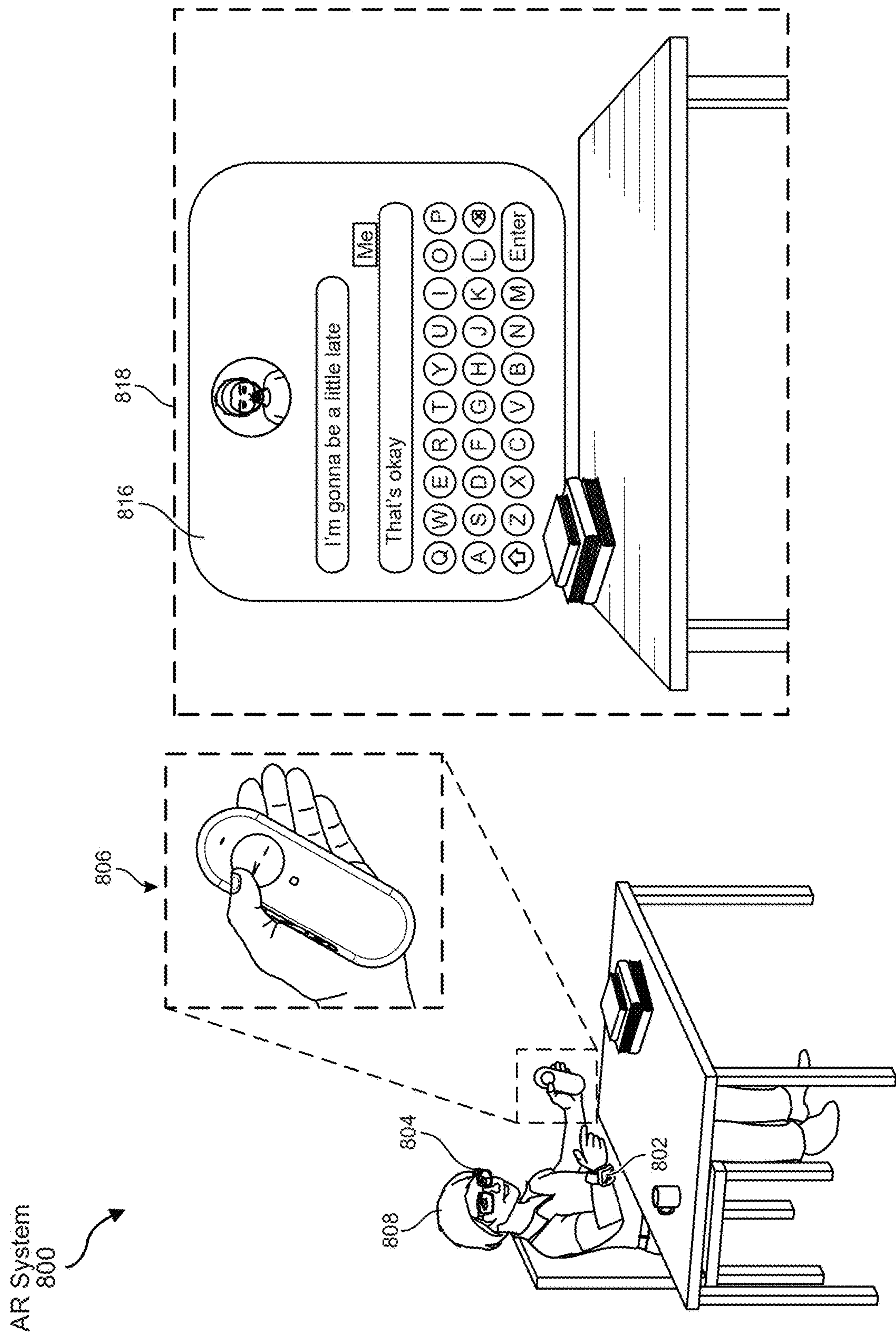


FIG. 8

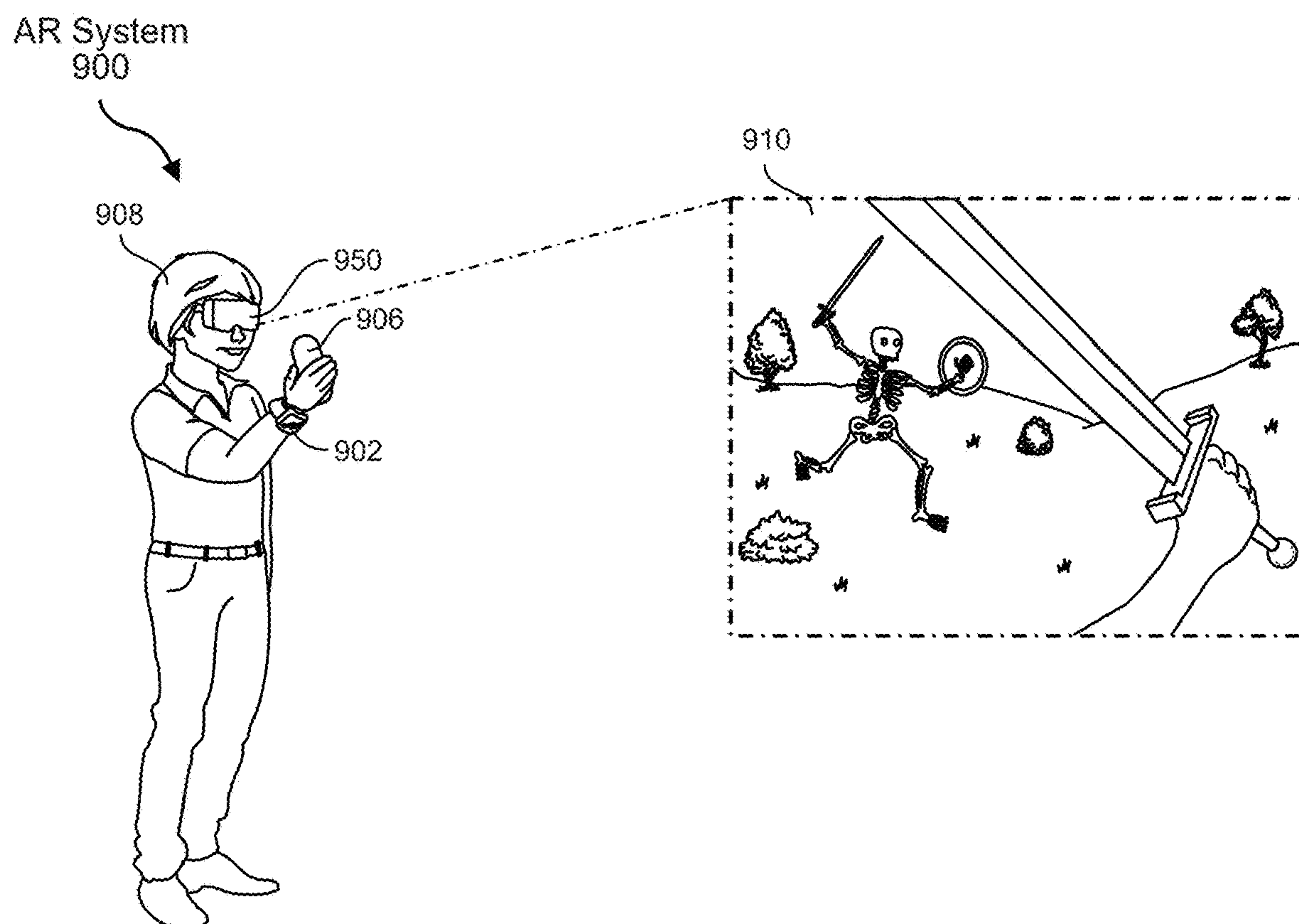


FIG. 9A

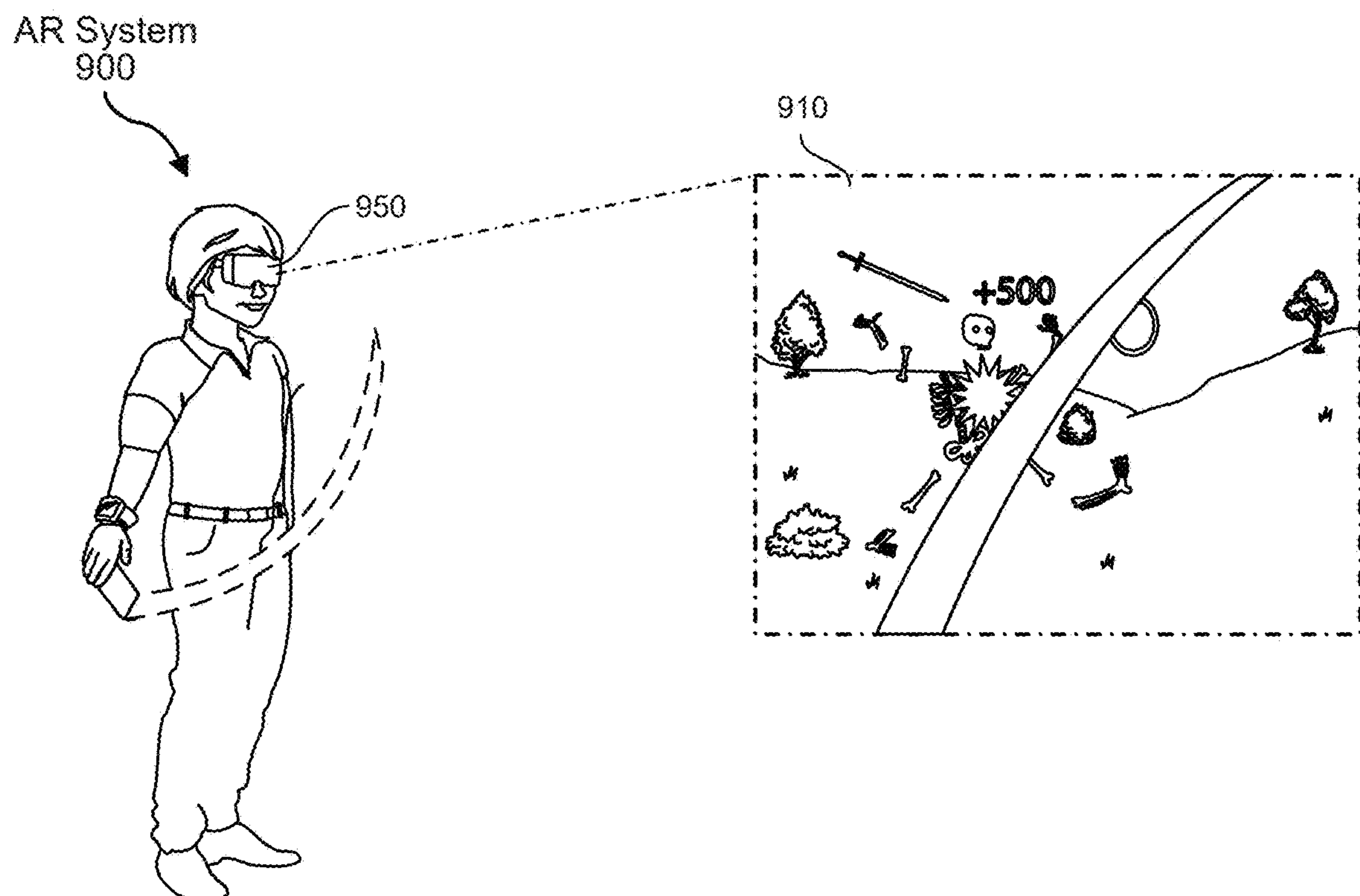


FIG. 9B

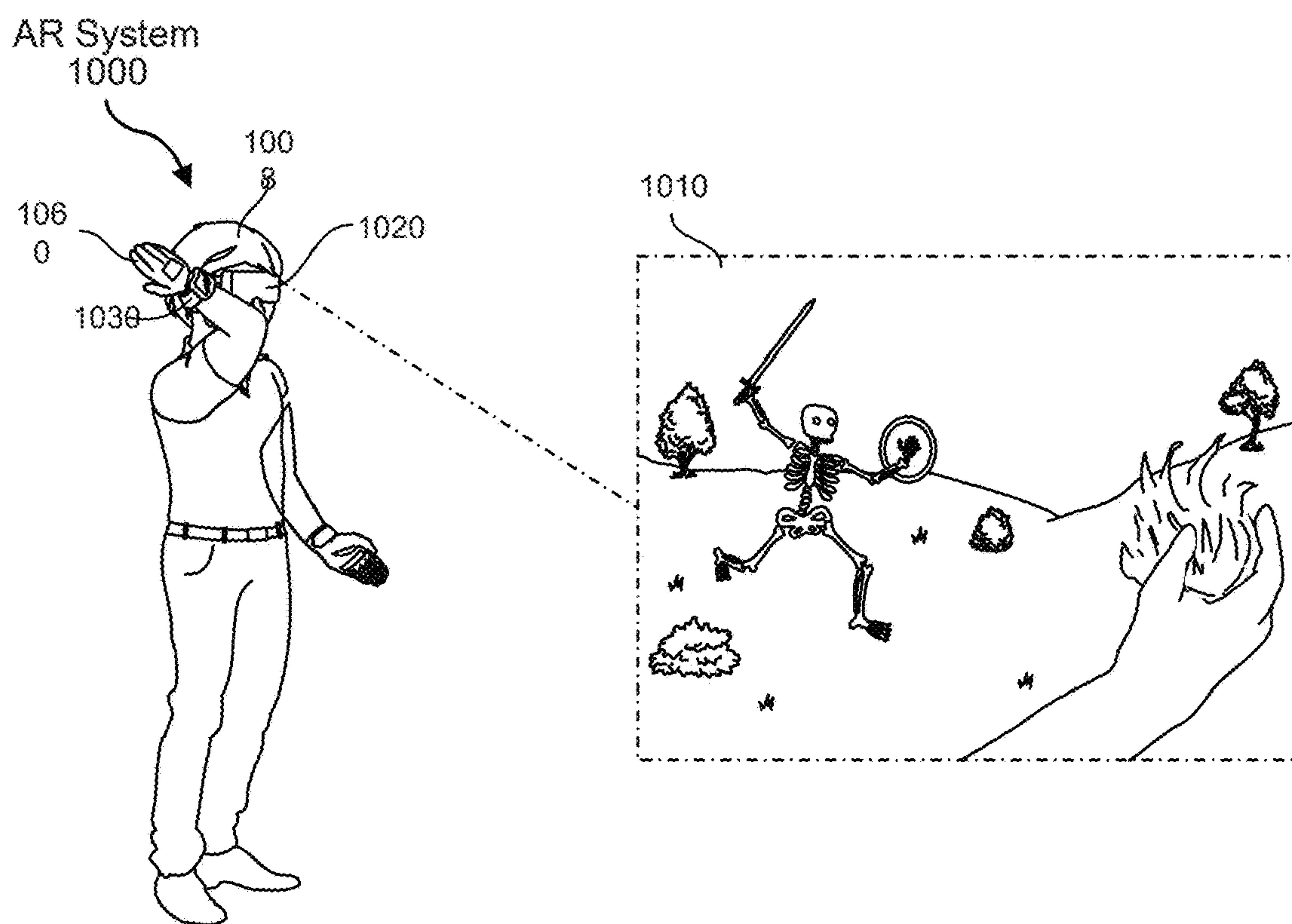


FIG. 10A

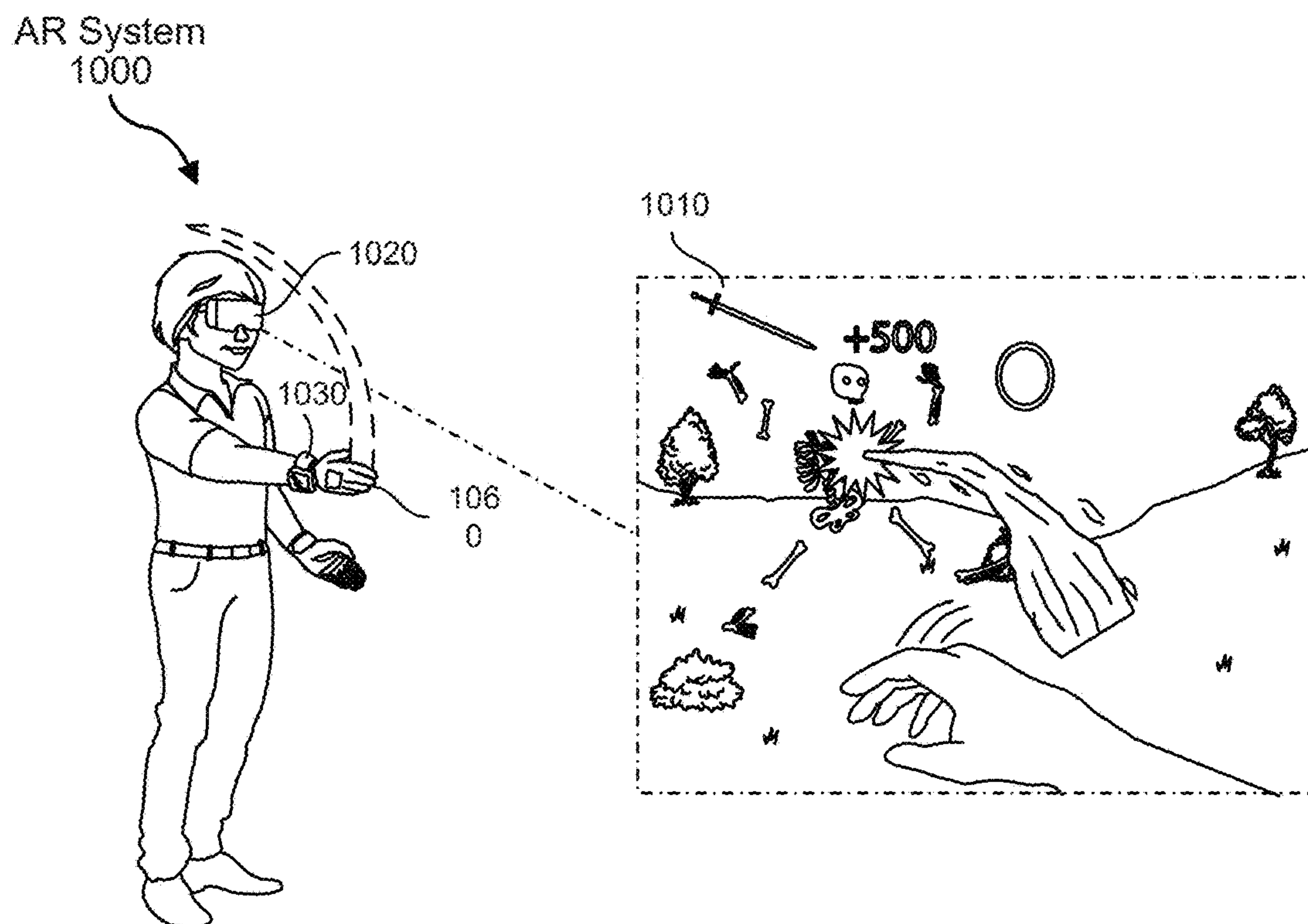


FIG. 10B

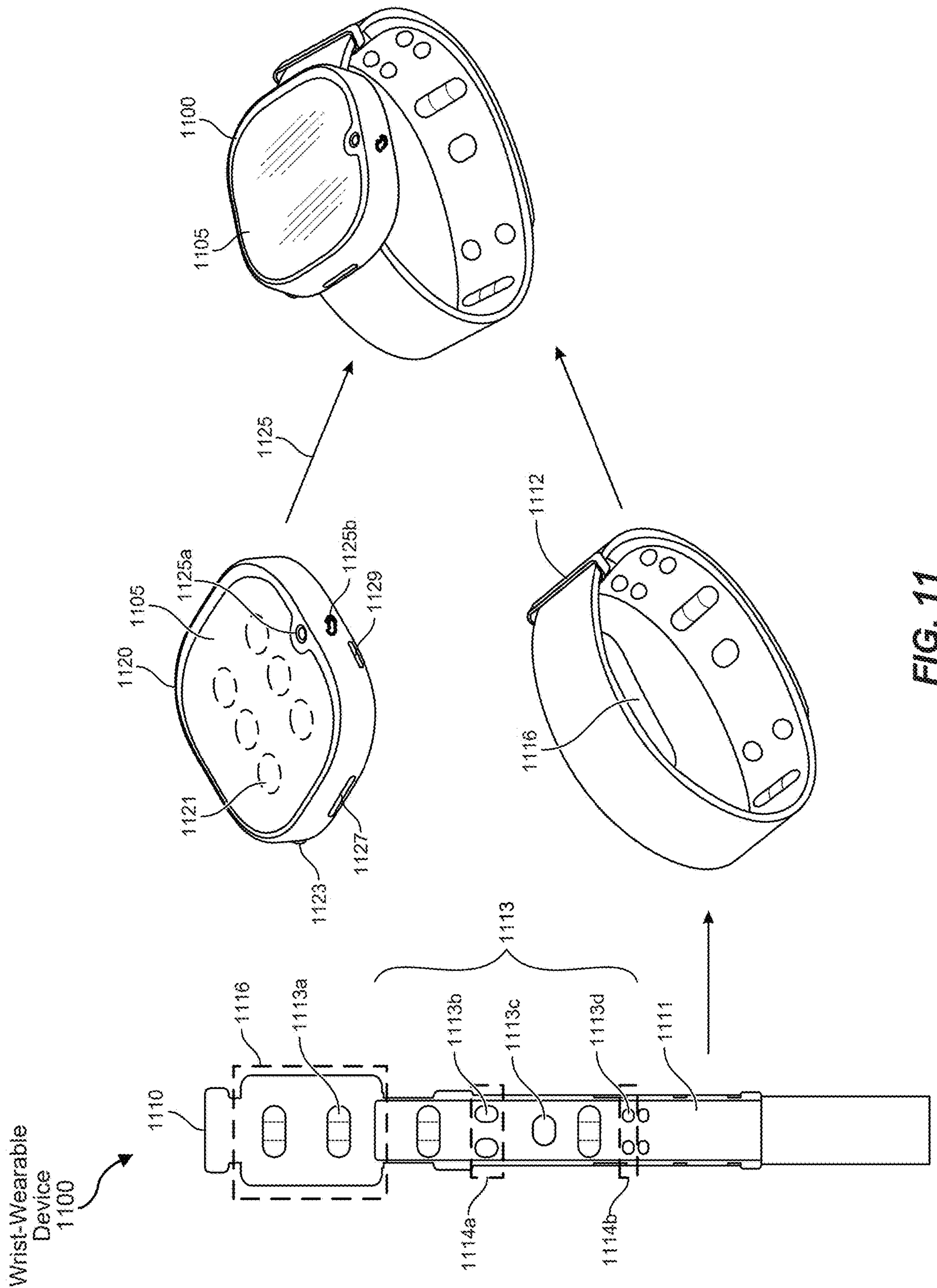


FIG. 11

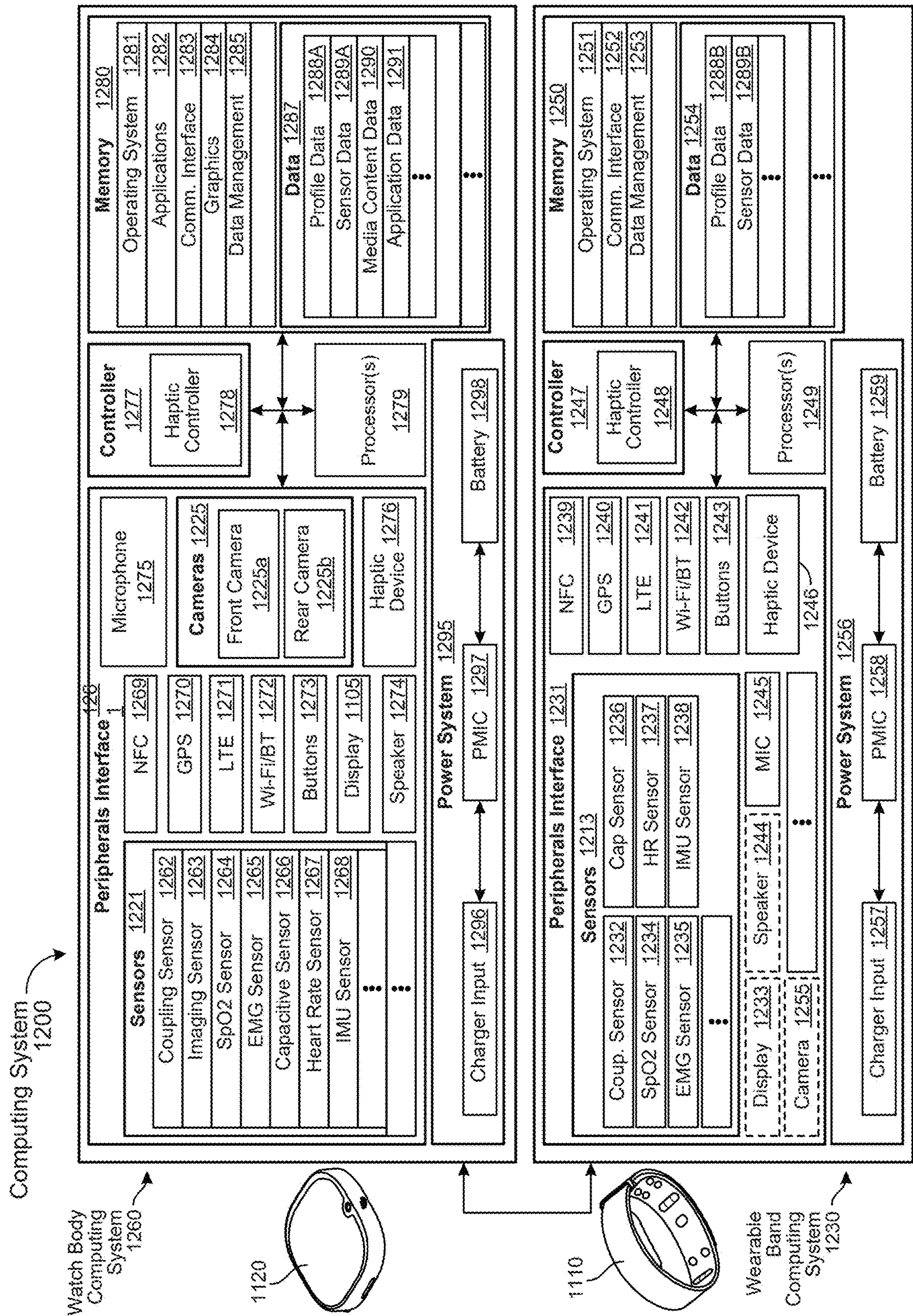


FIG. 12

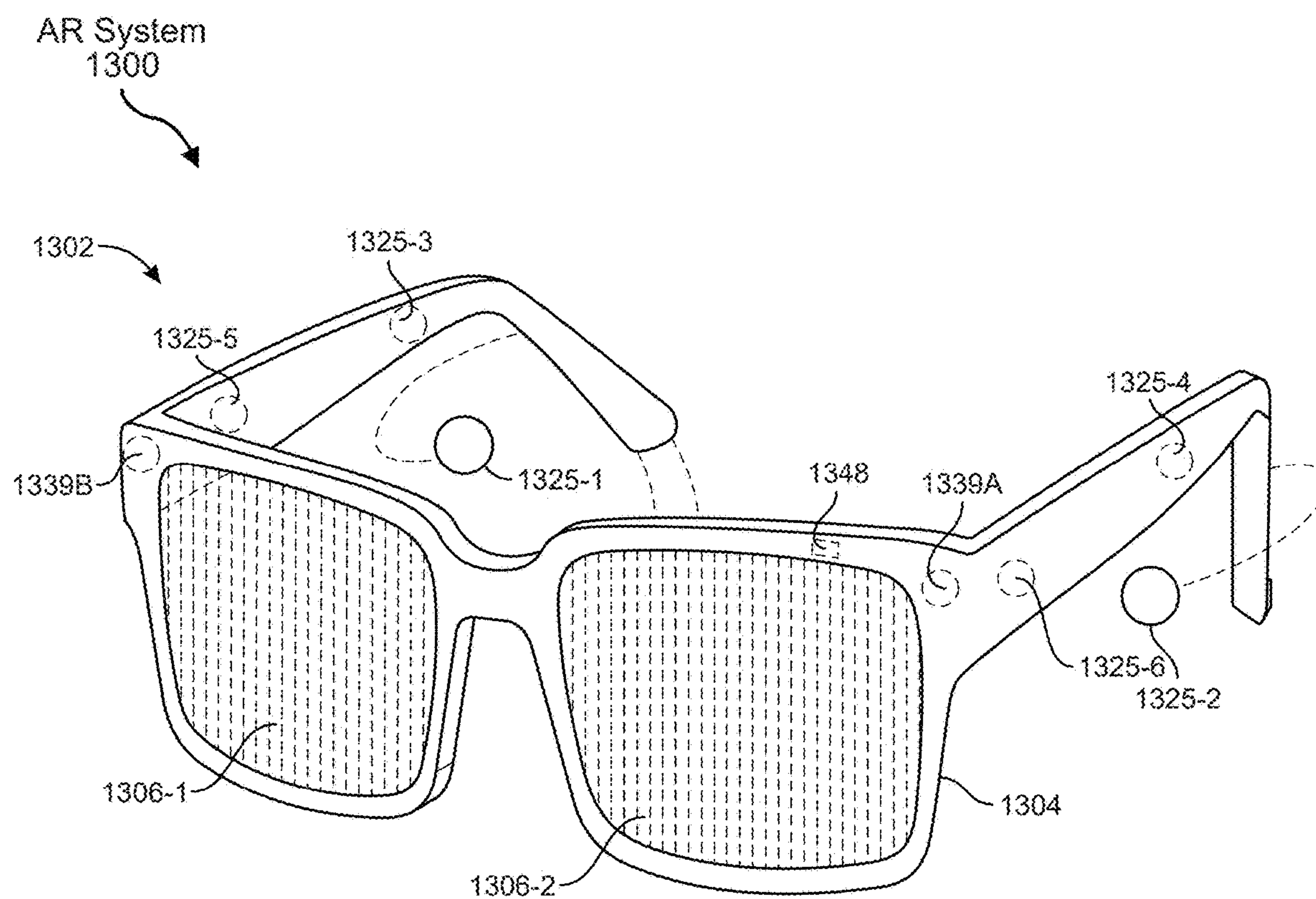


FIG. 13

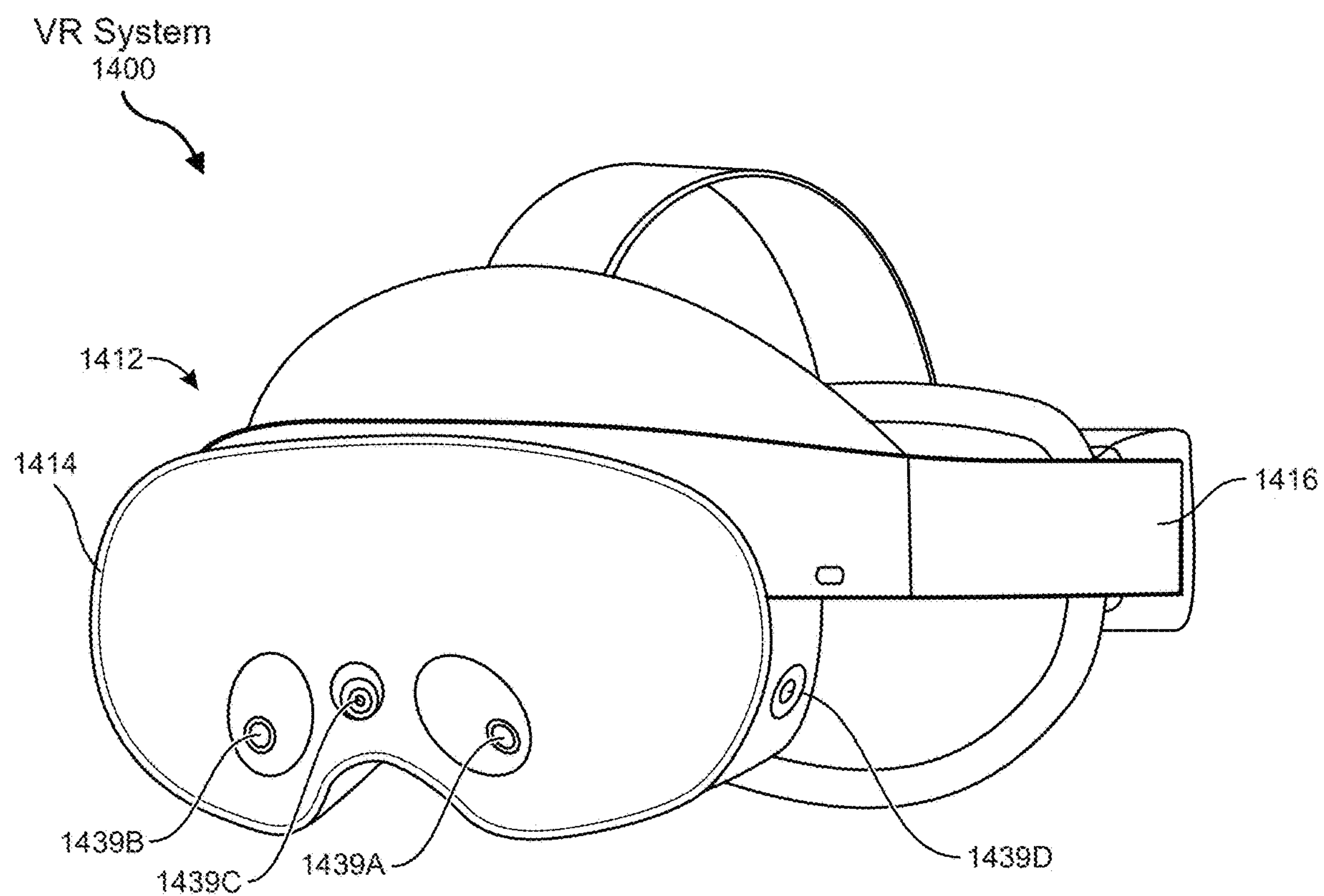


FIG. 14A

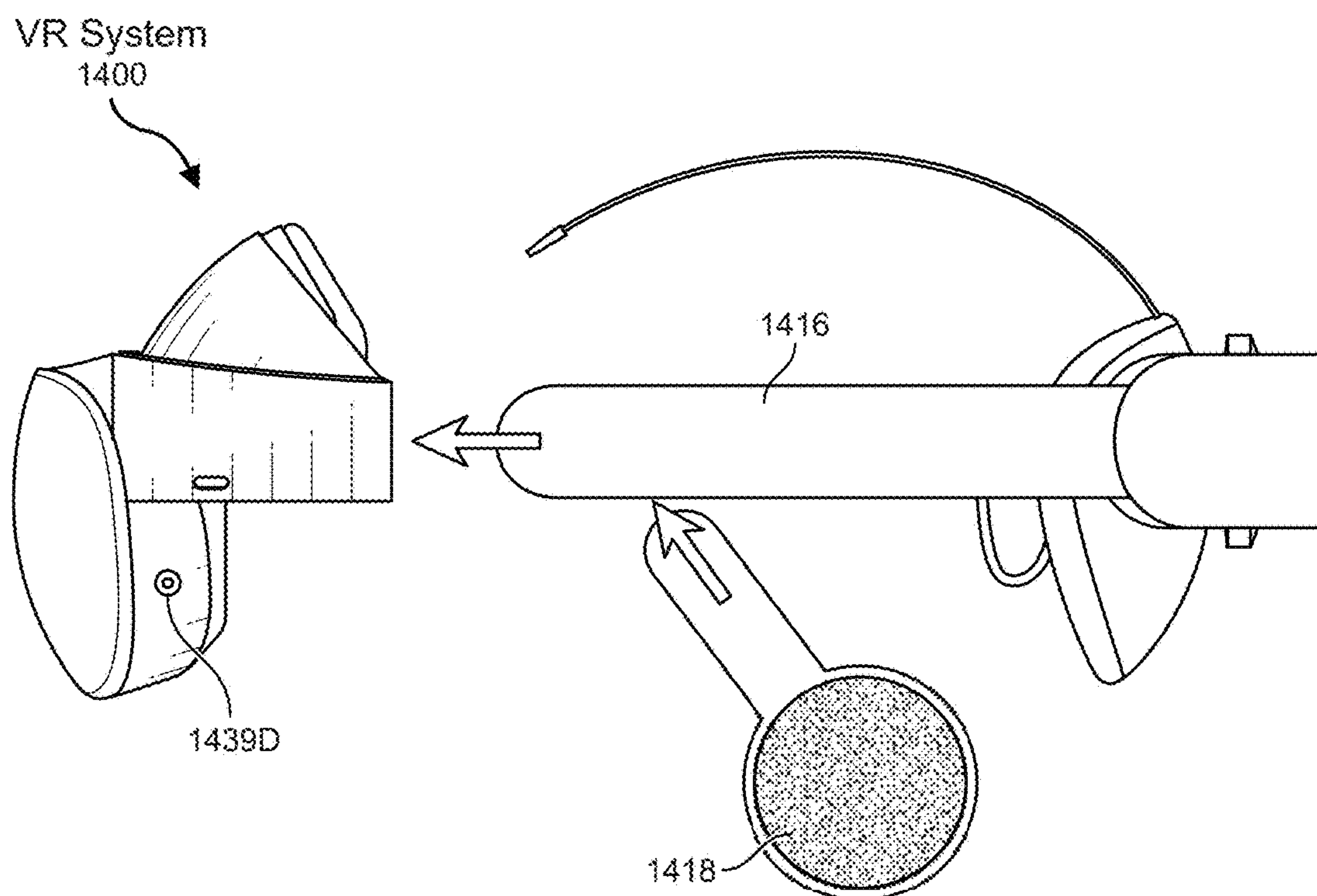


FIG. 14B

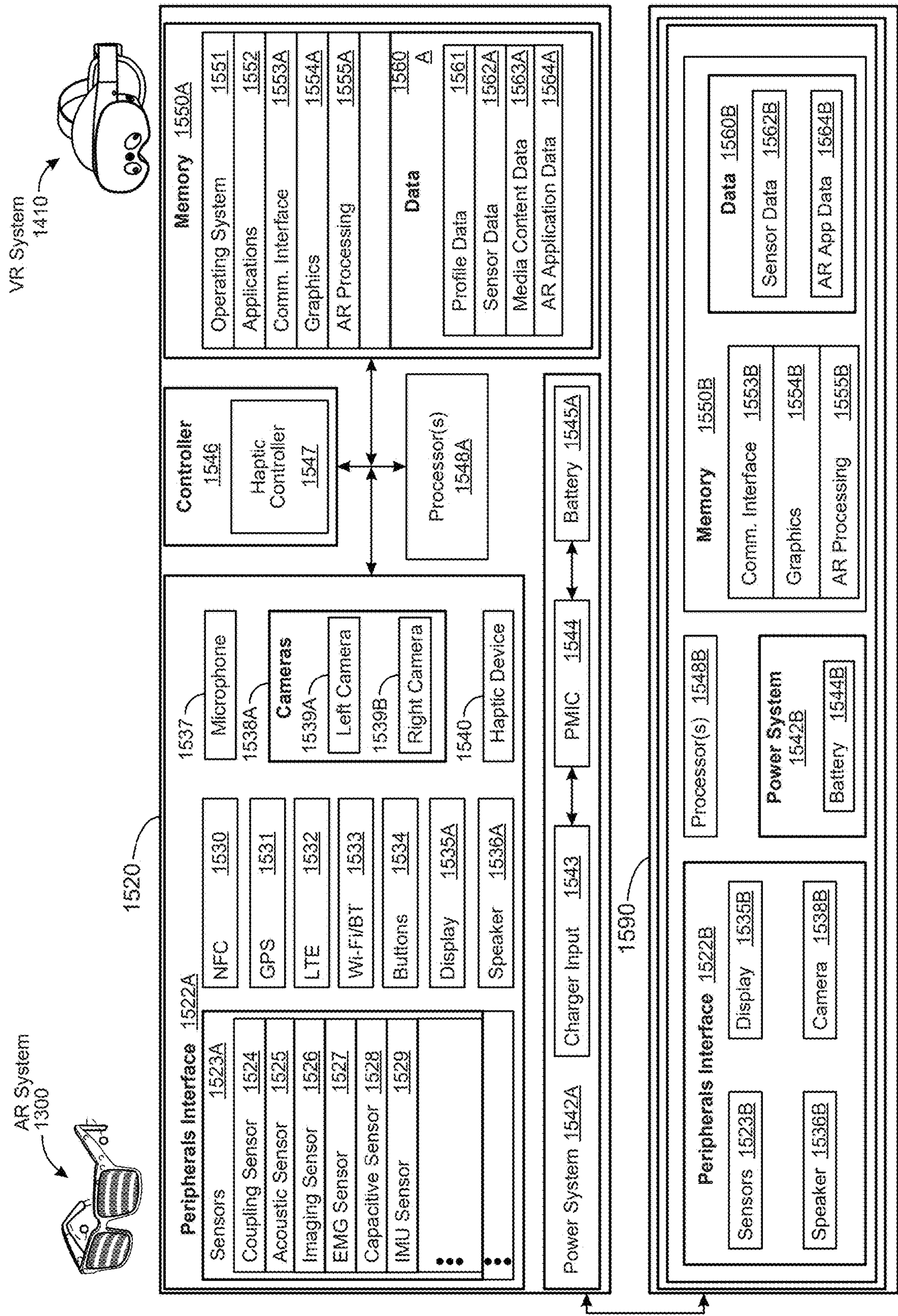


FIG. 15

SMART GLASSES SYSTEMS FOR HEARABLE CONVERSATIONS

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of and priority to U.S. Provisional Patent Application No. 63/767,613, filed Mar. 6, 2025, the disclosure of which is incorporated herein, in its entirety, by this reference.

SUMMARY

[0002] The accompanying drawings illustrate a number of exemplary embodiments and are a part of the specification. Together with the following description, these drawings demonstrate and explain various principles of the present disclosure.

[0003] According to an aspect of the present disclosure, a computer-implemented method is provided in which at least one processor of smart glasses belonging to a first user establishes a wireless communication link with a wearable audio device of a second user. The smart glasses detect voice audio from the first user using at least one microphone and transmit the voice audio to the wearable audio device via the wireless communication link.

[0004] According to another aspect of the present disclosure, a system is provided that includes at least one physical processor and physical memory with computer-executable instructions. When executed by the physical processor, these instructions cause the processor to establish a wireless communication link between smart glasses of a first user and a wearable audio device of a second user, detect voice audio from the first user using at least one microphone of the smart glasses, and transmit the voice audio to the wearable audio device over the wireless communication link.

[0005] According to a further aspect of the present disclosure, a non-transitory computer-readable medium is provided with one or more computer-executable instructions. When executed by at least one processor of a computing device, these instructions cause the computing device to establish a wireless communication link between smart glasses of a first user and a wearable audio device of a second user, detect voice audio from the first user using at least one microphone of the smart glasses, and transmit the voice audio to the wearable audio device over the wireless communication link.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The accompanying drawings illustrate a number of exemplary embodiments and are a part of the specification. Together with the following description, these drawings demonstrate and explain various principles of the present disclosure.

[0007] FIG. 1 is an illustration of a conversational enhancement system scene using smart glasses and hearables to improve speech intelligibility in background noise according to some embodiments of this disclosure.

[0008] FIG. 2 is a flowchart illustrating an audio enhancement process, including multi-channel audio capture, near-field speech enhancement, wireless transmission, and playback on hearables according to some embodiments of this disclosure.

[0009] FIG. 3 is a system diagram illustrating multiple audio paths, including air and Bluetooth paths, between

talkers and a user within a conversation scenario according to some embodiments of this disclosure.

[0010] FIG. 4 is a block diagram illustrating an audio processing system for capturing, enhancing, and rendering audio signals in a wearable ecosystem according to some embodiments of this disclosure.

[0011] FIG. 5 is a system diagram illustrating various configurations of smart glasses and earbuds for capturing and transmitting audio in different scenarios according to some embodiments of this disclosure.

[0012] FIG. 6 is a flowchart of a method for establishing a wireless communication link, detecting voice audio, and transmitting the audio to a wearable audio device according to some embodiments of this disclosure.

[0013] FIG. 7 is an illustration of an example artificial-reality system according to some embodiments of this disclosure.

[0014] FIG. 8 is an illustration of an example artificial-reality system with a handheld device according to some embodiments of this disclosure.

[0015] FIG. 9A is an illustration of example user interactions within an artificial-reality system according to some embodiments of this disclosure.

[0016] FIG. 9B is an illustration of example user interactions within an artificial-reality system according to some embodiments of this disclosure.

[0017] FIG. 10A is an illustration of example user interactions within an artificial-reality system according to some embodiments of this disclosure.

[0018] FIG. 10B is an illustration of example user interactions within an artificial-reality system according to some embodiments of this disclosure.

[0019] FIG. 11 is an illustration of an example wrist-wearable device of an artificial-reality system according to some embodiments of this disclosure.

[0020] FIG. 12 is an illustration of an example wearable artificial-reality system according to some embodiments of this disclosure.

[0021] FIG. 13 is an illustration of an example augmented-reality system according to some embodiments of this disclosure.

[0022] FIG. 14A is an illustration of an example virtual-reality system according to some embodiments of this disclosure.

[0023] FIG. 14B is an illustration of another perspective of the virtual-reality systems shown in FIG. 14A.

[0024] FIG. 15 is a block diagram showing system components of example artificial-and virtual-reality systems.

[0025] Throughout the drawings, identical reference characters and descriptions indicate similar, but not necessarily identical, elements. While the exemplary embodiments described herein are susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and will be described in detail herein. However, the exemplary embodiments described herein are not intended to be limited to the particular forms disclosed. Rather, the present disclosure covers all modifications, equivalents, and alternatives falling within the scope of the appended claims.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0026] Individuals frequently encounter difficulties in comprehending speech in environments with elevated ambi-

ent noise and challenging signal-to-noise ratios. Conventional wearable devices, such as hearing aids and smart glasses equipped with multi-microphone arrays and basic signal processing techniques, including beamforming and denoising, have been developed to address these issues. However, these systems often fail to provide adequate speech enhancement in high-noise environments exceeding 75 dB or in situations where the signal-to-noise ratio (SNR) is particularly poor. Additionally, such devices may inadvertently amplify sound to levels that pose risks to hearing health, including noise-induced hearing loss. These limitations underscore the need for a more robust and integrated approach to improving speech comprehension and protecting hearing health.

[0027] The subject matter described herein provides a wearable ecosystem that leverages smart glasses with advanced audio processing capabilities and hearables. The wearable ecosystem may further include additional hearing amplification devices, such as hearing aids, cochlear implants, or any other suitable auditory enhancement systems to overcome the shortcomings of prior solutions. The smart glasses are equipped with a mouth-directed beamformer (e.g., near-field beamformer) utilizing spatially distributed microphone arrays and specialized signal processing algorithms to isolate and enhance the user's voice while suppressing ambient noise. Enhanced audio is further processed using machine learning-based and digital signal processing-based denoising techniques, such as Deep Neural Network (DNN)-based noise reduction (NR) and spatial noise reduction, to improve speech clarity. The processed audio is then wirelessly transmitted to hearables worn by the conversation partner via low-latency Bluetooth technology, ensuring synchronized and high-quality audio playback. Hearables, which may include earbuds, hearing aids, or cochlear implants, are configured to receive the enhanced audio and provide additional noise attenuation through active and passive noise cancellation mechanisms. In certain embodiments, the system dynamically adjusts noise cancellation and transparency levels based on environmental noise conditions, environmental sensing, and SNR sensing, utilizing AI-driven algorithms to optimize hearing protection and speech intelligibility. The system may also incorporate an integrated AI assistant to facilitate device pairing, manage settings, and enhance group conversation scenarios by intelligently switching between user roles such as group lead, team member, or listener.

[0028] By capturing and processing near-field audio at the source device, rather than relying on far-field audio processing at the listener's device, the described system significantly improves speech comprehension in noisy environments, including concerts, bars, and stadiums. The architecture enables a tightly integrated and scalable solution, offering substantial improvement in SNR compared to conventional devices. This approach not only enhances user experience but also establishes a new standard for augmented hearing technologies in wearable devices.

[0029] FIGS. 1-6 illustrate example implementations of systems and methods for enabling comfortable conversations in acoustically challenging environments by capturing a talker's voice at a source device (e.g., smart glasses worn by the talker), enhancing the captured voice, and transmitting the enhanced voice to one or more wearable audio devices of one or more listeners (e.g., hearables, hearing aids, cochlear implants, additional smart glasses, smart

watches, or combinations thereof). In some embodiments, the techniques described herein improve speech intelligibility while also safeguarding hearing health by reducing reliance on far-field pickup at a listener device and/or by enabling increased attenuation of ambient noise at a listener device without sacrificing the audibility of the talker's speech.

[0030] As used herein, the term "smart glasses" refers to a head-wearable device including at least one microphone and at least one processor configured to perform audio capture and processing, and including at least one wireless communication interface (e.g., a Bluetooth interface). Smart glasses may include, without limitation, augmented-reality glasses, camera glasses, glasses with open-ear speakers, glasses with bone conduction transducers, glasses with cartilage conduction transducers, or other eyewear devices including computing and audio capabilities. In some embodiments, smart glasses include a plurality of microphones spatially distributed on a frame of the glasses (e.g., on a bridge, temples, rims, end pieces, or combinations thereof).

[0031] As used herein, the term "wearable audio device" refers to any wearable device configured to receive audio (and, in some embodiments, associated control data) over a wireless communication link and provide playback to a user. Examples of wearable audio devices include, without limitation, earbuds, headphones, headsets, hearable devices, hearing aids, cochlear implants, smart watches with integrated loudspeakers, neckbands with speakers, and smart glasses configured to play audio through open-air speakers. In some embodiments, a wearable audio device includes at least one microphone and supports a transparency (hear-through) mode and/or active noise cancellation (ANC).

[0032] As used herein, the term "hearable device" (or "hearables") refers to a wearable audio device configured to be worn at an ear of a user and configured to provide audio playback to the user. In some embodiments, a hearable device at least partially occludes an ear canal opening (e.g., an earbud with an ear tip), although certain hearable devices may be open-fit. In some embodiments, the term "hearable device" encompasses hearing aids and/or cochlear implants. In other embodiments, hearing aids and cochlear implants are treated as distinct classes of wearable audio devices that may receive enhanced voice audio as described herein.

[0033] As used herein, the term "wireless communication link" refers to a data communication link established between at least two devices via wireless signaling. In some embodiments, the wireless communication link includes a low-latency Bluetooth link. In some embodiments, the wireless communication link includes a broadcast and/or multi-cast channel (e.g., a Bluetooth audio broadcast channel) enabling a single sending device to transmit audio to multiple receiving devices as part of a group communication session. In some embodiments, a sending device negotiates backward compatibility with a legacy receiving device by selecting at least one audio protocol supported by the legacy receiving device, selecting an audio codec supported by the legacy receiving device, selecting a transport configuration supported by the legacy receiving device, or a combination thereof. For example, a sending device may support a newer Bluetooth audio feature set while still interoperating with receiving devices that support older Bluetooth audio capabilities.

[0034] As used herein, the term “voice audio” refers to audio content corresponding to speech produced by a user (e.g., the wearer of the smart glasses). Voice audio may include, without limitation, a near-field capture of the user’s speech, an enhanced version of the user’s speech, encoded audio frames representing the user’s speech, or combinations thereof. In some embodiments, voice audio includes metadata or side information that facilitates rendering at a receiving device (e.g., spatial cues, level cues, or recommended mixing parameters).

[0035] As used herein, the term “mouth-directed beamformer” refers to any beamforming technique (implemented in hardware, software, or a combination thereof) that is configured to emphasize sound arriving from a region proximate a wearer’s mouth and de-emphasize ambient sound arriving from other directions. In some embodiments, the mouth-directed beamformer enhances a SNR of speech produced by the wearer relative to ambient sound. In some embodiments, a mouth-directed beamformer is implemented using at least two microphones spatially distributed on smart glasses. In some embodiments, a mouth-directed beamformer leverages a known geometry of the smart glasses (e.g., microphone placement on a frame) and/or a known approximate mouth location relative to the microphones. In some embodiments, audio capture toward the wearer’s mouth may be achieved using a single microphone positioned or configured to capture sound produced by the wearer’s mouth. For example, audio from the single microphone may be streamed, transmitted, or processed exclusively from the single microphone.

[0036] As used herein, the term “denoising” refers to any digital-signal-processing-based and/or machine-learning-based technique for reducing noise and/or interference relative to desired speech content. Examples of denoising include, without limitation, spectral subtraction, Wiener filtering, neural network denoisers, and spatial noise reduction using multiple microphones. In some embodiments, denoising is performed after mouth-directed beamforming. In other embodiments, denoising is performed before beamforming, jointly with beamforming, or iteratively with beamforming.

[0037] As used herein, the term “control-channel metadata” refers to data transmitted in association with voice audio that is usable by a receiving device to control a playback configuration and/or an audio processing configuration. In some embodiments, control-channel metadata includes, without limitation, (i) a command that configures a receiving device to adjust an active noise cancellation level, a transparency level, or a mixing ratio between received voice audio and locally captured ambient audio, (ii) spatial rendering data for rendering received voice audio with a spatial cue (e.g., left/right balance, interaural time difference, interaural level difference, head-related transfer function selection), (iii) recommended dynamic range parameters, (iv) equalization parameters, or (v) any combination thereof.

[0038] FIG. 1 illustrates an example scene 100 in which a first user 102 (is wearing smart glasses 106 and hearables 104, and a second user 112 is wearing smart glasses 116 and hearables 114. In the example of FIG. 1, background noise 108 is present, such as noise encountered in a restaurant, bar, stadium, concert venue, or other acoustically challenging environment. In some embodiments, the background noise 108 corresponds to an ambient noise level greater than about

70 dB sound pressure level. In the illustrated configuration, each user may speak while their respective smart glasses capture that user’s speech using at least one microphone of the smart glasses.

[0039] In some embodiments, smart glasses 106 capture voice audio of user 102 using a mouth-directed beamformer implemented with a plurality of microphones on the frame of the smart glasses 106. In some embodiments, smart glasses 106 additionally or alternatively capture voice audio of user 102 using a contact microphone housed in a nose pad region of the smart glasses 106 (e.g., a vibration sensor configured to detect speech-related vibrations). In some embodiments, smart glasses 116 similarly capture voice audio of user 112 using beamforming microphones, a contact microphone, or a combination thereof.

[0040] FIG. 1 further illustrates that enhanced voice audio may be exchanged between the two users over one or more wireless communication links. In some embodiments, smart glasses 106 transmit enhanced voice audio corresponding to user 102 to the hearables 114 of user 112 (e.g., directly to hearables 114 or via smart glasses 116 acting as an intermediary device). In some embodiments, smart glasses 116 transmit enhanced voice audio corresponding to user 112 to the hearables 104 of user 102 (e.g., transmit enhanced voice audio directly to hearables 104 or via smart glasses 106 acting as an intermediary device). In this manner, each listener may receive a cleaned and enhanced version of the other talker’s voice, which may enable comfortable conversation in the presence of background noise 108.

[0041] In some embodiments, the system of FIG. 1 operates in an open-ear playback mode in which one or both users receive audio via open-air speakers of smart glasses (e.g., speakers integrated into smart glasses 106 and/or 116), including air conduction speakers and/or bone conduction or cartilage conduction transducers. In some embodiments, the system operates in a hearable playback mode in which one or both users receive audio via ear-worn hearables (e.g., hearables 104 and/or 114) that may provide passive attenuation and/or active noise cancellation. In some embodiments, an integrated artificial intelligence (AI) assistant on one or more devices (e.g., on smart glasses 106 and/or 116, on a paired phone, or on another wearable) assists with pairing, feature start/stop, switching between open-ear playback mode and hearable playback mode, and/or applying settings that improve group conversations.

[0042] FIG. 2 illustrates an example process 200 for near-field speech pick-up, enhancement, and wireless transmission. In the example of FIG. 2, multi-channel audio from glasses 202 is obtained using a plurality of microphones on smart glasses (e.g., smart glasses 106 or 116 of FIG. 1). The multi-channel audio may include a mixture of a wearer’s speech and ambient noise. At block 204, near-field speech pick-up and enhancement is performed. In some embodiments, block 204 includes mouth-directed beamforming to emphasize the wearer’s voice relative to background noise. In some embodiments, block 204 further includes denoising using digital-signal-processing-based techniques, machine-learning-based techniques (e.g., a deep neural network denoiser), spatial noise reduction using the plurality of microphones, or combinations thereof. In some embodiments, block 204 further includes speech enhancement operations such as automatic gain control, dereverberation, echo suppression, or combinations thereof.

[0043] In some embodiments, the output of block 204 is enhanced voice audio 206. Enhanced voice audio 206 may include an encoded audio stream suitable for wireless transmission, and may be produced with a target latency selected to support natural conversational interaction. In some embodiments, enhanced voice audio 206 is produced and transmitted to achieve an end-to-end latency (from capture at the talker device to playback at the listener device) of less than about 25 milliseconds, although higher latencies may be acceptable in certain noisy environments and/or certain use cases. For instance, users with severe or profound hearing loss who use hearing aids or cochlear implants may accept much higher end to end latency.

[0044] At block 208, wireless communication is performed to deliver the enhanced voice audio 206 to one or more receiving devices. In some embodiments, wireless communication is implemented using low-latency Bluetooth. In some embodiments, wireless communication is implemented using a group communication session in which enhanced voice audio is transmitted to a plurality of wearable audio devices associated with a plurality of users. In some embodiments, the wireless communication includes a unicast stream, a broadcast stream, or a combination thereof. In some embodiments, the wireless communication is configured to be backward compatible with at least one legacy wearable audio device by negotiating a compatible protocol and/or codec, while still supporting improved performance with newer devices.

[0045] FIG. 2 further illustrates that the receiving device(s) 210 may include hearables, hearing aids, cochlear implants, or other wearable audio devices. In some embodiments, the receiving device(s) 210 apply transparency and/or active noise cancellation in coordination with the receipt of enhanced voice audio. For example, in noisier environments, a receiving hearable may increase ANC and reduce transparency to protect hearing and reduce background noise, while continuing to present the enhanced voice audio received from the talker's smart glasses. In some embodiments, the receiving device(s) 210 apply occlusion mitigation processing (e.g., processing that reduces the perception of occlusion-related artifacts for a wearer), and/or mixing between locally captured ambient sound and the received enhanced voice audio, to provide improved naturalness and environmental awareness. In some embodiments, the receiving device(s) 210 render the enhanced voice audio as a "cleaned overlay" on top of locally perceived sound, with a mixing ratio selected based on ambient noise level and/or estimated signal-to-noise ratio.

[0046] In some embodiments in which the receiving device is a hearing aid or cochlear implant, the receiving device may render the cleaned and enhanced speech without performing the same type of ANC used by consumer hearables. In certain such embodiments, intelligibility is still improved because the system provides near-field beamforming and denoising at the talker location rather than relying on far-field pickup at the listener. In some embodiments, the enhanced voice audio is individualized for a hearing-impaired listener using a dynamic range compression technique (e.g., wide dynamic range compression (WDRC)) that is fit to the listener's hearing loss profile. In other embodiments, the enhanced voice audio is provided as non-individualized audio and individualization is performed by a receiving hearing aid or cochlear implant according to its fitting parameters.

[0047] FIG. 3 illustrates an example scene 300 showing multiple audio paths that may be present during a conversation. In the example of FIG. 3, a user 306 (e.g., a listener) may receive audio from a first talker 302 via a wireless path (illustrated as a Bluetooth path) and may receive audio from another talker 304 via an acoustic air path. In certain environments, the listener may also receive an air path version of talker 302's speech in addition to the wireless path version (e.g., due to direct acoustic propagation). In some embodiments, the system manages these simultaneous paths to improve intelligibility and reduce perceptual artifacts.

[0048] In some embodiments, the system dynamically activates, deactivates, or attenuates (e.g., "ducks") a received wireless voice stream based on an estimated signal-to-noise ratio (SNR) corresponding to the talker. For example, when the air-path SNR for talker 302 is sufficiently good such that the direct path would be audible and clear, the system may reduce reliance on the wireless overlay to reduce multipath or comb-filtering perceptual effects. Conversely, when the air-path SNR is poor, the system may increase reliance on the wireless overlay. In some embodiments, the system estimates SNR by steering a beam toward a talker and comparing estimated speech energy to estimated noise energy, using microphone signals, camera signals, inertial measurement unit (IMU) signals, or combinations thereof.

[0049] FIG. 4 illustrates an example system 400 for multi-modal talker tracking and per-source audio processing and rendering. In the example of FIG. 4, glasses acoustics 402 provide microphone signals from a microphone array 412 to a processing pipeline. In some embodiments, the system 400 additionally receives sensor signals from cameras 404 and an IMU 406. The cameras 404 and IMU 406 may be used, for example, to localize and/or track conversation participants. In some embodiments, the system identifies talkers by combining cues including visual detections (e.g., face detections, mouth motion), motion cues (e.g., head pose from IMU), and audio cues (e.g., direction-of-arrival estimates from the microphone array 412).

[0050] In the example of FIG. 4, a tracking module 408 may maintain estimated states for one or more talkers, such as relative angles, distances, trajectories, or identifiers. In some embodiments, the tracking module 408 distinguishes participants associated with a coordinated wireless conversation system (e.g., participants whose devices are paired and exchanging enhanced voice audio) from non-participants (e.g., by using device identifiers, correlation between locally captured audio and received wireless audio envelopes, or other association techniques).

[0051] In the example of FIG. 4, a front-end control module 410 may control one or more aspects of audio pre-processing. In some embodiments, the front-end control module 410 controls beamformer steering, selection of microphone channels, adaptation parameters, noise estimation, or combinations thereof. In some embodiments, the front-end control module 410 provides per-talker control signals that are used to generate per-talker audio objects for subsequent processing stages.

[0052] FIG. 4 further illustrates a set of chat channels 414. In some embodiments, chat channels 414 represent one or more incoming wireless audio streams associated with one or more remote talkers and/or one or more outgoing streams to be transmitted to remote users (e.g., Bluetooth encoders

and decoders). In some embodiments, a “channel” corresponds to an audio object representing a talker, where different talkers may be processed separately. For example, a talker indexed as may have a corresponding spatial focusing block **416**, a corresponding frequency shaping block **418**, and a corresponding rendering block **420**. Similar processing may be performed for additional talkers T1 to Tn. In some embodiments, the system additionally performs an “own voice” processing path (e.g., a mouth-directed beamformer and denoising applied to the wearer’s speech), which may be transmitted to other participants.

[0053] In some embodiments, spatial focusing **416** implements beamforming and/or spatial filtering to emphasize a selected talker and suppress other sources. Spatial focusing **416** may use microphone array signals, estimated talker positions from the tracking module **408**, or combinations thereof. In some embodiments, frequency shaping **418** implements per-source equalization, dynamic range control, audibility enhancement, or combinations thereof. In some embodiments, rendering **420** generates one or more output signals configured for playback at glasses acoustics **424** (e.g., open-air speakers) and/or for transmission to an earbud acoustics subsystem **426** (e.g., a paired earbud device). In some embodiments, rendering includes spatial rendering such that a talker is presented at a perceived location consistent with that talker’s direction relative to the listener, thereby enabling “world-locked” rendering. For example, if a sending device wearer is standing to the receiving device wearer’s left, the system may increase a left ear channel level relative to a right ear channel level and/or apply interaural timing differences to preserve spatial cues.

[0054] FIG. **4** further illustrates limiting **422**, which may include one or more limiters (e.g., a left-hand side limiter and a right-hand side limiter) configured to constrain output levels for comfort and safety. In some embodiments, limiting **422** is selected and/or controlled to reduce risk of overamplification and to promote hearing health. In some embodiments, limiting parameters are adapted based on estimated ambient noise level, user preferences, or receiving device type (e.g., consumer hearables versus hearing aids).

[0055] In some embodiments, system **400** sends audio and/or control data to earbuds and/or other wearable audio devices. In some embodiments, the system transmits control-channel metadata along with audio to instruct a receiving device how to set ANC, transparency, and/or mixing. For example, a sending device may command a receiving earbud to reduce a low-latency hear-through amount in one or more frequency bands and increase a level of the received enhanced voice audio, or vice versa. In some embodiments, the system coordinates a mixing strategy across frequency bands to preserve naturalness and avoid undesirable effects (e.g., inhibited Lombard effect), such as by maintaining some low-frequency hear-through while increasing cancellation at other frequencies.

[0056] FIG. **5** illustrates example deployment configurations. In a first configuration (scene **510**), the voice of a talker **512** is captured and processed and then rendered by smart glasses **516** using glasses-only playback (e.g., open-ear speakers). In this configuration, enhanced audio may be played at the glasses or transmitted to another device for playback, depending on the use case.

[0057] In a second configuration (scene **520**), smart glasses **526** operate in conjunction with earbuds **528**. In some embodiments, smart glasses **526** receive the voice of

talker **522** that is near-field speech captured, beamformed, and denoised, and transmit enhanced voice audio to earbuds **528** for playback. In some embodiments, earbuds **528** apply ANC and/or transparency adjustments based on control-channel metadata received from the glasses, thereby enabling a combination of hearing protection and improved intelligibility.

[0058] In a third configuration (scene **530**), smart glasses **536** operate in a latency-optimized mode with earbuds **538**. In some embodiments, the glasses **536** and earbuds **538** perform an automatic smart wireless handover for optimal latency. For example, the glasses may transmit talker localization metadata (and, in some embodiments, other rendering parameters) to the earbuds, and the earbuds perform at least a portion of frequency shaping and/or rendering locally. In certain such embodiments, local earbud processing reduces end-to-end latency by reducing double handling and/or rebroadcast time. In some embodiments, the glasses select between (i) sending fully rendered audio to the earbuds and (ii) sending partially processed audio plus metadata to enable local rendering at the earbuds, based on measured link latency, compute availability, battery constraints, environmental noise, or combinations thereof.

[0059] FIG. **6** illustrates an example computer-implemented method **600**. In the example of FIG. **6**, at step **610**, at least one processor of smart glasses of a first user establishes a wireless communication link with a wearable audio device of a second user. In some embodiments, step **610** includes discovering the wearable audio device, authenticating and pairing, negotiating a protocol and/or codec, establishing a unicast stream and/or joining a group communication session, or combinations thereof. In some embodiments, step **610** includes negotiating backward compatibility with at least one Bluetooth audio protocol supported by a legacy wearable audio device, such that the system interoperates across different generations and manufacturers of receiving devices.

[0060] At step **620**, the smart glasses detect voice audio of the first user via at least one microphone of the smart glasses. In some embodiments, step **620** includes capturing the voice audio using at least two microphones spatially distributed on the smart glasses and performing mouth-directed beamforming. In some embodiments, step **620** includes sensing the voice audio using a contact microphone housed in a nose pad of the smart glasses. In some embodiments, step **620** further includes enhancing the voice audio prior to transmission by applying digital-signal-processing-based denoising and/or machine-learning-based denoising. In some embodiments, spatial noise reduction is performed using a plurality of microphones of the smart glasses. In some embodiments, the system determines an ambient noise level and/or an estimated SNR associated with the conversation while performing step **620**.

[0061] At step **630**, the smart glasses transmit the voice audio to the wearable audio device via the wireless communication link. In some embodiments, step **630** includes transmitting control-channel metadata associated with playback of the voice audio. For example, the control-channel metadata may include a command configuring the wearable audio device to adjust an ANC level, a transparency level, and/or a mixing ratio between received voice audio and ambient audio. Additionally or alternatively, the control-channel metadata may include spatial rendering data for rendering the voice audio with a spatial cue. In some

embodiments, the control-channel metadata is generated based on at least one of an ambient noise level or an estimated SNR, such that the receiving device behavior adapts to the environment.

[0062] In some embodiments, step **630** includes transmitting the voice audio to a plurality of wearable audio devices using a group communication session (e.g., for group conversations). In some embodiments, the system assigns a conversational role to at least one user (e.g., group lead, team member, listener) and tailors at least one of the voice audio or the control-channel metadata per user based on the assigned conversational role. For example, a group lead's voice may be prioritized (e.g., higher level, different frequency shaping, lower ducking threshold), while a listener's device may be configured for higher hearing protection (e.g., more ANC, reduced transparency) while still receiving intelligible enhanced speech.

[0063] In some embodiments, the system includes an artificial agent (e.g., an integrated AI assistant) configured to assist with operations of method **600**. In some embodiments, the artificial agent switches between open-ear playback mode and hearable playback mode based on an environmental condition, such as ambient noise level, SNR, user motion, or user preference. For example, in lower noise conditions, the artificial agent may bias toward open-ear playback and higher transparency. In higher noise conditions, the artificial agent may bias toward hearable playback with increased ANC and reduced transparency while maintaining intelligibility by increasing reliance on the enhanced voice audio stream.

[0064] Although FIG. 6 illustrates one example ordering of steps **610-630**, the steps may be performed in other orders, repeated, performed concurrently for multiple participants, or extended with additional sub-steps. For example, the system may continuously re-estimate SNR and adjust ducking, mixing, or transparency settings during an ongoing conversation. Additionally, although certain examples herein refer to Bluetooth-based links and specific feature sets, the techniques described herein are not limited to any particular wireless technology and may be implemented using any suitable short-range wireless protocol capable of supporting the audio and control data described herein.

[0065] The preceding description has been provided to enable those skilled in the art to make and use the disclosed systems and methods for enabling comfortable conversations in acoustically challenging environments by capturing a talker's voice at smart glasses, enhancing the captured voice (e.g., via mouth-directed beamforming and denoising), and transmitting the enhanced voice to one or more wearable audio devices of one or more listeners over a wireless communication link (e.g., a low-latency Bluetooth link supporting unicast, broadcast, and/or group sessions, including backward-compatible configurations). The exemplary embodiments described herein are susceptible to various modifications and alternative forms, including variations in microphone configurations (e.g., frame-mounted arrays and/or contact microphones), enhancement techniques (e.g., DSP-based and/or machine-learning-based processing), control strategies (e.g., transmission of control-channel metadata for ANC/transparency/mixing/spatial rendering, SNR-based ducking, and/or per-role tailoring in group conversations), and deployment architectures (e.g., open-ear playback at glasses, hearable playback with coordinated

ANC/transparency, and/or latency-optimized handover with local earbud rendering). Accordingly, the disclosure is not intended to be limited to the particular embodiments shown and described, but rather is intended to cover all modifications, equivalents, and alternatives falling within the scope of the appended claims.

EXAMPLE EMBODIMENTS

[0066] Clause 1. A computer-implemented method comprising: establishing, by at least one processor of smart glasses of a first user, a wireless communication link with a wearable audio device of a second user; detecting, via at least one microphone of the smart glasses, voice audio of the first user; and transmitting, via the wireless communication link, the voice audio to the wearable audio device.

[0067] Clause 2. The computer-implemented method of clause 1, wherein the wearable audio device comprises additional smart glasses configured to play the voice audio through open air speakers.

[0068] Clause 3. The computer-implemented method of clause 1, wherein the wearable audio device comprises a hearable device configured to at least partially occlude an ear canal opening of the second user.

[0069] Clause 4. The computer-implemented method of clause 3, wherein the hearable device comprises at least one of a hearing aid or a cochlear implant.

[0070] Clause 5. The computer-implemented method of clause 1, wherein: the wearable audio device comprises additional smart glasses worn by the second user; and the additional smart glasses is configured to play the voice audio through a wireless connection with at least one hearable device worn by the second user.

[0071] Clause 6. The computer-implemented method of clause 5, wherein the wireless connection between the additional smart glasses and the at least one hearable device provides an end-to-end latency of less than 25 milliseconds for playback of the voice audio at the at least one hearable device.

[0072] Clause 7. The computer-implemented method of clause 1, wherein detecting the voice audio comprises: capturing the voice audio with at least two microphones spatially distributed on the smart glasses; and performing mouth-directed beamforming.

[0073] Clause 8. The computer-implemented method of clause 1, wherein detecting the voice audio comprises sensing the voice audio using a contact microphone housed in a nose pad of the smart glasses.

[0074] Clause 9. The computer-implemented method of clause 1, further comprising, prior to transmitting the voice audio, enhancing the voice audio by applying digital-signal-processing-based denoising.

[0075] Clause 10. The computer-implemented method of clause 9, wherein enhancing the voice audio comprises applying a machine-learning-based denoising model.

[0076] Clause 11. The computer-implemented method of clause 9, wherein enhancing the voice audio comprises applying spatial noise reduction using a plurality of microphones of the smart glasses.

[0077] Clause 12. The computer-implemented method of clause 1, wherein the wireless communication link comprises a low-latency Bluetooth link.

- [0078] Clause 13. The computer-implemented method of clause 12, wherein establishing the wireless communication link comprises negotiating backward compatibility with at least one Bluetooth audio protocol supported by a legacy wearable audio device.
- [0079] Clause 14. The computer-implemented method of clause 1, wherein transmitting the voice audio comprises transmitting, to the wearable audio device, control-channel metadata associated with playback of the voice audio, the control-channel metadata comprising at least one of (i) a command that configures the wearable audio device to adjust an active noise cancellation level, a transparency level, or a mixing ratio between the voice audio and ambient audio, or (ii) spatial rendering data for rendering the voice audio with a spatial cue.
- [0080] Clause 15. The computer-implemented method of clause 14, further comprising determining, by the smart glasses, at least one of an ambient noise level or an estimated signal-to-noise ratio, and generating the control-channel metadata based on at least one of the ambient noise level or the estimated signal-to-noise ratio.
- [0081] Clause 16. The computer-implemented method of clause 1, wherein establishing the wireless communication link comprises establishing wireless communication links with a plurality of wearable audio devices associated with a plurality of users, and wherein transmitting comprises transmitting the voice audio to the plurality of wearable audio devices using a group communication session.
- [0082] Clause 17. The computer-implemented method of clause 16, further comprising assigning a conversational role to at least one user of the plurality of users and tailoring at least one of the voice audio or control-channel metadata per user based on the assigned conversational role.
- [0083] Clause 18. The computer-implemented method of clause 1, further comprising switching, by an artificial agent, between an open-ear playback mode and a hearable playback mode based on an environmental condition.
- [0084] Clause 19. A system comprising: at least one physical processor; physical memory comprising computer-executable instructions that, when executed by the physical processor, cause the physical processor to: establish a wireless communication link between smart glasses of a first user and a wearable audio device of a second user; detect, via at least one microphone of the smart glasses, voice audio of the first user; and transmit, via the wireless communication link, the voice audio to the wearable audio device.
- [0085] Clause 20. A non-transitory computer-readable medium comprising one or more computer-executable instructions that, when executed by at least one processor of a computing device, cause the computing device to: establish a wireless communication link between smart glasses of a first user and a wearable audio device of a second user; detect, via at least one microphone of the smart glasses, voice audio of the first user; and transmit, via the wireless communication link, the voice audio to the wearable audio device.
- [0086] Embodiments of the present disclosure may include or be implemented in conjunction with various types

of Artificial-Reality (AR) systems. AR may be any superimposed functionality and/or sensory-detectable content presented by an artificial-reality system within a user's physical surroundings. In other words, AR is a form of reality that has been adjusted in some manner before presentation to a user. AR can include and/or represent virtual reality (VR), augmented reality, mixed AR (MAR), or some combination and/or variation of these types of realities. Similarly, AR environments may include VR environments (including non-immersive, semi-immersive, and fully immersive VR environments), augmented-reality environments (including marker-based augmented-reality environments, markerless augmented-reality environments, location-based augmented-reality environments, and projection-based augmented-reality environments), hybrid-reality environments, and/or any other type or form of mixed-or alternative-reality environments.

[0087] AR content may include completely computer-generated content or computer-generated content combined with captured (e.g., real-world) content. Such AR content may include video, audio, haptic feedback, or some combination thereof, any of which may be presented in a single channel or in multiple channels (such as stereo video that produces a three-dimensional (3D) effect to the viewer). Additionally, in some embodiments, AR may also be associated with applications, products, accessories, services, or some combination thereof, that are used to, for example, create content in an artificial reality and/or are otherwise used in (e.g., to perform activities in) an artificial reality.

[0088] AR systems may be implemented in a variety of different form factors and configurations. Some AR systems may be designed to work without near-eye displays (NEDs). Other AR systems may include a NED that also provides visibility into the real world (such as, e.g., augmented-reality system 1300 in FIG. 13) or that visually immerses a user in an artificial reality (such as, e.g., virtual-reality system 1400 in FIGS. 14A and 14B). While some AR devices may be self-contained systems, other AR devices may communicate and/or coordinate with external devices to provide an AR experience to a user. Examples of such external devices include handheld controllers, mobile devices, desktop computers, devices worn by a user, devices worn by one or more other users, and/or any other suitable external system.

[0089] FIGS. 7-10B illustrate example artificial-reality (AR) systems in accordance with some embodiments. FIG. 7 shows a first AR system 700 and first example user interactions using a wrist-wearable device 702, a head-wearable device (e.g., AR glasses 1300), and/or a handheld intermediary processing device (HIPD) 706. FIG. 8 shows a second AR system 800 and second example user interactions using a wrist-wearable device 802, AR glasses 804, and/or an HIPD 806. FIGS. 9A and 9B show a third AR system 900 and third example user interactions using a wrist-wearable device 902, a head-wearable device (e.g., VR headset 950), and/or an HIPD 906. FIGS. 10A and 10B show a fourth AR system 1000 and fourth example user interactions using a wrist-wearable device 1030, VR headset 1020, and/or a haptic device 1060 (e.g., wearable gloves).

[0090] A wrist-wearable device 1100, which can be used for wrist-wearable device 702, 802, 902, 1030, and one or more of its components, are described below in reference to FIGS. 11 and 12; head-wearable devices 1300 and 1400, which can respectively be used for AR glasses 704, 804 or

VR headset **950**, **1020**, and their one or more components are described below in reference to FIGS. **13-15**.

[0091] Referring to FIG. **7**, wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** can communicatively couple via a network **725** (e.g., cellular, near field, Wi-Fi, personal area network, wireless LAN, etc.). Additionally, wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** can also communicatively couple with one or more servers **730**, computers **740** (e.g., laptops, computers, etc.), mobile devices **750** (e.g., smartphones, tablets, etc.), and/or other electronic devices via network **725** (e.g., cellular, near field, Wi-Fi, personal area network, wireless LAN, etc.).

[0092] In FIG. **7**, a user **708** is shown wearing wrist-wearable device **702** and AR glasses **704** and having HIPD **706** on their desk. The wrist-wearable device **702**, AR glasses **704**, and HIPD **706** facilitate user interaction with an AR environment. In particular, as shown by first AR system **700**, wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** cause presentation of one or more avatars **710**, digital representations of contacts **712**, and virtual objects **714**. As discussed below, user **708** can interact with one or more avatars **710**, digital representations of contacts **712**, and virtual objects **714** via wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706**.

[0093] User **708** can use any of wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** to provide user inputs. For example, user **708** can perform one or more hand gestures that are detected by wrist-wearable device **702** (e.g., using one or more EMG sensors and/or IMUs, described below in reference to FIGS. **11** and **12**) and/or AR glasses **704** (e.g., using one or more image sensor or camera, described below in reference to FIGS. **13-10**) to provide a user input. Alternatively, or additionally, user **708** can provide a user input via one or more touch surfaces of wrist-wearable device **702**, AR glasses **704**, HIPD **706**, and/or voice commands captured by a microphone of wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706**. In some embodiments, wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** include a digital assistant to help user **708** in providing a user input (e.g., completing a sequence of operations, suggesting different operations or commands, providing reminders, confirming a command, etc.). In some embodiments, user **708** can provide a user input via one or more facial gestures and/or facial expressions. For example, cameras of wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** can track eyes of user **708** for navigating a user interface.

[0094] Wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** can operate alone or in conjunction to allow user **708** to interact with the AR environment. In some embodiments, HIPD **706** is configured to operate as a central hub or control center for the wrist-wearable device **702**, AR glasses **704**, and/or another communicatively coupled device. For example, user **708** can provide an input to interact with the AR environment at any of wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706**, and HIPD **706** can identify one or more back-end and front-end tasks to cause the performance of the requested interaction and distribute instructions to cause the performance of the one or more back-end and front-end tasks at wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706**. In some embodiments, a back-end task is a background processing task that is not perceptible by the user (e.g., rendering content, decompression, compression, etc.), and a front-end task is a user-facing task that is perceptible to the user (e.g., presenting informa-

tion to the user, providing feedback to the user, etc.). HIPD **706** can perform the back-end tasks and provide wrist-wearable device **702** and/or AR glasses **704** operational data corresponding to the performed back-end tasks such that wrist-wearable device **702** and/or AR glasses **704** can perform the front-end tasks. In this way, HIPD **706**, which has more computational resources and greater thermal headroom than wrist-wearable device **702** and/or AR glasses **704**, performs computationally intensive tasks and reduces the computer resource utilization and/or power usage of wrist-wearable device **702** and/or AR glasses **704**.

[0095] In the example shown by first AR system **700**, HIPD **706** identifies one or more back-end tasks and front-end tasks associated with a user request to initiate an AR video call with one or more other users (represented by avatar **710** and the digital representation of contact **712**) and distributes instructions to cause the performance of the one or more back-end tasks and front-end tasks. In particular, HIPD **706** performs back-end tasks for processing and/or rendering image data (and other data) associated with the AR video call and provides operational data associated with the performed back-end tasks to AR glasses **704** such that the AR glasses **704** perform front-end tasks for presenting the AR video call (e.g., presenting avatar **710** and digital representation of contact **712**).

[0096] In some embodiments, HIPD **706** can operate as a focal or anchor point for causing the presentation of information. This allows user **708** to be generally aware of where information is presented. For example, as shown in first AR system **700**, avatar **710** and the digital representation of contact **712** are presented above HIPD **706**. In particular, HIPD **706** and AR glasses **704** operate in conjunction to determine a location for presenting avatar **710** and the digital representation of contact **712**. In some embodiments, information can be presented a predetermined distance from HIPD **706** (e.g., within 5 meters). For example, as shown in first AR system **700**, virtual object **714** is presented on the desk some distance from HIPD **706**. Similar to the above example, HIPD **706** and AR glasses **704** can operate in conjunction to determine a location for presenting virtual object **714**. Alternatively, in some embodiments, presentation of information is not bound by HIPD **706**. More specifically, avatar **710**, digital representation of contact **712**, and virtual object **714** do not have to be presented within a predetermined distance of HIPD **706**.

[0097] User inputs provided at wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** are coordinated such that the user can use any device to initiate, continue, and/or complete an operation. For example, user **708** can provide a user input to AR glasses **704** to cause AR glasses **704** to present virtual object **714** and, while virtual object **714** is presented by AR glasses **704**, user **708** can provide one or more hand gestures via wrist-wearable device **702** to interact and/or manipulate virtual object **714**.

[0098] FIG. **8** shows a user **808** wearing a wrist-wearable device **802** and AR glasses **804**, and holding an HIPD **806**. In second AR system **800**, the wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** are used to receive and/or provide one or more messages to a contact of user **808**. In particular, wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** detect and coordinate one or more user inputs to initiate a messaging application and prepare a response to a received message via the messaging application.

[0099] In some embodiments, user **808** initiates, via a user input, an application on wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** that causes the application to initiate on at least one device. For example, in second AR system **800**, user **808** performs a hand gesture associated with a command for initiating a messaging application (represented by messaging user interface **816**), wrist-wearable device **802** detects the hand gesture and, based on a determination that user **808** is wearing AR glasses **804**, causes AR glasses **804** to present a messaging user interface **816** of the messaging application. AR glasses **804** can present messaging user interface **816** to user **808** via its display (e.g., as shown by a field of view **818** of user **808**). In some embodiments, the application is initiated and executed on the device (e.g., wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806**) that detects the user input to initiate the application, and the device provides another device operational data to cause the presentation of the messaging application. For example, wrist-wearable device **802** can detect the user input to initiate a messaging application, initiate and run the messaging application, and provide operational data to AR glasses **804** and/or HIPD **806** to cause presentation of the messaging application. Alternatively, the application can be initiated and executed at a device other than the device that detected the user input. For example, wrist-wearable device **802** can detect the hand gesture associated with initiating the messaging application and cause HIPD **806** to run the messaging application and coordinate the presentation of the messaging application.

[0100] Further, user **808** can provide a user input provided at wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** to continue and/or complete an operation initiated at another device. For example, after initiating the messaging application via wrist-wearable device **802** and while AR glasses **804** present messaging user interface **816**, user **808** can provide an input at HIPD **806** to prepare a response (e.g., shown by the swipe gesture performed on HIPD **806**). Gestures performed by user **808** on HIPD **806** can be provided and/or displayed on another device. For example, a swipe gesture performed on HIPD **806** is displayed on a virtual keyboard of messaging user interface **816** displayed by AR glasses **804**.

[0101] In some embodiments, wrist-wearable device **802**, AR glasses **804**, HIPD **806**, and/or any other communicatively coupled device can present one or more notifications to user **808**. The notification can be an indication of a new message, an incoming call, an application update, a status update, etc. User **808** can select the notification via wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** and can cause presentation of an application or operation associated with the notification on at least one device. For example, user **808** can receive a notification that a message was received at wrist-wearable device **802**, AR glasses **804**, HIPD **806**, and/or any other communicatively coupled device and can then provide a user input at wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** to review the notification, and the device detecting the user input can cause an application associated with the notification to be initiated and/or presented at wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806**.

[0102] While the above example describes coordinated inputs used to interact with a messaging application, user inputs can be coordinated to interact with any number of applications including, but not limited to, gaming applica-

tions, social media applications, camera applications, web-based applications, financial applications, etc. For example, AR glasses **804** can present to user **808** game application data, and HIPD **806** can be used as a controller to provide inputs to the game. Similarly, user **808** can use wrist-wearable device **802** to initiate a camera of AR glasses **804**, and user **808** can use wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** to manipulate the image capture (e.g., zoom in or out, apply filters, etc.) and capture image data.

[0103] Users may interact with the devices disclosed herein in a variety of ways. For example, as shown in FIGS. **9A** and **9B**, a user **908** may interact with an AR system **900** by donning a VR headset **950** while holding HIPD **906** and wearing wrist-wearable device **902**. In this example, AR system **900** may enable a user to interact with a game **910** by swiping their arm. One or more of VR headset **950**, HIPD **906**, and wrist-wearable device **902** may detect this gesture and, in response, may display a sword strike in game **910**. Similarly, in FIGS. **10A** and **10B**, a user **1008** may interact with an AR system **1000** by donning a VR headset **1020** while wearing haptic device **1060** and wrist-wearable device **1030**. In this example, AR system **1000** may enable a user to interact with a game **1010** by swiping their arm. One or more of VR headset **1020**, haptic device **1060**, and wrist-wearable device **1030** may detect this gesture and, in response, may display a spell being cast in game **910**.

[0104] Having discussed example AR systems, devices for interacting with such AR systems and other computing systems more generally will now be discussed in greater detail. Some explanations of devices and components that can be included in some or all of the example devices discussed below are explained herein for ease of reference. Certain types of the components described below may be more suitable for a particular set of devices, and less suitable for a different set of devices. But subsequent reference to the components explained here should be considered to be encompassed by the descriptions provided.

[0105] In some embodiments discussed below, example devices and systems, including electronic devices and systems, will be addressed. Such example devices and systems are not intended to be limiting, and one of skill in the art will understand that alternative devices and systems to the example devices and systems described herein may be used to perform the operations and construct the systems and devices that are described herein.

[0106] An electronic device may be a device that uses electrical energy to perform a specific function. An electronic device can be any physical object that contains electronic components such as transistors, resistors, capacitors, diodes, and integrated circuits. Examples of electronic devices include smartphones, laptops, digital cameras, televisions, gaming consoles, and music players, as well as the example electronic devices discussed herein. As described herein, an intermediary electronic device may be a device that sits between two other electronic devices and/or a subset of components of one or more electronic devices and facilitates communication, data processing, and/or data transfer between the respective electronic devices and/or electronic components.

[0107] An integrated circuit may be an electronic device made up of multiple interconnected electronic components such as transistors, resistors, and capacitors. These components may be etched onto a small piece of semiconductor material, such as silicon. Integrated circuits may include

analog integrated circuits, digital integrated circuits, mixed signal integrated circuits, and/or any other suitable type or form of integrated circuit. Examples of integrated circuits include application-specific integrated circuits (ASICs), processing units, central processing units (CPUs), co-processors, and accelerators.

[0108] Analog integrated circuits, such as sensors, power management circuits, and operational amplifiers, may process continuous signals and perform analog functions such as amplification, active filtering, demodulation, and mixing. Examples of analog integrated circuits include linear integrated circuits and radio frequency circuits.

[0109] Digital integrated circuits, which may be referred to as logic integrated circuits, may include microprocessors, microcontrollers, memory chips, interfaces, power management circuits, programmable devices, and/or any other suitable type or form of integrated circuit. In some embodiments, examples of integrated circuits include central processing units (CPUs),

[0110] Processing units, such as CPUs, may be electronic components that are responsible for executing instructions and controlling the operation of an electronic device (e.g., a computer). There are various types of processors that may be used interchangeably, or may be specifically required, by embodiments described herein. For example, a processor may be: (i) a general processor designed to perform a wide range of tasks, such as running software applications, managing operating systems, and performing arithmetic and logical operations; (ii) a microcontroller designed for specific tasks such as controlling electronic devices, sensors, and motors; (iii) an accelerator, such as a graphics processing unit (GPU), designed to accelerate the creation and rendering of images, videos, and animations (e.g., virtual-reality animations, such as three-dimensional modeling); (iv) a field-programmable gate array (FPGA) that can be programmed and reconfigured after manufacturing and/or can be customized to perform specific tasks, such as signal processing, cryptography, and machine learning; and/or (v) a digital signal processor (DSP) designed to perform mathematical operations on signals such as audio, video, and radio waves. One or more processors of one or more electronic devices may be used in various embodiments described herein.

[0111] Memory generally refers to electronic components in a computer or electronic device that store data and instructions for the processor to access and manipulate. Examples of memory can include: (i) random access memory (RAM) configured to store data and instructions temporarily; (ii) read-only memory (ROM) configured to store data and instructions permanently (e.g., one or more portions of system firmware, and/or boot loaders) and/or semi-permanently; (iii) flash memory, which can be configured to store data in electronic devices (e.g., USB drives, memory cards, and/or solid-state drives (SSDs)); and/or (iv) cache memory configured to temporarily store frequently accessed data and instructions. Memory, as described herein, can store structured data (e.g., SQL databases, MongoDB databases, GraphQL data, JSON data, etc.). Other examples of data stored in memory can include (i) profile data, including user account data, user settings, and/or other user data stored by the user, (ii) sensor data detected and/or otherwise obtained by one or more sensors, (iii) media content data including stored image data, audio data, documents, and the like, (iv) application data, which can include

data collected and/or otherwise obtained and stored during use of an application, and/or any other types of data described herein.

[0112] Controllers may be electronic components that manage and coordinate the operation of other components within an electronic device (e.g., controlling inputs, processing data, and/or generating outputs). Examples of controllers can include: (i) microcontrollers, including small, low-power controllers that are commonly used in embedded systems and Internet of Things (IoT) devices; (ii) programmable logic controllers (PLCs) that may be configured to be used in industrial automation systems to control and monitor manufacturing processes; (iii) system-on-a-chip (SoC) controllers that integrate multiple components such as processors, memory, I/O interfaces, and other peripherals into a single chip; and/or (iv) DSPs.

[0113] A power system of an electronic device may be configured to convert incoming electrical power into a form that can be used to operate the device. A power system can include various components, such as (i) a power source, which can be an alternating current (AC) adapter or a direct current (DC) adapter power supply, (ii) a charger input, which can be configured to use a wired and/or wireless connection (which may be part of a peripheral interface, such as a USB, micro-USB interface, near-field magnetic coupling, magnetic inductive and magnetic resonance charging, and/or radio frequency (RF) charging), (iii) a power-management integrated circuit, configured to distribute power to various components of the device and to ensure that the device operates within safe limits (e.g., regulating voltage, controlling current flow, and/or managing heat dissipation), and/or (iv) a battery configured to store power to provide usable power to components of one or more electronic devices.

[0114] Peripheral interfaces may be electronic components (e.g., of electronic devices) that allow electronic devices to communicate with other devices or peripherals and can provide the ability to input and output data and signals. Examples of peripheral interfaces can include (i) universal serial bus (USB) and/or micro-USB interfaces configured for connecting devices to an electronic device, (ii) Bluetooth interfaces configured to allow devices to communicate with each other, including Bluetooth low energy (BLE), (iii) near field communication (NFC) interfaces configured to be short-range wireless interfaces for operations such as access control, (iv) POGO pins, which may be small, spring-loaded pins configured to provide a charging interface, (v) wireless charging interfaces, (vi) GPS interfaces, (vii) Wi-Fi interfaces for providing a connection between a device and a wireless network, and/or (viii) sensor interfaces.

[0115] Sensors may be electronic components (e.g., in and/or otherwise in electronic communication with electronic devices, such as wearable devices) configured to detect physical and environmental changes and generate electrical signals. Examples of sensors can include (i) imaging sensors for collecting imaging data (e.g., including one or more cameras disposed on a respective electronic device), (ii) biopotential-signal sensors, (iii) inertial measurement units (e.g., IMUs) for detecting, for example, angular rate, force, magnetic field, and/or changes in acceleration, (iv) heart rate sensors for measuring a user's heart rate, (v) SpO2 sensors for measuring blood oxygen saturation and/or other biometric data of a user, (vi) capacitive sensors for detecting

changes in potential at a portion of a user's body (e.g., a sensor-skin interface), and/or (vii) light sensors (e.g., time-of-flight sensors, infrared light sensors, visible light sensors, etc.).

[0116] Biopotential-signal-sensing components may be devices used to measure electrical activity within the body (e.g., biopotential-signal sensors). Some types of biopotential-signal sensors include (i) electroencephalography (EEG) sensors configured to measure electrical activity in the brain to diagnose neurological disorders, (ii) electrocardiography (ECG or EKG) sensors configured to measure electrical activity of the heart to diagnose heart problems, (iii) electromyography (EMG) sensors configured to measure the electrical activity of muscles and to diagnose neuromuscular disorders, and (iv) electrooculography (EOG) sensors configured to measure the electrical activity of eye muscles to detect eye movement and diagnose eye disorders.

[0117] An application stored in memory of an electronic device (e.g., software) may include instructions stored in the memory. Examples of such applications include (i) games, (ii) word processors, (iii) messaging applications, (iv) media-streaming applications, (v) financial applications, (vi) calendars, (vii) clocks, and (viii) communication interface modules for enabling wired and/or wireless connections between different respective electronic devices (e.g., IEEE 1302.15.4, Wi-Fi, ZigBee, 6LoWPAN, Thread, Z-Wave, Bluetooth Smart, ISA100.11a, WirelessHART, or MiWi), custom or standard wired protocols (e.g., Ethernet or HomePlug), and/or any other suitable communication protocols).

[0118] A communication interface may be a mechanism that enables different systems or devices to exchange information and data with each other, including hardware, software, or a combination of both hardware and software. For example, a communication interface can refer to a physical connector and/or port on a device that enables communication with other devices (e.g., USB, Ethernet, HDMI, Bluetooth). In some embodiments, a communication interface can refer to a software layer that enables different software programs to communicate with each other (e.g., application programming interfaces (APIs), protocols like HTTP and TCP/IP, etc.).

[0119] A graphics module may be a component or software module that is designed to handle graphical operations and/or processes and can include a hardware module and/or a software module.

[0120] Non-transitory computer-readable storage media may be physical devices or storage media that can be used to store electronic data in a non-transitory form (e.g., such that the data is stored permanently until it is intentionally deleted or modified).

[0121] FIGS. 11 and 12 illustrate an example wrist-wearable device 1100 and an example computer system 1200, in accordance with some embodiments. Wrist-wearable device 1100 is an instance of wearable device 702 described in FIG. 7 herein, such that the wearable device 702 should be understood to have the features of the wrist-wearable device 1100 and vice versa. FIG. 12 illustrates components of the wrist-wearable device 1100, which can be used individually or in combination, including combinations that include other electronic devices and/or electronic components.

[0122] FIG. 11 shows a wearable band 1110 and a watch body 1120 (or capsule) being coupled, as discussed below, to form wrist-wearable device 1100. Wrist-wearable device 1100 can perform various functions and/or operations asso-

ciated with navigating through user interfaces and selectively opening applications as well as the functions and/or operations described above with reference to FIGS. 7-10B.

[0123] As will be described in more detail below, operations executed by wrist-wearable device 1100 can include (i) presenting content to a user (e.g., displaying visual content via a display 1105), (ii) detecting (e.g., sensing) user input (e.g., sensing a touch on peripheral button 1123 and/or at a touch screen of the display 1105, a hand gesture detected by sensors (e.g., biopotential sensors)), (iii) sensing biometric data (e.g., neuromuscular signals, heart rate, temperature, sleep, etc.) via one or more sensors 1113, messaging (e.g., text, speech, video, etc.); image capture via one or more imaging devices or cameras 1125, wireless communications (e.g., cellular, near field, Wi-Fi, personal area network, etc.), location determination, financial transactions, providing haptic feedback, providing alarms, providing notifications, providing biometric authentication, providing health monitoring, providing sleep monitoring, etc.

[0124] The above-example functions can be executed independently in watch body 1120, independently in wearable band 1110, and/or via an electronic communication between watch body 1120 and wearable band 1110. In some embodiments, functions can be executed on wrist-wearable device 1100 while an AR environment is being presented (e.g., via one of AR systems 700 to 1000). The wearable devices described herein can also be used with other types of AR environments.

[0125] Wearable band 1110 can be configured to be worn by a user such that an inner surface of a wearable structure 1111 of wearable band 1110 is in contact with the user's skin. In this example, when worn by a user, sensors 1113 may contact the user's skin. In some examples, one or more of sensors 1113 can sense biometric data such as a user's heart rate, a saturated oxygen level, temperature, sweat level, neuromuscular signals, or a combination thereof. One or more of sensors 1113 can also sense data about a user's environment including a user's motion, altitude, location, orientation, gait, acceleration, position, or a combination thereof. In some embodiment, one or more of sensors 1113 can be configured to track a position and/or motion of wearable band 1110. One or more of sensors 1113 can include any of the sensors defined above and/or discussed below with respect to FIG. 11.

[0126] One or more of sensors 1113 can be distributed on an inside and/or an outside surface of wearable band 1110. In some embodiments, one or more of sensors 1113 are uniformly spaced along wearable band 1110. Alternatively, in some embodiments, one or more of sensors 1113 are positioned at distinct points along wearable band 1110. As shown in FIG. 11, one or more of sensors 1113 can be the same or distinct. For example, in some embodiments, one or more of sensors 1113 can be shaped as a pill (e.g., sensor 1113a), an oval, a circle a square, an oblong (e.g., sensor 1113c) and/or any other shape that maintains contact with the user's skin (e.g., such that neuromuscular signal and/or other biometric data can be accurately measured at the user's skin). In some embodiments, one or more sensors of 1113 are aligned to form pairs of sensors (e.g., for sensing neuromuscular signals based on differential sensing within each respective sensor). For example, sensor 1113b may be aligned with an adjacent sensor to form sensor pair 1114a and sensor 1113d may be aligned with an adjacent sensor to form sensor pair 1114b. In some embodiments, wearable

band 1110 does not have a sensor pair. Alternatively, in some embodiments, wearable band 1110 has a predetermined number of sensor pairs (one pair of sensors, three pairs of sensors, four pairs of sensors, six pairs of sensors, sixteen pairs of sensors, etc.).

[0127] Wearable band 1110 can include any suitable number of sensors 1113. In some embodiments, the number and arrangement of sensors 1113 depends on the particular application for which wearable band 1110 is used. For instance, wearable band 1110 can be configured as an armband, wristband, or chest-band that include a plurality of sensors 1113 with different number of sensors 1113, a variety of types of individual sensors with the plurality of sensors 1113, and different arrangements for each use case, such as medical use cases as compared to gaming or general day-to-day use cases.

[0128] In accordance with some embodiments, wearable band 1110 further includes an electrical ground electrode and a shielding electrode. The electrical ground and shielding electrodes, like the sensors 1113, can be distributed on the inside surface of the wearable band 1110 such that they contact a portion of the user's skin. For example, the electrical ground and shielding electrodes can be at an inside surface of a coupling mechanism 1116 or an inside surface of a wearable structure 1111. The electrical ground and shielding electrodes can be formed and/or use the same components as sensors 1113. In some embodiments, wearable band 1110 includes more than one electrical ground electrode and more than one shielding electrode.

[0129] Sensors 1113 can be formed as part of wearable structure 1111 of wearable band 1110. In some embodiments, sensors 1113 are flush or substantially flush with wearable structure 1111 such that they do not extend beyond the surface of wearable structure 1111. While flush with wearable structure 1111, sensors 1113 are still configured to contact the user's skin (e.g., via a skin-contacting surface). Alternatively, in some embodiments, sensors 1113 extend beyond wearable structure 1111 a predetermined distance (e.g., 0.1-2 mm) to make contact and depress into the user's skin. In some embodiment, sensors 1113 are coupled to an actuator (not shown) configured to adjust an extension height (e.g., a distance from the surface of wearable structure 1111) of sensors 1113 such that sensors 1113 make contact and depress into the user's skin. In some embodiments, the actuators adjust the extension height between 0.01 mm-1.2 mm. This may allow a the user to customize the positioning of sensors 1113 to improve the overall comfort of the wearable band 1110 when worn while still allowing sensors 1113 to contact the user's skin. In some embodiments, sensors 1113 are indistinguishable from wearable structure 1111 when worn by the user.

[0130] Wearable structure 1111 can be formed of an elastic material, elastomers, etc., configured to be stretched and fitted to be worn by the user. In some embodiments, wearable structure 1111 is a textile or woven fabric. As described above, sensors 1113 can be formed as part of a wearable structure 1111. For example, sensors 1113 can be molded into the wearable structure 1111, be integrated into a woven fabric (e.g., sensors 1113 can be sewn into the fabric and mimic the pliability of fabric and can and/or be constructed from a series woven strands of fabric).

[0131] Wearable structure 1111 can include flexible electronic connectors that interconnect sensors 1113, the electronic circuitry, and/or other electronic components (de-

scribed below in reference to FIG. 12) that are enclosed in wearable band 1110. In some embodiments, the flexible electronic connectors are configured to interconnect sensors 1113, the electronic circuitry, and/or other electronic components of wearable band 1110 with respective sensors and/or other electronic components of another electronic device (e.g., watch body 1120). The flexible electronic connectors are configured to move with wearable structure 1111 such that the user adjustment to wearable structure 1111 (e.g., resizing, pulling, folding, etc.) does not stress or strain the electrical coupling of components of wearable band 1110.

[0132] As described above, wearable band 1110 is configured to be worn by a user. In particular, wearable band 1110 can be shaped or otherwise manipulated to be worn by a user. For example, wearable band 1110 can be shaped to have a substantially circular shape such that it can be configured to be worn on the user's lower arm or wrist. Alternatively, wearable band 1110 can be shaped to be worn on another body part of the user, such as the user's upper arm (e.g., around a bicep), forearm, chest, legs, etc. Wearable band 1110 can include a retaining mechanism 1112 (e.g., a buckle, a hook and loop fastener, etc.) for securing wearable band 1110 to the user's wrist or other body part. While wearable band 1110 is worn by the user, sensors 1113 sense data (referred to as sensor data) from the user's skin. In some examples, sensors 1113 of wearable band 1110 obtain (e.g., sense and record) neuromuscular signals.

[0133] The sensed data (e.g., sensed neuromuscular signals) can be used to detect and/or determine the user's intention to perform certain motor actions. In some examples, sensors 1113 may sense and record neuromuscular signals from the user as the user performs muscular activations (e.g., movements, gestures, etc.). The detected and/or determined motor actions (e.g., phalange (or digit) movements, wrist movements, hand movements, and/or other muscle intentions) can be used to determine control commands or control information (instructions to perform certain commands after the data is sensed) for causing a computing device to perform one or more input commands. For example, the sensed neuromuscular signals can be used to control certain user interfaces displayed on display 1105 of wrist-wearable device 1100 and/or can be transmitted to a device responsible for rendering an artificial-reality environment (e.g., a head-mounted display) to perform an action in an associated artificial-reality environment, such as to control the motion of a virtual device displayed to the user. The muscular activations performed by the user can include static gestures, such as placing the user's hand palm down on a table, dynamic gestures, such as grasping a physical or virtual object, and covert gestures that are imperceptible to another person, such as slightly tensing a joint by co-contracting opposing muscles or using sub-muscular activations. The muscular activations performed by the user can include symbolic gestures (e.g., gestures mapped to other gestures, interactions, or commands, for example, based on a gesture vocabulary that specifies the mapping of gestures to commands).

[0134] The sensor data sensed by sensors 1113 can be used to provide a user with an enhanced interaction with a physical object (e.g., devices communicatively coupled with wearable band 1110) and/or a virtual object in an artificial-reality application generated by an artificial-reality system

(e.g., user interface objects presented on the display 1105, or another computing device (e.g., a smartphone)).

[0135] In some embodiments, wearable band 1110 includes one or more haptic devices 1246 (e.g., a vibratory haptic actuator) that are configured to provide haptic feedback (e.g., a cutaneous and/or kinesthetic sensation, etc.) to the user's skin. Sensors 1113 and/or haptic devices 1246 (shown in FIG. 12) can be configured to operate in conjunction with multiple applications including, without limitation, health monitoring, social media, games, and artificial reality (e.g., the applications associated with artificial reality).

[0136] Wearable band 1110 can also include coupling mechanism 1116 for detachably coupling a capsule (e.g., a computing unit) or watch body 1120 (via a coupling surface of the watch body 1120) to wearable band 1110. For example, a cradle or a shape of coupling mechanism 1116 can correspond to shape of watch body 1120 of wrist-wearable device 1100. In particular, coupling mechanism 1116 can be configured to receive a coupling surface proximate to the bottom side of watch body 1120 (e.g., a side opposite to a front side of watch body 1120 where display 1105 is located), such that a user can push watch body 1120 downward into coupling mechanism 1116 to attach watch body 1120 to coupling mechanism 1116. In some embodiments, coupling mechanism 1116 can be configured to receive a top side of the watch body 1120 (e.g., a side proximate to the front side of watch body 1120 where display 1105 is located) that is pushed upward into the cradle, as opposed to being pushed downward into coupling mechanism 1116. In some embodiments, coupling mechanism 1116 is an integrated component of wearable band 1110 such that wearable band 1110 and coupling mechanism 1116 are a single unitary structure. In some embodiments, coupling mechanism 1116 is a type of frame or shell that allows watch body 1120 coupling surface to be retained within or on wearable band 1110 coupling mechanism 1116 (e.g., a cradle, a tracker band, a support base, a clasp, etc.).

[0137] Coupling mechanism 1116 can allow for watch body 1120 to be detachably coupled to the wearable band 1110 through a friction fit, magnetic coupling, a rotation-based connector, a shear-pin coupler, a retention spring, one or more magnets, a clip, a pin shaft, a hook and loop fastener, or a combination thereof. A user can perform any type of motion to couple the watch body 1120 to wearable band 1110 and to decouple the watch body 1120 from the wearable band 1110. For example, a user can twist, slide, turn, push, pull, or rotate watch body 1120 relative to wearable band 1110, or a combination thereof, to attach watch body 1120 to wearable band 1110 and to detach watch body 1120 from wearable band 1110. Alternatively, as discussed below, in some embodiments, the watch body 1120 can be decoupled from the wearable band 1110 by actuation of a release mechanism 1129.

[0138] Wearable band 1110 can be coupled with watch body 1120 to increase the functionality of wearable band 1110 (e.g., converting wearable band 1110 into wrist-wearable device 1100, adding an additional computing unit and/or battery to increase computational resources and/or a battery life of wearable band 1110, adding additional sensors to improve sensed data, etc.). As described above, wearable band 1110 and coupling mechanism 1116 are configured to operate independently (e.g., execute functions independently) from watch body 1120. For example, coupling mechanism 1116 can include one or more sensors 1113 that

contact a user's skin when wearable band 1110 is worn by the user, with or without watch body 1120 and can provide sensor data for determining control commands.

[0139] A user can detach watch body 1120 from wearable band 1110 to reduce the encumbrance of wrist-wearable device 1100 to the user. For embodiments in which watch body 1120 is removable, watch body 1120 can be referred to as a removable structure, such that in these embodiments wrist-wearable device 1100 includes a wearable portion (e.g., wearable band 1110) and a removable structure (e.g., watch body 1120).

[0140] Turning to watch body 1120, in some examples watch body 1120 can have a substantially rectangular or circular shape. Watch body 1120 is configured to be worn by the user on their wrist or on another body part. More specifically, watch body 1120 is sized to be easily carried by the user, attached on a portion of the user's clothing, and/or coupled to wearable band 1110 (forming the wrist-wearable device 1100). As described above, watch body 1120 can have a shape corresponding to coupling mechanism 1116 of wearable band 1110. In some embodiments, watch body 1120 includes a single release mechanism 1129 or multiple release mechanisms (e.g., two release mechanisms 1129 positioned on opposing sides of watch body 1120, such as spring-loaded buttons) for decoupling watch body 1120 from wearable band 1110. Release mechanism 1129 can include, without limitation, a button, a knob, a plunger, a handle, a lever, a fastener, a clasp, a dial, a latch, or a combination thereof.

[0141] A user can actuate release mechanism 1129 by pushing, turning, lifting, depressing, shifting, or performing other actions on release mechanism 1129. Actuation of release mechanism 1129 can release (e.g., decouple) watch body 1120 from coupling mechanism 1116 of wearable band 1110, allowing the user to use watch body 1120 independently from wearable band 1110 and vice versa. For example, decoupling watch body 1120 from wearable band 1110 can allow a user to capture images using rear-facing camera 1125b. Although release mechanism 1129 is shown positioned at a corner of watch body 1120, release mechanism 1129 can be positioned anywhere on watch body 1120 that is convenient for the user to actuate. In addition, in some embodiments, wearable band 1110 can also include a respective release mechanism for decoupling watch body 1120 from coupling mechanism 1116. In some embodiments, release mechanism 1129 is optional and watch body 1120 can be decoupled from coupling mechanism 1116 as described above (e.g., via twisting, rotating, etc.).

[0142] Watch body 1120 can include one or more peripheral buttons 1123 and 1127 for performing various operations at watch body 1120. For example, peripheral buttons 1123 and 1127 can be used to turn on or wake (e.g., transition from a sleep state to an active state) display 1105, unlock watch body 1120, increase or decrease a volume, increase or decrease a brightness, interact with one or more applications, interact with one or more user interfaces, etc. Additionally or alternatively, in some embodiments, display 1105 operates as a touch screen and allows the user to provide one or more inputs for interacting with watch body 1120.

[0143] In some embodiments, watch body 1120 includes one or more sensors 1121. Sensors 1121 of watch body 1120 can be the same or distinct from sensors 1113 of wearable band 1110. Sensors 1121 of watch body 1120 can be

distributed on an inside and/or an outside surface of watch body **1120**. In some embodiments, sensors **1121** are configured to contact a user's skin when watch body **1120** is worn by the user. For example, sensors **1121** can be placed on the bottom side of watch body **1120** and coupling mechanism **1116** can be a cradle with an opening that allows the bottom side of watch body **1120** to directly contact the user's skin. Alternatively, in some embodiments, watch body **1120** does not include sensors that are configured to contact the user's skin (e.g., including sensors internal and/or external to the watch body **1120** that are configured to sense data of watch body **1120** and the surrounding environment). In some embodiments, sensors **1121** are configured to track a position and/or motion of watch body **1120**.

[0144] Watch body **1120** and wearable band **1110** can share data using a wired communication method (e.g., a Universal Asynchronous Receiver/Transmitter (UART), a USB transceiver, etc.) and/or a wireless communication method (e.g., near field communication, Bluetooth, etc.). For example, watch body **1120** and wearable band **1110** can share data sensed by sensors **1113** and **1121**, as well as application and device specific information (e.g., active and/or available applications, output devices (e.g., displays, speakers, etc.), input devices (e.g., touch screens, microphones, imaging sensors, etc.).

[0145] In some embodiments, watch body **1120** can include, without limitation, a front-facing camera **1125a** and/or a rear-facing camera **1125b**, sensors **1121** (e.g., a biometric sensor, an IMU, a heart rate sensor, a saturated oxygen sensor, a neuromuscular signal sensor, an altimeter sensor, a temperature sensor, a bioimpedance sensor, a pedometer sensor, an optical sensor (e.g., imaging sensor **1263**), a touch sensor, a sweat sensor, etc.). In some embodiments, watch body **1120** can include one or more haptic devices **1276** (e.g., a vibratory haptic actuator) that is configured to provide haptic feedback (e.g., a cutaneous and/or kinesthetic sensation, etc.) to the user. Sensors **1221** and/or haptic device **1276** can also be configured to operate in conjunction with multiple applications including, without limitation, health monitoring applications, social media applications, game applications, and artificial reality applications (e.g., the applications associated with artificial reality).

[0146] As described above, watch body **1120** and wearable band **1110**, when coupled, can form wrist-wearable device **1100**. When coupled, watch body **1120** and wearable band **1110** may operate as a single device to execute functions (operations, detections, communications, etc.) described herein. In some embodiments, each device may be provided with particular instructions for performing the one or more operations of wrist-wearable device **1100**. For example, in accordance with a determination that watch body **1120** does not include neuromuscular signal sensors, wearable band **1110** can include alternative instructions for performing associated instructions (e.g., providing sensed neuromuscular signal data to watch body **1120** via a different electronic device). Operations of wrist-wearable device **1100** can be performed by watch body **1120** alone or in conjunction with wearable band **1110** (e.g., via respective processors and/or hardware components) and vice versa. In some embodiments, operations of wrist-wearable device **1100**, watch body **1120**, and/or wearable band **1110** can be performed in conjunction with one or more processors and/or hardware components.

[0147] As described below with reference to the block diagram of FIG. **12**, wearable band **1110** and/or watch body **1120** can each include independent resources required to independently execute functions. For example, wearable band **1110** and/or watch body **1120** can each include a power source (e.g., a battery), a memory, data storage, a processor (e.g., a central processing unit (CPU)), communications, a light source, and/or input/output devices.

[0148] FIG. **12** shows block diagrams of a computing system **1230** corresponding to wearable band **1110** and a computing system **1260** corresponding to watch body **1120** according to some embodiments. Computing system **1200** of wrist-wearable device **1100** may include a combination of components of wearable band computing system **1230** and watch body computing system **1260**, in accordance with some embodiments.

[0149] Watch body **1120** and/or wearable band **1110** can include one or more components shown in watch body computing system **1260**. In some embodiments, a single integrated circuit may include all or a substantial portion of the components of watch body computing system **1260** included in a single integrated circuit. Alternatively, in some embodiments, components of the watch body computing system **1260** may be included in a plurality of integrated circuits that are communicatively coupled. In some embodiments, watch body computing system **1260** may be configured to couple (e.g., via a wired or wireless connection) with wearable band computing system **1230**, which may allow the computing systems to share components, distribute tasks, and/or perform other operations described herein (individually or as a single device).

[0150] Watch body computing system **1260** can include one or more processors **1279**, a controller **1277**, a peripherals interface **1261**, a power system **1295**, and memory (e.g., a memory **1280**).

[0151] Power system **1295** can include a charger input **1296**, a power-management integrated circuit (PMIC) **1297**, and a battery **1298**. In some embodiments, a watch body **1120** and a wearable band **1110** can have respective batteries (e.g., battery **1298** and **1259**) and can share power with each other. Watch body **1120** and wearable band **1110** can receive a charge using a variety of techniques. In some embodiments, watch body **1120** and wearable band **1110** can use a wired charging assembly (e.g., power cords) to receive the charge. Alternatively, or in addition, watch body **1120** and/or wearable band **1110** can be configured for wireless charging. For example, a portable charging device can be designed to mate with a portion of watch body **1120** and/or wearable band **1110** and wirelessly deliver usable power to battery **1298** of watch body **1120** and/or battery **1259** of wearable band **1110**. Watch body **1120** and wearable band **1110** can have independent power systems (e.g., power system **1295** and **1256**, respectively) to enable each to operate independently. Watch body **1120** and wearable band **1110** can also share power (e.g., one can charge the other) via respective PMICs (e.g., PMICs **1297** and **1258**) and charger inputs (e.g., **1257** and **1296**) that can share power over power and ground conductors and/or over wireless charging antennas.

[0152] In some embodiments, peripherals interface **1261** can include one or more sensors **1221**. Sensors **1221** can include one or more coupling sensors **1262** for detecting when watch body **1120** is coupled with another electronic device (e.g., a wearable band **1110**). Sensors **1221** can include one or more imaging sensors **1263** (e.g., one or more

of cameras **1225**, and/or separate imaging sensors **1263** (e.g., thermal-imaging sensors)). In some embodiments, sensors **1221** can include one or more SpO2 sensors **1264**. In some embodiments, sensors **1221** can include one or more biopotential-signal sensors (e.g., EMG sensors **1265**, which may be disposed on an interior, user-facing portion of watch body **1120** and/or wearable band **1110**). In some embodiments, sensors **1221** may include one or more capacitive sensors **1266**. In some embodiments, sensors **1221** may include one or more heart rate sensors **1267**. In some embodiments, sensors **1221** may include one or more IMU sensors **1268**. In some embodiments, one or more IMU sensors **1268** can be configured to detect movement of a user's hand or other location where watch body **1120** is placed or held.

[0153] In some embodiments, one or more of sensors **1221** may provide an example human-machine interface. For example, a set of neuromuscular sensors, such as EMG sensors **1265**, may be arranged circumferentially around wearable band **1110** with an interior surface of EMG sensors **1265** being configured to contact a user's skin. Any suitable number of neuromuscular sensors may be used (e.g., between 2 and 20 sensors). The number and arrangement of neuromuscular sensors may depend on the particular application for which the wearable device is used. For example, wearable band **1110** can be used to generate control information for controlling an augmented reality system, a robot, controlling a vehicle, scrolling through text, controlling a virtual avatar, or any other suitable control task.

[0154] In some embodiments, neuromuscular sensors may be coupled together using flexible electronics incorporated into the wireless device, and the output of one or more of the sensing components can be optionally processed using hardware signal processing circuitry (e.g., to perform amplification, filtering, and/or rectification). In other embodiments, at least some signal processing of the output of the sensing components can be performed in software such as processors **1279**. Thus, signal processing of signals sampled by the sensors can be performed in hardware, software, or by any suitable combination of hardware and software, as aspects of the technology described herein are not limited in this respect.

[0155] Neuromuscular signals may be processed in a variety of ways. For example, the output of EMG sensors **1265** may be provided to an analog front end, which may be configured to perform analog processing (e.g., amplification, noise reduction, filtering, etc.) on the recorded signals. The processed analog signals may then be provided to an analog-to-digital converter, which may convert the analog signals to digital signals that can be processed by one or more computer processors. Furthermore, although this example is as discussed in the context of interfaces with EMG sensors, the embodiments described herein can also be implemented in wearable interfaces with other types of sensors including, but not limited to, mechanomyography (MMG) sensors, sonomyography (SMG) sensors, and electrical impedance tomography (EIT) sensors.

[0156] In some embodiments, peripherals interface **1261** includes a near-field communication (NFC) component **1269**, a global-position system (GPS) component **1270**, a long-term evolution (LTE) component **1271**, and/or a Wi-Fi and/or Bluetooth communication component **1272**. In some embodiments, peripherals interface **1261** includes one or more buttons **1273** (e.g., peripheral buttons **1123** and **1127**

in FIG. 11), which, when selected by a user, cause operation to be performed at watch body **1120**. In some embodiments, the peripherals interface **1261** includes one or more indicators, such as a light emitting diode (LED), to provide a user with visual indicators (e.g., message received, low battery, active microphone and/or camera, etc.).

[0157] Watch body **1120** can include at least one display **1105** for displaying visual representations of information or data to a user, including user-interface elements and/or three-dimensional virtual objects. The display can also include a touch screen for inputting user inputs, such as touch gestures, swipe gestures, and the like. Watch body **1120** can include at least one speaker **1274** and at least one microphone **1275** for providing audio signals to the user and receiving audio input from the user. The user can provide user inputs through microphone **1275** and can also receive audio output from speaker **1274** as part of a haptic event provided by haptic controller **1278**. Watch body **1120** can include at least one camera **1225**, including a front camera **1225a** and a rear camera **1225b**. Cameras **1225** can include ultra-wide-angle cameras, wide angle cameras, fish-eye cameras, spherical cameras, telephoto cameras, depth-sensing cameras, or other types of cameras.

[0158] Watch body computing system **1260** can include one or more haptic controllers **1278** and associated componentry (e.g., haptic devices **1276**) for providing haptic events at watch body **1120** (e.g., a vibrating sensation or audio output in response to an event at the watch body **1120**). Haptic controllers **1278** can communicate with one or more haptic devices **1276**, such as electroacoustic devices, including a speaker of the one or more speakers **1274** and/or other audio components and/or electromechanical devices that convert energy into linear motion such as a motor, solenoid, electroactive polymer, piezoelectric actuator, electrostatic actuator, or other tactile output generating components (e.g., a component that converts electrical signals into tactile outputs on the device). Haptic controller **1278** can provide haptic events to that are capable of being sensed by a user of watch body **1120**. In some embodiments, one or more haptic controllers **1278** can receive input signals from an application of applications **1282**.

[0159] In some embodiments, wearable band computing system **1230** and/or watch body computing system **1260** can include memory **1280**, which can be controlled by one or more memory controllers of controllers **1277**. In some embodiments, software components stored in memory **1280** include one or more applications **1282** configured to perform operations at the watch body **1120**. In some embodiments, one or more applications **1282** may include games, word processors, messaging applications, calling applications, web browsers, social media applications, media streaming applications, financial applications, calendars, clocks, etc. In some embodiments, software components stored in memory **1280** include one or more communication interface modules **1283** as defined above. In some embodiments, software components stored in memory **1280** include one or more graphics modules **1284** for rendering, encoding, and/or decoding audio and/or visual data and one or more data management modules **1285** for collecting, organizing, and/or providing access to data **1287** stored in memory **1280**. In some embodiments, one or more of applications **1282** and/or one or more modules can work in conjunction with one another to perform various tasks at the watch body **1120**.

[0160] In some embodiments, software components stored in memory 1280 can include one or more operating systems 1281 (e.g., a Linux-based operating system, an Android operating system, etc.). Memory 1280 can also include data 1287. Data 1287 can include profile data 1288A, sensor data 1289A, media content data 1290, and application data 1291.

[0161] It should be appreciated that watch body computing system 1260 is an example of a computing system within watch body 1120, and that watch body 1120 can have more or fewer components than shown in watch body computing system 1260, can combine two or more components, and/or can have a different configuration and/or arrangement of the components. The various components shown in watch body computing system 1260 are implemented in hardware, software, firmware, or a combination thereof, including one or more signal processing and/or application-specific integrated circuits.

[0162] Turning to the wearable band computing system 1230, one or more components that can be included in wearable band 1110 are shown. Wearable band computing system 1230 can include more or fewer components than shown in watch body computing system 1260, can combine two or more components, and/or can have a different configuration and/or arrangement of some or all of the components. In some embodiments, all, or a substantial portion of the components of wearable band computing system 1230 are included in a single integrated circuit. Alternatively, in some embodiments, components of wearable band computing system 1230 are included in a plurality of integrated circuits that are communicatively coupled. As described above, in some embodiments, wearable band computing system 1230 is configured to couple (e.g., via a wired or wireless connection) with watch body computing system 1260, which allows the computing systems to share components, distribute tasks, and/or perform other operations described herein (individually or as a single device).

[0163] Wearable band computing system 1230, similar to watch body computing system 1260, can include one or more processors 1249, one or more controllers 1247 (including one or more haptics controllers 1248), a peripherals interface 1231 that can include one or more sensors 1213 and other peripheral devices, a power source (e.g., a power system 1256), and memory (e.g., a memory 1250) that includes an operating system (e.g., an operating system 1251), data (e.g., data 1254 including profile data 1288B, sensor data 1289B, etc.), and one or more modules (e.g., a communications interface module 1252, a data management module 1253, etc.).

[0164] One or more of sensors 1213 can be analogous to sensors 1221 of watch body computing system 1260. For example, sensors 1213 can include one or more coupling sensors 1232, one or more SpO2 sensors 1234, one or more EMG sensors 1235, one or more capacitive sensors 1236, one or more heart rate sensors 1237, and one or more IMU sensors 1238.

[0165] Peripherals interface 1231 can also include other components analogous to those included in peripherals interface 1261 of watch body computing system 1260, including an NFC component 1239, a GPS component 1240, an LTE component 1241, a Wi-Fi and/or Bluetooth communication component 1242, and/or one or more haptic devices 1246 as described above in reference to peripherals interface 1261. In some embodiments, peripherals interface 1231 includes one or more buttons 1243, a display 1233, a

speaker 1244, a microphone 1245, and a camera 1255. In some embodiments, peripherals interface 1231 includes one or more indicators, such as an LED.

[0166] It should be appreciated that wearable band computing system 1230 is an example of a computing system within wearable band 1110, and that wearable band 1110 can have more or fewer components than shown in wearable band computing system 1230, combine two or more components, and/or have a different configuration and/or arrangement of the components. The various components shown in wearable band computing system 1230 can be implemented in one or more of a combination of hardware, software, or firmware, including one or more signal processing and/or application-specific integrated circuits.

[0167] Wrist-wearable device 1100 with respect to FIG. 11 is an example of wearable band 1110 and watch body 1120 coupled together, so wrist-wearable device 1100 will be understood to include the components shown and described for wearable band computing system 1230 and watch body computing system 1260. In some embodiments, wrist-wearable device 1100 has a split architecture (e.g., a split mechanical architecture, a split electrical architecture, etc.) between watch body 1120 and wearable band 1110. In other words, all of the components shown in wearable band computing system 1230 and watch body computing system 1260 can be housed or otherwise disposed in a combined wrist-wearable device 1100 or within individual components of watch body 1120, wearable band 1110, and/or portions thereof (e.g., a coupling mechanism 1116 of wearable band 1110).

[0168] The techniques described above can be used with any device for sensing neuromuscular signals but could also be used with other types of wearable devices for sensing neuromuscular signals (such as body-wearable or head-wearable devices that might have neuromuscular sensors closer to the brain or spinal column).

[0169] In some embodiments, wrist-wearable device 1100 can be used in conjunction with a head-wearable device (e.g., AR glasses 1300 and VR system 1410) and/or an HIPD, and wrist-wearable device 1100 can also be configured to be used to allow a user to control any aspect of the artificial reality (e.g., by using EMG-based gestures to control user interface objects in the artificial reality and/or by allowing a user to interact with the touchscreen on the wrist-wearable device to also control aspects of the artificial reality). Having thus described example wrist-wearable devices, attention will now be turned to example head-wearable devices, such as AR glasses 1300 and VR headset 1410.

[0170] FIGS. 13 to 15 show example artificial-reality systems, which can be used as or in connection with wrist-wearable device 1100. In some embodiments, AR system 1300 includes an eyewear device 1302, as shown in FIG. 13. In some embodiments, VR system 1410 includes a head-mounted display (HMD) 1412, as shown in FIGS. 14A and 14B. In some embodiments, AR system 1300 and VR system 1410 can include one or more analogous components (e.g., components for presenting interactive artificial-reality environments, such as processors, memory, and/or presentation devices, including one or more displays and/or one or more waveguides), some of which are described in more detail with respect to FIG. 15. As described herein, a head-wearable device can include components of eyewear device 1302 and/or head-mounted display 1412. Some

embodiments of head-wearable devices do not include any displays, including any of the displays described with respect to AR system **1300** and/or VR system **1410**. While the example artificial-reality systems are respectively described herein as AR system **1300** and VR system **1410**, either or both of the example AR systems described herein can be configured to present fully-immersive virtual-reality scenes presented in substantially all of a user's field of view or subtler augmented-reality scenes that are presented within a portion, less than all, of the user's field of view.

[0171] FIG. **13** show an example visual depiction of AR system **1300**, including an eyewear device **1302** (which may also be described herein as augmented-reality glasses, and/or smart glasses). AR system **1300** can include additional electronic components that are not shown in FIG. **13**, such as a wearable accessory device and/or an intermediary processing device, in electronic communication or otherwise configured to be used in conjunction with the eyewear device **1302**. In some embodiments, the wearable accessory device and/or the intermediary processing device may be configured to couple with eyewear device **1302** via a coupling mechanism in electronic communication with a coupling sensor **1524** (FIG. **15**), where coupling sensor **1524** can detect when an electronic device becomes physically or electronically coupled with eyewear device **1302**. In some embodiments, eyewear device **1302** can be configured to couple to a housing **1590** (FIG. **15**), which may include one or more additional coupling mechanisms configured to couple with additional accessory devices. The components shown in FIG. **13** can be implemented in hardware, software, firmware, or a combination thereof, including one or more signal-processing components and/or application-specific integrated circuits (ASICs).

[0172] Eyewear device **1302** includes mechanical glasses components, including a frame **1304** configured to hold one or more lenses (e.g., one or both lenses **1306-1** and **1306-2**). One of ordinary skill in the art will appreciate that eyewear device **1302** can include additional mechanical components, such as hinges configured to allow portions of frame **1304** of eyewear device **1302** to be folded and unfolded, a bridge configured to span the gap between lenses **1306-1** and **1306-2** and rest on the user's nose, nose pads configured to rest on the bridge of the nose and provide support for eyewear device **1302**, earpieces configured to rest on the user's ears and provide additional support for eyewear device **1302**, temple arms configured to extend from the hinges to the earpieces of eyewear device **1302**, and the like. One of ordinary skill in the art will further appreciate that some examples of AR system **1300** can include none of the mechanical components described herein. For example, smart contact lenses configured to present artificial reality to users may not include any components of eyewear device **1302**.

[0173] Eyewear device **1302** includes electronic components, many of which will be described in more detail below with respect to FIG. **15**. Some example electronic components are illustrated in FIG. **13**, including acoustic sensors **1325-1**, **1325-2**, **1325-3**, **1325-4**, **1325-5**, and **1325-6**, which can be distributed along a substantial portion of the frame **1304** of eyewear device **1302**. Eyewear device **1302** also includes a left camera **1339A** and a right camera **1339B**, which are located on different sides of the frame **1304**. Eyewear device **1302** also includes a processor **1348** (or any

other suitable type or form of integrated circuit) that is embedded into a portion of the frame **1304**.

[0174] FIGS. **14A** and **14B** show a VR system **1410** that includes a head-mounted display (HMD) **1412** (e.g., also referred to herein as an artificial-reality headset, a head-wearable device, a VR headset, etc.), in accordance with some embodiments. As noted, some artificial-reality systems (e.g., AR system **1300**) may, instead of blending an artificial reality with actual reality, substantially replace one or more of a user's visual and/or other sensory perceptions of the real world with a virtual experience (e.g., AR systems **900** and **1000**).

[0175] HMD **1412** includes a front body **1414** and a frame **1416** (e.g., a strap or band) shaped to fit around a user's head. In some embodiments, front body **1414** and/or frame **1416** include one or more electronic elements for facilitating presentation of and/or interactions with an AR and/or VR system (e.g., displays, IMUs, tracking emitter or detectors). In some embodiments, HMD **1412** includes output audio transducers (e.g., an audio transducer **1418**), as shown in FIG. **14B**. In some embodiments, one or more components, such as the output audio transducer(s) **1418** and frame **1416**, can be configured to attach and detach (e.g., are detachably attachable) to HMD **1412** (e.g., a portion or all of frame **1416**, and/or audio transducer **1418**), as shown in FIG. **14B**. In some embodiments, coupling a detachable component to HMD **1412** causes the detachable component to come into electronic communication with HMD **1412**.

[0176] FIGS. **14A** and **14B** also show that VR system **1410** includes one or more cameras, such as left camera **1439A** and right camera **1439B**, which can be analogous to left and right cameras **1339A** and **1339B** on frame **1304** of eyewear device **1302**. In some embodiments, VR system **1410** includes one or more additional cameras (e.g., cameras **1439C** and **1439D**), which can be configured to augment image data obtained by left and right cameras **1439A** and **1439B** by providing more information. For example, camera **1439C** can be used to supply color information that is not discerned by cameras **1439A** and **1439B**. In some embodiments, one or more of cameras **1439A** to **1439D** can include an optional IR cut filter configured to remove IR light from being received at the respective camera sensors.

[0177] FIG. **15** illustrates a computing system **1520** and an optional housing **1590**, each of which show components that can be included in AR system **1300** and/or VR system **1410**. In some embodiments, more or fewer components can be included in optional housing **1590** depending on practical restraints of the respective AR system being described.

[0178] In some embodiments, computing system **1520** can include one or more peripherals interfaces **1522A** and/or optional housing **1590** can include one or more peripherals interfaces **1522B**. Each of computing system **1520** and optional housing **1590** can also include one or more power systems **1542A** and **1542B**, one or more controllers **1546** (including one or more haptic controllers **1547**), one or more processors **1548A** and **1548B** (as defined above, including any of the examples provided), and memory **1550A** and **1550B**, which can all be in electronic communication with each other. For example, the one or more processors **1548A** and **1548B** can be configured to execute instructions stored in memory **1550A** and **1550B**, which can cause a controller of one or more of controllers **1546** to cause operations to be performed at one or more peripheral devices connected to peripherals interface **1522A** and/or **1522B**. In some embodi-

ments, each operation described can be powered by electrical power provided by power system **1542A** and/or **1542B**.

[0179] In some embodiments, peripherals interface **1522A** can include one or more devices configured to be part of computing system **1520**, some of which have been defined above and/or described with respect to the wrist-wearable devices shown in FIGS. **11** and **12**. For example, peripherals interface **1522A** can include one or more sensors **1523A**. Some example sensors **1523A** include one or more coupling sensors **1524**, one or more acoustic sensors **1525**, one or more imaging sensors **1526**, one or more EMG sensors **1527**, one or more capacitive sensors **1528**, one or more IMU sensors **1529**, and/or any other types of sensors explained above or described with respect to any other embodiments discussed herein.

[0180] In some embodiments, peripherals interfaces **1522A** and **1522B** can include one or more additional peripheral devices, including one or more NFC devices **1530**, one or more GPS devices **1531**, one or more LTE devices **1532**, one or more Wi-Fi and/or Bluetooth devices **1533**, one or more buttons **1534** (e.g., including buttons that are slidable or otherwise adjustable), one or more displays **1535A** and **1535B**, one or more speakers **1536A** and **1536B**, one or more microphones **1537**, one or more cameras **1538A** and **1538B** (e.g., including the left camera **1539A** and/or a right camera **1539B**), one or more haptic devices **1540**, and/or any other types of peripheral devices defined above or described with respect to any other embodiments discussed herein.

[0181] AR systems can include a variety of types of visual feedback mechanisms (e.g., presentation devices). For example, display devices in AR system **1300** and/or VR system **1410** can include one or more liquid-crystal displays (LCDs), light emitting diode (LED) displays, organic LED (OLED) displays, and/or any other suitable types of display screens. Artificial-reality systems can include a single display screen (e.g., configured to be seen by both eyes), and/or can provide separate display screens for each eye, which can allow for additional flexibility for varifocal adjustments and/or for correcting a refractive error associated with a user's vision. Some embodiments of AR systems also include optical subsystems having one or more lenses (e.g., conventional concave or convex lenses, Fresnel lenses, or adjustable liquid lenses) through which a user can view a display screen.

[0182] For example, respective displays **1535A** and **1535B** can be coupled to each of the lenses **1306-1** and **1306-2** of AR system **1300**. Displays **1535A** and **1535B** may be coupled to each of lenses **1306-1** and **1306-2**, which can act together or independently to present an image or series of images to a user. In some embodiments, AR system **1300** includes a single display **1535A** or **1535B** (e.g., a near-eye display) or more than two displays **1535A** and **1535B**. In some embodiments, a first set of one or more displays **1535A** and **1535B** can be used to present an augmented-reality environment, and a second set of one or more display devices **1535A** and **1535B** can be used to present a virtual-reality environment. In some embodiments, one or more waveguides are used in conjunction with presenting artificial-reality content to the user of AR system **1300** (e.g., as a means of delivering light from one or more displays **1535A** and **1535B** to the user's eyes). In some embodiments, one or more waveguides are fully or partially integrated into the eyewear device **1302**. Additionally, or alternatively to dis-

play screens, some artificial-reality systems include one or more projection systems. For example, display devices in AR system **1300** and/or VR system **1410** can include micro-LED projectors that project light (e.g., using a waveguide) into display devices, such as clear combiner lenses that allow ambient light to pass through. The display devices can refract the projected light toward a user's pupil and can enable a user to simultaneously view both artificial-reality content and the real world. Artificial-reality systems can also be configured with any other suitable type or form of image projection system. In some embodiments, one or more waveguides are provided additionally or alternatively to the one or more display(s) **1535A** and **1535B**.

[0183] Computing system **1520** and/or optional housing **1590** of AR system **1300** or VR system **1410** can include some or all of the components of a power system **1542A** and **1542B**. Power systems **1542A** and **1542B** can include one or more charger inputs **1543**, one or more PMICs **1544**, and/or one or more batteries **1545A** and **1544B**.

[0184] Memory **1550A** and **1550B** may include instructions and data, some or all of which may be stored as non-transitory computer-readable storage media within the memories **1550A** and **1550B**. For example, memory **1550A** and **1550B** can include one or more operating systems **1551**, one or more applications **1552**, one or more communication interface applications **1553A** and **1553B**, one or more graphics applications **1554A** and **1554B**, one or more AR processing applications **1555A** and **1555B**, and/or any other types of data defined above or described with respect to any other embodiments discussed herein.

[0185] Memory **1550A** and **1550B** also include data **1560A** and **1560B**, which can be used in conjunction with one or more of the applications discussed above. Data **1560A** and **1560B** can include profile data **1561**, sensor data **1562A** and **1562B**, media content data **1563A**, AR application data **1564A** and **1564B**, and/or any other types of data defined above or described with respect to any other embodiments discussed herein.

[0186] In some embodiments, controller **1546** of eyewear device **1302** may process information generated by sensors **1523A** and/or **1523B** on eyewear device **1302** and/or another electronic device within AR system **1300**. For example, controller **1546** can process information from acoustic sensors **1325-1** and **1325-2**. For each detected sound, controller **1546** can perform a direction of arrival (DOA) estimation to estimate a direction from which the detected sound arrived at eyewear device **1302** of AR system **1300**. As one or more of acoustic sensors **1525** (e.g., the acoustic sensors **1325-1**, **1325-2**) detects sounds, controller **1546** can populate an audio data set with the information (e.g., represented in FIG. **15** as sensor data **1562A** and **1562B**).

[0187] In some embodiments, a physical electronic connector can convey information between eyewear device **1302** and another electronic device and/or between one or more processors **1348**, **1548A**, **1548B** of AR system **1300** or VR system **1410** and controller **1546**. The information can be in the form of optical data, electrical data, wireless data, or any other transmittable data form. Moving the processing of information generated by eyewear device **1302** to an intermediary processing device can reduce weight and heat in the eyewear device, making it more comfortable and safer for a user. In some embodiments, an optional wearable accessory device (e.g., an electronic neckband) is coupled to eyewear device **1302** via one or more connectors. The

connectors can be wired or wireless connectors and can include electrical and/or non-electrical (e.g., structural) components. In some embodiments, eyewear device **1302** and the wearable accessory device can operate independently without any wired or wireless connection between them.

[0188] In some situations, pairing external devices, such as an intermediary processing device (e.g., HIPD **706**, **806**, **906**) with eyewear device **1302** (e.g., as part of AR system **1300**) enables eyewear device **1302** to achieve a similar form factor of a pair of glasses while still providing sufficient battery and computation power for expanded capabilities. Some, or all, of the battery power, computational resources, and/or additional features of AR system **1300** can be provided by a paired device or shared between a paired device and eyewear device **1302**, thus reducing the weight, heat profile, and form factor of eyewear device **1302** overall while allowing eyewear device **1302** to retain its desired functionality. For example, the wearable accessory device can allow components that would otherwise be included on eyewear device **1302** to be included in the wearable accessory device and/or intermediary processing device, thereby shifting a weight load from the user's head and neck to one or more other portions of the user's body. In some embodiments, the intermediary processing device has a larger surface area over which to diffuse and disperse heat to the ambient environment. Thus, the intermediary processing device can allow for greater battery and computation capacity than might otherwise have been possible on eyewear device **1302** standing alone. Because weight carried in the wearable accessory device can be less invasive to a user than weight carried in the eyewear device **1302**, a user may tolerate wearing a lighter eyewear device and carrying or wearing the paired device for greater lengths of time than the user would tolerate wearing a heavier eyewear device standing alone, thereby enabling an artificial-reality environment to be incorporated more fully into a user's day-to-day activities.

[0189] AR systems can include various types of computer vision components and subsystems. For example, AR system **1300** and/or VR system **1410** can include one or more optical sensors such as two-dimensional (2D) or three-dimensional (3D) cameras, time-of-flight depth sensors, structured light transmitters and detectors, single-beam or sweeping laser rangefinders, 3D LiDAR sensors, and/or any other suitable type or form of optical sensor. An AR system can process data from one or more of these sensors to identify a location of a user and/or aspects of the user's real-world physical surroundings, including the locations of real-world objects within the real-world physical surroundings. In some embodiments, the methods described herein are used to map the real world, to provide a user with context about real-world surroundings, and/or to generate digital twins (e.g., interactable virtual objects), among a variety of other functions. For example, FIGS. **14A** and **14B** show VR system **1410** having cameras **1439A** to **1439D**, which can be used to provide depth information for creating a voxel field and a two-dimensional mesh to provide object information to the user to avoid collisions.

[0190] In some embodiments, AR system **1300** and/or VR system **1410** can include haptic (tactile) feedback systems, which may be incorporated into headwear, gloves, body suits, handheld controllers, environmental devices (e.g., chairs or floor mats), and/or any other type of device or

system, such as the wearable devices discussed herein. The haptic feedback systems may provide various types of cutaneous feedback, including vibration, force, traction, shear, texture, and/or temperature. The haptic feedback systems may also provide various types of kinesthetic feedback, such as motion and compliance. The haptic feedback may be implemented using motors, piezoelectric actuators, fluidic systems, and/or a variety of other types of feedback mechanisms. The haptic feedback systems may be implemented independently of other artificial-reality devices, within other artificial-reality devices, and/or in conjunction with other artificial-reality devices.

[0191] In some embodiments of an artificial reality system, such as AR system **1300** and/or VR system **1410**, ambient light (e.g., a live feed of the surrounding environment that a user would normally see) can be passed through a display element of a respective head-wearable device presenting aspects of the AR system. In some embodiments, ambient light can be passed through a portion less than all of an AR environment presented within a user's field of view (e.g., a portion of the AR environment co-located with a physical object in the user's real-world environment that is within a designated boundary (e.g., a guardian boundary) configured to be used by the user while they are interacting with the AR environment). For example, a visual user interface element (e.g., a notification user interface element) can be presented at the head-wearable device, and an amount of ambient light (e.g., 15-50% of the ambient light) can be passed through the user interface element such that the user can distinguish at least a portion of the physical environment over which the user interface element is being displayed.

[0192] In some examples, the augmented reality systems described herein may also include a microphone array with a plurality of acoustic transducers. Acoustic transducers may represent transducers that detect air pressure variations induced by sound waves. Each acoustic transducer may be configured to detect sound and convert the detected sound into an electronic format (e.g., an analog or digital format). A microphone array may include, for example, ten acoustic transducers that may be designed to be placed inside a corresponding ear of the user, acoustic transducers that may be positioned at various locations on an HMD frame a watch band, etc.

[0193] In some embodiments, one or more of acoustic transducers may be used as output transducers (e.g., speakers). For example, the artificial reality systems described herein may include acoustic transducers that are earbuds or any other suitable type of headphone or speaker.

[0194] The configuration of acoustic transducers of a microphone array may vary and may include any suitable number of transducers. In some embodiments, using higher numbers of acoustic transducers may increase the amount of audio information collected and/or the sensitivity and accuracy of the audio information. In contrast, using a lower number of acoustic transducers may decrease the computing power required by an associated controller to process the collected audio information. In addition, the position of each acoustic transducer of the microphone array may vary. For example, the position of an acoustic transducer may include a defined position on the user, a defined coordinate on a frame of an HMD, an orientation associated with each acoustic transducer, or some combination thereof.

[0195] Acoustic transducers and may be positioned on different parts of the user's ear, such as behind the pinna, behind the tragus, and/or within the auricle or fossa. Or, there may be additional acoustic transducers on or surrounding the ear in addition to acoustic transducers inside the ear canal. Having an acoustic transducer positioned next to an ear canal of a user may enable the microphone array to collect information on how sounds arrive at the ear canal. By positioning at least two of acoustic transducers on either side of a user's head (e.g., as binaural microphones), an artificial-reality device may simulate binaural hearing and capture a 3D stereo sound field around about a user's head. In some embodiments, acoustic transducers may be connected to artificial reality systems via a wired connection, and in other embodiments acoustic transducers may be connected to artificial-reality systems via a wireless connection (e.g., a BLUETOOTH connection).

[0196] Acoustic transducers may be positioned on HMDs frames in a variety of different ways, including along the length of the temples, across the bridge, above or below display devices, or some combination thereof. Acoustic transducers may also be oriented such that the microphone array is able to detect sounds in a wide range of directions surrounding the user wearing the augmented-reality system. In some embodiments, an optimization process may be performed during manufacturing of augmented-reality system to determine relative positioning of each acoustic transducer in the microphone array.

[0197] The artificial-reality systems described herein may also include one or more input and/or output audio transducers. Output audio transducers may include voice coil speakers, ribbon speakers, electrostatic speakers, piezoelectric speakers, bone conduction transducers, cartilage conduction transducers, tragus-vibration transducers, and/or any other suitable type or form of audio transducer. Similarly, input audio transducers may include condenser microphones, dynamic microphones, ribbon microphones, and/or any other type or form of input transducer. In some embodiments, a single transducer may be used for both audio input and audio output.

[0198] As detailed above, the computing devices and systems described and/or illustrated herein broadly represent any type or form of computing device or system capable of executing computer-readable instructions, such as those contained within the modules described herein. In their most basic configuration, these computing device(s) may each include at least one memory device and at least one physical processor.

[0199] In some examples, the term "memory device" generally refers to any type or form of volatile or non-volatile storage device or medium capable of storing data and/or computer-readable instructions. In one example, a memory device may store, load, and/or maintain one or more of the modules described herein. Examples of memory devices include, without limitation, Random Access Memory (RAM), Read Only Memory (ROM), flash memory, Hard Disk Drives (HDDs), Solid-State Drives (SSDs), optical disk drives, caches, variations or combinations of one or more of the same, or any other suitable storage memory.

[0200] In some examples, the term "physical processor" generally refers to any type or form of hardware-implemented processing unit capable of interpreting and/or executing computer-readable instructions. In one example, a

physical processor may access and/or modify one or more modules stored in the above-described memory device. Examples of physical processors include, without limitation, microprocessors, microcontrollers, Central Processing Units (CPUs), Field-Programmable Gate Arrays (FPGAs) that implement softcore processors, Application-Specific Integrated Circuits (ASICs), portions of one or more of the same, variations or combinations of one or more of the same, or any other suitable physical processor.

[0201] Although illustrated as separate elements, the modules described and/or illustrated herein may represent portions of a single module or application. In addition, in certain embodiments one or more of these modules may represent one or more software applications or programs that, when executed by a computing device, may cause the computing device to perform one or more tasks. For example, one or more of the modules described and/or illustrated herein may represent modules stored and configured to run on one or more of the computing devices or systems described and/or illustrated herein. One or more of these modules may also represent all or portions of one or more special-purpose computers configured to perform one or more tasks.

[0202] In addition, one or more of the modules described herein may transform data, physical devices, and/or representations of physical devices from one form to another. Additionally or alternatively, one or more of the modules recited herein may transform a processor, volatile memory, non-volatile memory, and/or any other portion of a physical computing device from one form to another by executing on the computing device, storing data on the computing device, and/or otherwise interacting with the computing device.

[0203] In some embodiments, the term "computer-readable medium" generally refers to any form of device, carrier, or medium capable of storing or carrying computer-readable instructions. Examples of computer-readable media include, without limitation, transmission-type media, such as carrier waves, and non-transitory-type media, such as magnetic-storage media (e.g., hard disk drives, tape drives, and floppy disks), optical-storage media (e.g., Compact Disks (CDs), Digital Video Disks (DVDs), and BLU-RAY disks), electronic-storage media (e.g., solid-state drives and flash media), and other distribution systems.

[0204] The process parameters and sequence of the steps described and/or illustrated herein are given by way of example only and can be varied as desired. For example, while the steps illustrated and/or described herein may be shown or discussed in a particular order, these steps do not necessarily need to be performed in the order illustrated or discussed. The various exemplary methods described and/or illustrated herein may also omit one or more of the steps described or illustrated herein or include additional steps in addition to those disclosed.

[0205] The preceding description has been provided to enable others skilled in the art to best utilize various aspects of the exemplary embodiments disclosed herein. This exemplary description is not intended to be exhaustive or to be limited to any precise form disclosed. Many modifications and variations are possible without departing from the spirit and scope of the present disclosure. The embodiments disclosed herein should be considered in all respects illustrative and not restrictive. Reference should be made to the appended claims and their equivalents in determining the scope of the present disclosure.

[0206] Unless otherwise noted, the terms “connected to” and “coupled to” (and their derivatives), as used in the specification and claims, are to be construed as permitting both direct and indirect (i.e., via other elements or components) connection. In addition, the terms “a” or “an,” as used in the specification and claims, are to be construed as meaning “at least one of.” Finally, for ease of use, the terms “including” and “having” (and their derivatives), as used in the specification and claims, are interchangeable with and have the same meaning as the word “comprising.”

What is claimed is:

1. A computer-implemented method comprising:
establishing, by at least one processor of smart glasses of a first user, a wireless communication link with a wearable audio device of a second user;
detecting, via at least one microphone of the smart glasses, voice audio of the first user; and
transmitting, via the wireless communication link, the voice audio to the wearable audio device.
2. The computer-implemented method of claim 1, wherein the wearable audio device comprises additional smart glasses configured to play the voice audio through open air speakers.
3. The computer-implemented method of claim 1, wherein the wearable audio device comprises a hearable device configured to at least partially occlude an ear canal opening of the second user.
4. The computer-implemented method of claim 3, wherein the hearable device comprises at least one of a hearing aid or a cochlear implant.
5. The computer-implemented method of claim 1, wherein:
the wearable audio device comprises additional smart glasses worn by the second user; and
the additional smart glasses is configured to play the voice audio through a wireless connection with at least one hearable device worn by the second user.
6. The computer-implemented method of claim 5, wherein the wireless connection between the additional smart glasses and the at least one hearable device provides an end-to-end latency of less than 25 milliseconds for playback of the voice audio at the at least one hearable device.
7. The computer-implemented method of claim 1, wherein detecting the voice audio comprises:
capturing the voice audio with at least two microphones spatially distributed on the smart glasses; and
performing mouth-directed beamforming.
8. The computer-implemented method of claim 1, wherein detecting the voice audio comprises sensing the voice audio using a contact microphone housed in a nose pad of the smart glasses.
9. The computer-implemented method of claim 1, further comprising, prior to transmitting the voice audio, enhancing the voice audio by applying digital-signal-processing-based denoising.
10. The computer-implemented method of claim 9, wherein enhancing the voice audio comprises applying a machine-learning-based denoising model.
11. The computer-implemented method of claim 9, wherein enhancing the voice audio comprises applying spatial noise reduction using a plurality of microphones of the smart glasses.

12. The computer-implemented method of claim 1, wherein the wireless communication link comprises a low-latency Bluetooth link.

13. The computer-implemented method of claim 12, wherein establishing the wireless communication link comprises negotiating backward compatibility with at least one Bluetooth audio protocol supported by a legacy wearable audio device.

14. The computer-implemented method of claim 1, wherein transmitting the voice audio comprises transmitting, to the wearable audio device, control-channel metadata associated with playback of the voice audio, the control-channel metadata comprising at least one of (i) a command that configures the wearable audio device to adjust an active noise cancellation level, a transparency level, or a mixing ratio between the voice audio and ambient audio, or (ii) spatial rendering data for rendering the voice audio with a spatial cue.

15. The computer-implemented method of claim 14, further comprising determining, by the smart glasses, at least one of an ambient noise level or an estimated signal-to-noise ratio, and generating the control-channel metadata based on at least one of the ambient noise level or the estimated signal-to-noise ratio.

16. The computer-implemented method of claim 1, wherein establishing the wireless communication link comprises establishing wireless communication links with a plurality of wearable audio devices associated with a plurality of users, and wherein transmitting comprises transmitting the voice audio to the plurality of wearable audio devices using a group communication session.

17. The computer-implemented method of claim 16, further comprising assigning a conversational role to at least one user of the plurality of users and tailoring at least one of the voice audio or control-channel metadata per user based on the assigned conversational role.

18. The computer-implemented method of claim 1, further comprising switching, by an artificial agent, between an open-ear playback mode and a hearable playback mode based on an environmental condition.

19. A system comprising:
at least one physical processor;
physical memory comprising computer-executable instructions that, when executed by the physical processor, cause the physical processor to:
establish a wireless communication link between smart glasses of a first user and a wearable audio device of a second user;
detect, via at least one microphone of the smart glasses, voice audio of the first user; and
transmit, via the wireless communication link, the voice audio to the wearable audio device.

20. A non-transitory computer-readable medium comprising one or more computer-executable instructions that, when executed by at least one processor of a computing device, cause the computing device to:

establish a wireless communication link between smart glasses of a first user and a wearable audio device of a second user;
detect, via at least one microphone of the smart glasses, voice audio of the first user; and
transmit, via the wireless communication link, the voice audio to the wearable audio device.