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Electronic Devices with Motion-Based Radio-Frequency Environment Mapping

Abstract

An electronic device may include radio-frequency sensing circuitry that transmits sensing signals and that receives reflected signals using one or more antennas. The sensing circuitry may generate digital sensor data based on the reflected signals. The sensor data may be indicative of moving objects moving through positions that occlude lines of sight between the electronic device and stationary objects behind the moving objects. The sensor circuitry may detect the locations on the stationary objects based on changes to the sensor data associated with motion of the moving objects through the positions. The sensor circuitry may accumulate an environment map of the detected locations as the moving objects move about the environment over time. This may allow the sensor circuitry to generate the environment map with high spatial resolution using as few antennas as possible. The sensor circuitry may detect boundaries of the environment based on the environment map.

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Background/Summary

FIELD

[0001] This disclosure relates generally to electronic devices and, more particularly, to electronic devices with wireless circuitry.

BACKGROUND

[0002] Electronic devices are often provided with wireless capabilities. An electronic device with wireless capabilities has wireless circuitry that includes one or more antennas. The wireless circuitry is sometimes used to perform wireless sensing operations in which radio-frequency signals are used to detect objects around the device.

[0003] If care is not taken, the wireless sensing operations may not exhibit sufficient resolution given the limited resources available at the electronic device.

SUMMARY

[0004] An electronic device may include wireless circuitry controlled by one or more processors. The wireless circuitry may include communications circuitry for performing wireless communications. The wireless circuitry may include sensing circuitry for performing range detection on an external object. The sensing circuitry may transmit sensing signals using one or more antennas. The sensing circuitry may receive corresponding reflected signals using the one or more antennas.

[0005] The sensing circuitry may generate digital sensor data based on the reflected signals received using the one or more antennas. The sensor data may be indicative of one or more moving objects moving through positions that occlude lines of sight between the electronic device and one or more stationary objects behind the moving objects. The sensor circuitry may detect the locations on the one or more stationary objects based on changes to the sensor data associated with motion of the one or more moving objects into and/or out of the positions between the device and the stationary objects (e.g., perturbations of the magnitude and/or phase of the sensor data generated from signals reflected off the stationary object(s), where the perturbations are produced by the motion of the moving object(s)). The sensor circuitry may, for example, include a moving target indicator (MTI) filter that filters out stationary portions of the sensor data (e.g., portions not perturbed by the moving object(s)) while preserving only the portions of the sensor data that exhibit changes due to the object(s) moving into and/or out of the positions in the foreground between the device and the stationary object(s).

[0006] The sensor circuitry may accumulate an environment map of the detected locations as the moving objects move about the environment around the device over time. This may allow the sensor circuitry to generate the environment map with higher spatial resolution than directly measuring reflections off each of the locations on the stationary objects, while using as few antennas as possible, thereby minimizing device resource consumption and cost. The sensor circuitry may detect edges or boundaries of the environment based on the environment map. The sensor circuitry may, for example, fit different environment boundary models to the environment map and may detect the edges or boundaries as the best-fitting environment boundary model. The device may perform any desired actions based on the detected edges or boundaries of the environment.

[0007] An aspect of the disclosure provides a method of operating an electronic device. The method can include transmitting, using one or more antennas, radio-frequency signals into an environment that contains a moving object and a stationary object. The method can include receiving, using the one or more antennas, reflected radio-frequency signals from the environment.

The method can include detecting, using one or more processors, a boundary of the environment based on a motion, as identified from the reflected radio-frequency signals, of the moving object into a position between the electronic device and the stationary object.

[0008] An aspect of the disclosure provides an electronic device. The electronic device can include one or more antennas configured to transmit radio-frequency signals into an environment and configured to receive reflected signals from the environment. The electronic device can include one or more processors configured to accumulate a map of stationary objects in the environment based on changes in the reflected signals produced by movement of one or more moving objects through different positions between the electronic device and the stationary objects over time, and configured to identify a boundary of the environment based on the accumulated map of stationary objects.

[0009] An aspect of the disclosure provides a method of operating an electronic device. The method can include transmitting, using one or more antennas, sensing signals into an environment that contains a moving object and a stationary object. The method can include receiving, using the one or more antennas, reflected signals corresponding to the sensing signals. The method can include generating, using an analog-to-digital converter (ADC), sensing data based on the reflected signals. The method can include generating, using one or more processors, filtered data by applying a moving target indicator (MTI) filter to the sensing signals, wherein the filtered data is indicative of a movement of the moving object through a position between the electronic device and the stationary object. The method can include detecting, using the one or more processors, a location on the stationary object based on the movement of the moving object through the position between the electronic device and the stationary object.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. **1** is a schematic diagram of an illustrative electronic device having wireless sensing circuitry that performs motion-based environment mapping in accordance with some embodiments.

[0011] FIG. **2** is a circuit diagram of illustrative wireless sensing circuitry that performs motion-based environment mapping using radio-frequency signals conveyed by one or more antennas in accordance with some embodiments.

[0012] FIG. **3** is a top view of an environment in which an illustrative electronic device performs motion-based environment mapping in accordance with some embodiments.

[0013] FIG. **4** is a schematic diagram of an illustrative receiver that includes a map generator and an environment boundary estimator for performing motion-based environment mapping in accordance with some embodiments.

[0014] FIG. **5** is a schematic circuit diagram of an illustrative map generator in a receiver that performs motion-based environment mapping in accordance with some embodiments.

[0015] FIG. **6** is a diagram showing how occlusion of stationary objects by one or more moving objects affects the amplitude of a local signal at illustrative wireless sensing circuitry in accordance with some embodiments.

[0016] FIG. **7** is a diagram showing how illustrative wireless sensing circuitry may map points on a stationary object based on motion of a moving object between the stationary object and the wireless sensing circuitry in accordance with some embodiments.

[0017] FIG. **8** is a three-dimensional plot of a spatial power spectrum that may be generated by an illustrative map generator while performing motion-based environment mapping in accordance with some embodiments.

[0018] FIG. **9** is a schematic circuit diagram of an illustrative environment boundary estimator that performs motion-based environment mapping in accordance with some embodiments.

[0019] FIG. **10** is a diagram showing how an illustrative environment boundary estimator may identify environment boundaries based on an environment map output by a map generator in accordance with some embodiments.

[0020] FIG. **11** is a flow chart of illustrative operations involved in using wireless sensing circuitry to perform motion-based environment mapping in accordance with some embodiments.

[0021] FIG. **12** is a flow chart of illustrative operations involved in using a map generator to output an environment map while performing motion-based environment mapping in accordance with some embodiments.

[0022] FIG. **13** is a flow chart of illustrative operations involved in using an environment boundary estimator to identify environmental boundaries based on an environment map output by a map generator in accordance with some embodiments.

DETAILED DESCRIPTION

[0023] Electronic device **10** of FIG. **1** may be a computing device such as a laptop computer, a desktop computer, a computer monitor containing an embedded computer, a tablet computer, a cellular telephone, a media player, or other handheld or portable electronic device, a smaller device such as a wristwatch device, a pendant device, a headphone or earpiece device, a device embedded in eyeglasses or other equipment worn on a user's head (e.g., virtual, mixed, and/or augmented reality goggles or glasses), or other wearable or miniature device, a television, a computer display that does not contain an embedded computer, a gaming device, a navigation device, an embedded system such as a system in which electronic equipment with a display is mounted in a kiosk or automobile, a wireless internet-connected voice-controlled speaker or other media device, a home entertainment device, a remote control device, a gaming controller, a peripheral user input device, a wireless base station or access point, equipment that implements the functionality of two or more of these devices, or other electronic equipment.

[0024] As shown in the functional block diagram of FIG. **1**, device **10** may include components located on or within an electronic device housing such as housing **12**. Housing **12**, which may sometimes be referred to as a case, may be formed of plastic, glass, ceramics, fiber composites, metal (e.g., stainless steel, aluminum, metal alloys, etc.), other suitable materials, or a combination of these materials. In some situations, part or all of housing **12** may be formed from dielectric or other low-conductivity material (e.g., glass, ceramic, plastic, sapphire, etc.). In other situations, housing **12** or at least some of the structures that make up housing **12** may be formed from metal elements.

[0025] Device **10** may include control circuitry **14**. Control circuitry **14** may include storage such as storage circuitry **16**. Storage circuitry **16** may include hard disk drive storage, nonvolatile memory (e.g., flash memory or other electrically-programmable-read-only memory configured to form a solid-state drive), volatile memory (e.g., static or dynamic random-access-memory), etc. Storage circuitry **16** may include storage that is integrated within device **10** and/or removable storage media.

[0026] Control circuitry **14** may include processing circuitry such as processing circuitry **18**. Processing circuitry **18** may be used to control the operation of device **10**. Processing circuitry **18** may include on one or more processors such as microprocessors, microcontrollers, digital signal processors, host processors, baseband processor integrated circuits, application specific integrated circuits, central processing units (CPUs), graphics processing units (GPUs), etc. Control circuitry **14** may be configured to perform operations in device **10** using hardware (e.g., dedicated hardware or circuitry), firmware, and/or software. Software code for performing operations in device **10** may be stored on storage circuitry **16** (e.g., storage circuitry **16** may include non-transitory (tangible) computer readable storage media that stores the software code). The software code may sometimes be referred to as program instructions, software, data, instructions, or code. Software code stored on storage circuitry **16** may be executed by processing circuitry **18**.

[0027] Control circuitry **14** may be used to run software on device **10** such as satellite navigation applications, internet browsing applications, voice-over-internet-protocol (VOIP) telephone call applications, email applications, media playback applications, operating system functions, etc. To support interactions with external equipment, control circuitry **14** may be used in implementing communications protocols. Communications protocols that may be implemented using control circuitry **14** include internet protocols, wireless local area network (WLAN) protocols (e.g., IEEE 802.11 protocols—sometimes referred to as Wi-Fi®), protocols for other short-range wireless communications links such as the Bluetooth® protocol or other wireless personal area network (WPAN) protocols, IEEE 802.11ad protocols (e.g., ultra-wideband protocols), cellular telephone protocols (e.g., 3G protocols, 4G (LTE) protocols, 3GPP Fifth Generation (5G) New Radio (NR) protocols, 6G protocols, etc.), antenna diversity protocols, satellite navigation system protocols (e.g., global positioning system (GPS) protocols, global navigation satellite system (GLONASS) protocols, etc.), antenna-based spatial ranging (e.g., radio detection and ranging (radar)) protocols, or any other desired communications protocols. Each communications protocol may be associated with a corresponding radio access technology (RAT) that specifies the physical connection methodology used in implementing the protocol.

[0028] Device **10** may include input-output circuitry **20**. Input-output circuitry **20** may include input-output devices **22**. Input-output devices **22** may be used to allow data to be supplied to device **10** and to allow data to be provided from device **10** to external devices. Input-output devices **22** may include user interface devices, data port devices, and other input-output components. For example, input-output devices **22** may include touch sensors, displays (e.g., touch-sensitive and/or force-sensitive displays), light-emitting components such as displays without touch sensor capabilities, buttons (mechanical, capacitive, optical, etc.), scrolling wheels, touch pads, key pads, keyboards, microphones, cameras, buttons, speakers, status indicators, audio jacks and other audio port components, digital data port devices, motion sensors (accelerometers, gyroscopes, and/or compasses that detect motion), capacitance sensors, proximity sensors, magnetic sensors, force sensors (e.g., force sensors coupled to a display to detect pressure applied to the display), temperature sensors, etc. In some configurations, keyboards, headphones, displays, pointing devices such as trackpads, mice, and joysticks, and other input-output devices may be coupled to device **10** using wired or wireless connections (e.g., some of input-output devices **22** may be peripherals that are coupled to a main processing unit or other portion of device **10** via a wired or wireless link).

[0029] Input-output circuitry **20** may include wireless circuitry **24** to support wireless communications and wireless sensing operations. Wireless circuitry **24** (sometimes referred to herein as wireless communications circuitry **24**) may include two or more antennas **30**. Wireless circuitry **24** may also include baseband processor circuitry, transceiver circuitry, amplifier circuitry, filter circuitry, switching circuitry, analog-to-digital converter (ADC) circuitry, digital-to-analog converter (DAC) circuitry, radio-frequency transmission lines, and/or any other circuitry for transmitting and/or receiving radio-frequency signals using antennas **30**.

[0030] Antennas **30** may be formed using any desired antenna structures for conveying radio-frequency signals. For example, antennas **30** may include antennas with resonating elements that are formed from loop antenna structures, patch antenna structures, inverted-F antenna structures, slot antenna structures, planar inverted-F antenna structures, helical antenna structures, dielectric resonator antenna structures, monopole antenna structures, dipole antenna structures, hybrids of these designs, etc. Filter circuitry, switching circuitry, impedance matching circuitry, and/or other antenna tuning components may be adjusted to adjust the frequency response and wireless performance of antennas **30** over time. If desired, two or more of antennas **30** may be integrated into a phased antenna array (sometimes referred to herein as a phased array antenna) in which each of the antennas conveys radio-frequency signals with a respective phase and magnitude that is adjusted over time so the radio-frequency signals constructively and destructively interfere to produce a signal beam in a given beam pointing direction.

[0031] The term "convey radio-frequency signals" as used herein means the transmission and/or reception of the radio-frequency signals (e.g., for performing unidirectional and/or bidirectional wireless communications with external wireless communications equipment and/or for performing wireless sensing). Antennas **30** may transmit the radio-frequency signals by radiating the radio-frequency signals into free space (or to free space through intervening device structures such as a dielectric cover layer). Antennas **30** may additionally or alternatively receive the radio-frequency signals from free space or through intervening devices structures such as a dielectric cover layer. The transmission and reception of radio-frequency signals by antennas **30** each involve the excitation or resonance of antenna currents on an antenna resonating element in the antenna by the radio-frequency signals within the frequency band(s) of operation of the antenna.

[0032] Wireless circuitry **24** may include communications circuitry **26** (sometimes referred to herein as wireless communications circuitry **26**) for transmitting and/or receiving wireless communications data using antennas **30** (e.g., using wireless signals **40** conveyed with external equipment **38** such as a wireless access point or base station). Communications circuitry **26** may include baseband circuitry (e.g., one or more baseband processors) and one or more radios (e.g., radio-frequency transceivers, modems, etc.) for conveying radio-frequency signals using one or more antennas **30**. Communications circuitry **26** may use antennas **30** to transmit and/or receive radio-frequency signals that convey the wireless communications data between device **10** and external equipment **38** (e.g., one or more other devices such as device **10**, a wireless access point or base station, etc.). The wireless communications data may be conveyed bidirectionally or unidirectionally. The wireless communications data may, for example, include data that has been encoded into corresponding data symbols, frames, and/or packets such as wireless data associated with a telephone call, streaming media content, internet browsing, wireless data associated with software applications running on device **10**, email messages, etc.

[0033] Wireless circuitry **24** may transmit and/or receive radio-frequency signals within corresponding frequency bands at radio frequencies (sometimes referred to herein as communications bands or simply as "bands"). The frequency bands handled by wireless circuitry **24** may include wireless local area network (WLAN) frequency bands (e.g., Wi-Fi® (IEEE 802.11) or other WLAN communications bands) such as a 2.4 GHz WLAN band (e.g., from 2400 to 2480 MHz), a 5 GHz WLAN band (e.g., from 5180 to 5825 MHz), a Wi-Fi® 6E band (e.g., from 5925-7125 MHz), and/or other Wi-Fi® bands (e.g., from 1875-5160 MHz), wireless personal area network (WPAN) frequency bands such as the 2.4 GHz Bluetooth® band or other WPAN communications bands, cellular telephone frequency bands (e.g., bands from about 600 MHz to about 5 GHz, 3G bands, 4G LTE bands, 5G New Radio Frequency Range **1** (FR1) bands below 10 GHz, 5G New Radio Frequency Range **2** (FR2) bands between 20 and 60 GHz, cellular sidebands, 6G bands between 100-1000 GHz (e.g., sub-THz, THz, or THF bands), etc.), other centimeter or millimeter wave frequency bands between 10-300 GHz, near-field communications frequency bands (e.g., at 13.56 MHz), satellite navigation frequency bands (e.g., a GPS band from 1565 to 1610 MHz, a Global Navigation Satellite System (GLONASS) band, a BeiDou Navigation Satellite System (BDS) band, etc.), ultra-wideband (UWB) frequency bands that operate under the IEEE 802.15.4 protocol and/or other ultra-wideband communications protocols, communications bands under the family of 3GPP wireless communications standards, communications bands under the IEEE 802.XX family of standards, industrial, scientific, and medical (ISM) bands such as an ISM band between around 900 MHz and 950 MHz or other ISM bands below or above 1 GHz, one or more unlicensed bands, one or more bands reserved for emergency and/or public services, and/or any other desired frequency bands of interest.

[0034] In addition to conveying wireless communications data, wireless circuitry **24** may also use antennas **30** to perform wireless sensing operations (sometimes referred to herein as radio-frequency sensing operations, radio-based sensing operations, spatial ranging operations, radio detection and ranging (radar) operations, or simply as sensing operations). The wireless sensing operations may allow device **10** to detect (e.g., sense or identify) the presence, location, orientation, and/or velocity (motion) of objects external to device **10** such as external objects **42**. Detecting, sensing, or identifying the presence, location, orientation, and/or velocity (motion) of external objects **42** at any given time or over a given time period may sometimes be referred to herein simply as detecting the external object or performing spatial ranging operations, ranging operations, radio-based sensing operations, or range detection. The sensing operations may be performed over a relatively short range such as ranges of a few mm or cm from antennas **30** or over longer ranges such as ranges of dozens of cm, a few meters, dozens of meters, etc.

[0035] External objects **42** may include, for example, the ground, a building, part of a building, a wall, a floor, furniture, a ceiling, a person, a body part (e.g., the head, hand, finger, or other body part of the user of device **10** or other humans in the vicinity of device **10**), an animal, a vehicle, a landscape or geographic feature, an obstacle, external communications equipment, another device of the same type as device **10** or a peripheral/accessory device such as a gaming controller, stylus (e.g., for providing input to a touch and/or force-sensitive display on device **10**), or remote control, or any other physical object or entity that is external to device **10**.

[0036] External objects **42** may include one or more animate objects (e.g., an external object that is living and/or in motion within its own reference frame) and/or one or more inanimate objects (e.g., objects that are non-living and/or stationary within its own reference frame). External objects **42** may include one or more stationary objects that are at a fixed location, position, and/or orientation with respect to device **10** while device **10** is stationary and/or may include one or more moving objects that change location, position, and/or orientation with respect to device **10** while device **10** is stationary (e.g., that are in a reference frame that is in motion relative to the reference frame of device **10**). Moving objects may include animate objects and/or inanimate objects (e.g., the moving objects need not be living).

[0037] External objects **42** are sometimes also referred to herein as target objects **42** or targets **42**. The wireless (radio-frequency) sensing performed by sensing circuitry **28** may include target (object) detection on external objects **42**. As used herein, target detection, object detection, radio-frequency sensing, wireless sensing, or detecting external objects **42** involve the detection, monitoring, measurement, and/or sensing, by sensing circuitry **28**, of a selected characteristic of external objects **42** using radio-frequency signals conveyed using one or more antennas **30**. The characteristic may be the presence or absence of external objects (e.g., at or adjacent to device **10**, at a particular position relative to device **10**, within a threshold range of device **10**, at an expected position, etc.), the location, position, velocity, speed, movement, rotation, and/or orientation of external objects **42** (e.g., over time), the occlusion of other objects behind external objects **42** from device **10**, the distance between device **10** and external objects **42** (sometimes referred to herein as range R), that external objects **42** include an expected or particular type of object as opposed to another type of object (e.g., to verify or authenticate that an external object **42** is a particular object instead of a different object, that external object **42** is formed from a particular material and not another material, etc.), a particular motion or movement of external objects **42** (e.g., a gesture or action performed by external objects **42** that matches a predetermined gesture or action), that external objects **42** include animate, inanimate, stationary, and/or moving objects, and/or any other information associated with external objects **42**.

[0038] Control circuitry **14** may use the detection of external objects **42** (e.g., detection of the selected characteristic of external objects **42**) to perform any desired device operations. As examples, control circuitry **14** may use the detection of external objects **42** to identify a corresponding user input for one or more software applications running on device **10** such as a gesture input performed by the user's hand(s) or other body parts or performed by an external stylus, gaming controller, head-mounted device, or other peripheral devices or accessories, to determine when one or more antennas **30** needs to be disabled or provided with a reduced maximum transmit power level (e.g., for satisfying regulatory limits on radio-frequency exposure when an external object **42** is a body part located within a threshold range of device **10**), to determine how to steer a radio-frequency signal beam produced by antennas **30** for communications circuitry **26** (e.g., in scenarios where antennas **30** include a phased array of antennas **30**), to map or model the environment around device **10** (e.g., to produce a software model of the room where device **10** is located for use by an augmented reality application, gaming application, map application, home design application, engineering application, etc.), to detect the presence of obstacles in the vicinity of (e.g., around) device **10** or in the direction of motion of the user of device **10**, etc. Implementations in control circuitry **14** maps or models the environment around device **10** using the detection of external objects **42** by wireless circuitry **24** are described herein as an example.

[0039] Wireless circuitry **24** may include wireless sensing circuitry **28** for performing wireless sensing operations using antennas **30**. Wireless sensing circuitry **28** is sometimes also referred to herein as wireless sensor **28**, radio-frequency sensor **28**, or simply as sensing circuitry **28**. Sensing circuitry **28** may include a sensing transmitter (e.g., transmitter circuitry including signal generators, synthesizers, etc.), a sensing receiver, mixer circuitry, amplifier circuitry, filter circuitry, baseband circuitry, ADC circuitry, DAC circuitry, and/or any other desired components used in performing sensing operations using antennas **30**. Sensing circuitry **28** may perform the sensing operations using radio-frequency sensing signals such as sensing signals **34** that are transmitted by antennas **30** (sometimes referred to herein as radar signals **34** when transmitted using a radar scheme) and using reflected (back-scattered) versions of the transmitted sensing signals that have reflected off an external object around device **10** such as external object **42** (sometimes referred to herein as reflected sensing signals **36**, reflected signals **36**, or reflected radar signals **36**).

[0040] Sensing circuitry **28** may, for example, transmit and receive radar signals using a frequency-modulated continuous-wave (FMCW) radar scheme, a full-duplex ranging scheme, an orthogonal frequency division multiplexing (OFDM) radar scheme, a phase-modulated continuous-wave (PMCW) radar scheme, a stepped frequency continuous wave (SFCW) radar scheme, a pulse radar scheme, or other ranging schemes. Sensing circuitry **28** need not transmit and receive signals **34** and **36** using a radar scheme and may, if desired, transmit and receive signals **34** and **36** using any desired radio-based sensing scheme. Antennas **30** may include separate antennas for conveying wireless communications data for communications circuitry **26** and for conveying radar signals or may include one or more antennas **30** that are used to both convey wireless communications data and to perform sensing operations. Using a single antenna **30** to both convey wireless communications data and perform sensing operations may, for example, serve to minimize the amount of space occupied in device **10** by antennas **30**.

[0041] Sensing circuitry **28** may be coupled to antennas **30** over at least two radio-frequency transmission line paths **32**. Communications circuitry **26** may be coupled to antennas **30** over at least one radio-frequency transmission line path **32**. Separate radio-frequency transmission line paths **32** may couple sensing circuitry **28** and communications circuitry **26** to antennas **30** (e.g., as shown in FIG. **1**) or one or more radio-frequency transmission line paths **32** may couple one or more antennas **30** to both sensing circuitry **28** and communications circuitry **26**. If desired, sensing circuitry **28** may be integrated into communications circuitry **26** (e.g., communications circuitry **26** may also perform spatial ranging operations using a joint communication and sensing (JCAS) scheme).

[0042] Radio-frequency transmission line paths **32** may include coaxial cables, microstrip transmission lines, stripline transmission lines, edge-coupled microstrip transmission lines, edge-coupled stripline transmission lines, transmission lines formed from combinations of transmission lines of these types, etc. Radio-frequency transmission line paths **32** may be integrated into rigid and/or flexible printed circuit boards if desired. Radio-frequency front end (RFFE) modules may be interposed on one or more radio-frequency transmission line paths **32**. The radio-frequency front end modules may include substrates, integrated circuits, chips, or packages that are separate from sensing circuitry **28** and communications circuitry **26** and may include filter circuitry, switching circuitry, amplifier circuitry, impedance matching circuitry, radio-frequency coupler circuitry, and/or any other desired radio-frequency circuitry for operating on the radio-frequency signals conveyed over radio-frequency transmission line paths **32**.

[0043] The example of FIG. **1** is illustrative and non-limiting. While control circuitry **14** is shown separately from wireless circuitry **24** in the example of FIG. **1** for the sake of clarity, wireless circuitry **24** may include processing circuitry (e.g., one or more processors) that forms a part of processing circuitry **18** and/or storage circuitry that forms a part of storage circuitry **16** of control circuitry **14** (e.g., portions of control circuitry **14** may be implemented on wireless circuitry **24**). As an example, control circuitry **14** may include baseband circuitry (e.g., one or more baseband processors), digital control circuitry, analog control circuitry, and/or other control circuitry that forms part of communications circuitry **26** and/or sensing circuitry **28**. The baseband circuitry may, for example, access a communication protocol stack on control circuitry **14** (e.g., storage circuitry **20**) to: perform user plane functions at a PHY layer, MAC layer, RLC layer, PDCP layer, SDAP layer, and/or PDU layer, and/or to perform control plane functions at the PHY layer, MAC layer, RLC layer, PDCP layer, RRC, layer, and/or non-access stratum layer. If desired, the PHY layer operations may additionally or alternatively be performed by radio-frequency (RF) interface circuitry in wireless circuitry **24**.

[0044] FIG. **2** is a circuit diagram of sensing circuitry **28**. As shown in FIG. **2**, sensing circuitry **28** may include at least one sensing transmitter **44** and at least one sensing receiver **56**. The output of sensing transmitter **44** may be communicably coupled to a first antenna **30** such as antenna **30**TX (sometimes referred to herein as transmit antenna **30**TX) over radio-frequency transmission line path **32**TX (sometimes referred to herein as transmit path **32**TX or transmit chain **32**TX). The input of sensing receiver **56** may be communicably coupled to a second antenna **30** such as antenna **30**RX (sometimes referred to herein as receive antenna **30**RX) over radio-frequency transmission line path **32**RX (sometimes referred to herein as receive path **32**RX or receive chain **32**RX). One or more amplifiers such as power amplifier **46** may be disposed on transmit path **32**TX between sensing transmitter **44** and transmit antenna **30**TX. One or more amplifiers such as low noise amplifier **48** may be disposed on receive path **32**RX between receive antenna **30**RX and sensing receiver **56**.

[0045] If desired, transmit antenna **30**TX may also be used to transmit and/or receive radio-frequency signals that convey wireless communications data for communications circuitry **26** (FIG. **1**). Similarly, if desired, receive antenna **30**RX may also be used to transmit and/or receive radio-frequency signals that convey wireless communications data for communications circuitry **26**. The transmit antenna and the receive antenna may be the same antenna or portions of the same antenna if desired (e.g., sensing transmitter **44** and sensing receiver **56** may be coupled to a single antenna over transmit path **32**TX and receive path **32**RX respectively). In general, sensing circuitry **28** may use a set of one or more antennas **30** to perform radio-frequency sensing.

[0046] Sensing transmitter **44** may transmit radio-frequency sensing signals SIGTX over transmit path **32**TX and antenna **30**TX. Power amplifier **46** amplifies the sensing signals SIGTX on transmit path **32**TX. Sensing signals SIGTX may include any desired signals or waveforms for performing spatial ranging operations (e.g., chirp signals, one or more tones, continuous waves of radio-frequency energy, other radar waveforms, etc.). Sensing signals SIGTX may be transmitted using any desired carrier frequencies (e.g., frequencies greater than 10 GHz, greater than 20 GHz, less than 60 GHz, less than 10 GHz, less than 6 GHz, less than 1 GHz, greater than 100 GHz, etc.).

[0047] An implementation in which sensing signals SIGTX include chirp signals is described herein as an example. Chirp signals include frequency ramps (sometimes referred to as chirps) that periodically ramp up or down over time. In this example, sensing transmitter **44** may include a signal generator or synthesizer (e.g., a digital chirp generator) that generates the chirp signals and provides the chirp signals to a digital-to-analog converter (DAC) in sensing transmitter **44**. The

DAC converts the chirp signals to the analog domain and provides the analog chirp signals to a mixer in sensing transmitter **44**. The mixer up-converts the analog chirp signals to radio frequencies (as sensing signals SIGTX) using a clocking signal such as a local oscillator signal produced by a local oscillator (LO) in sensing transmitter **44**. Antenna **30**TX radiates sensing signals SIGTX as sensing signals **34** (e.g., wireless radio-frequency signals having a radar waveform or another sensing waveform). Unlike the radio-frequency signals transmitted by communications circuitry **26** of FIG. **1**, sensing signals SIGTX and sensing signals **34** may be free from wireless communications data (e.g., cellular communications data packets, WLAN communications data packets, etc.).

[0048] Sensing signals **34** may reflect off objects external to device **10** (e.g., external object **42**) as reflected signals **36**. As shown in FIG. **2**, sensing circuitry **28** may include a mixer such as mixer **54** disposed on receive path **32**RX between low noise amplifier **48** and sensing receiver **56**. Mixer **54** may have a first input coupled to node **50** on transmit path **32**TX over de-chirp path **52**. Node **50** may be disposed on transmit path **32**TX between sensing transmitter **44** and power amplifier **46**, for example. Mixer **54** may have a second input coupled to the output of low noise amplifier **48**. The output of mixer **54** may be coupled to the input of sensing receiver **56**. Mixer **54** is sometimes also referred to herein as de-chirp mixer **54**. Low noise amplifier **48** may be omitted if desired.

[0049] Receive antenna **30**RX may receive reflected signals **36** (e.g., a reflected version of sensing signals **34** that has reflected off external object **42** or and/other external objects) and may pass the reflected signals to mixer **54** via receive path **32**RX and low noise amplifier **48** (e.g., as received sensing signals SIGRX). Received sensing signals SIGRX may include the sensing signals SIGTX (e.g., chirp signals) that have reflected off external object **42** and that have been received by receive antenna **30**RX. Node **50** on transmit path **32**TX may include a radio-frequency signal coupler or signal splitter that couples some of the sensing signals SIGTX propagating along transmit path **32**TX onto de-chirp path **52**. If desired, one or more amplifiers (not shown) may be disposed on de-chirp path **52** to boost the amplitude of the sensing signals SIGTX provided to de-chirp mixer **54**.

[0050] De-chirp mixer **54** may receive sensing signals SIGRX at its second input (e.g., from low noise amplifier **48**). De-chirp mixer **54** may mix the sensing signals SIGTX received at its first input (over de-chirp path **52**) with the received sensing signals SIGRX received at its second input (over receive path **32**RX) to produce or generate signals SIGB at baseband or an intermediate frequency. Signals SIGB may correspond to beats associated with the difference in phase between the transmitted sensing signals SIGTX and the received sensing signals SIGRX. Signals SIGB may therefore sometimes be referred to herein as beat signals SIGB. If desired, additional mixers (not shown) may be disposed on receive path **32**RX between de-chirp mixer **54** and sensing receiver **56** for further downconverting beat signals SIGB to baseband in implementations where de-chirp mixer **54** outputs the beat signals at an intermediate frequency.

[0051] Sensing receiver **56** may receive beat signals SIGB from de-chirp mixer **54**. Sensing receiver **56** may include an analog-to-digital converter (ADC) that converts beat signals SIGB from the analog domain to the digital domain, as digital sensing data SDT. Sensing data SDT may have any desired data format. As one example, sensing data SDT may include a radar data cube of sensing data. The data cube is a three-dimensional representation (matrix) of the data output by ADC **58**. The data cube has orthogonal spatial, fast time, and slow time axes. Different points or bins along the spatial axis correspond to different receive antennas **30**RX used to receive reflected signals **36** (e.g., when multiple receive antennas are used to receive reflected signals **36**). Different points or bins along the fast time axis correspond to different time ADC samples of the received sensing signals SIGRX produced by given pulse (e.g., one chirp) in sensing signals SIGTX. Different points or bins along the slow time axis correspond to different transmitted pulses in sensing signals SIGTX (e.g., N chirps over a single frame). Sensing circuitry **28** may capture multiple frames (data cubes) over time. Each frame may have a corresponding frame duration. The time interval between the frames is referred to as the frame repetition interval (FRI). Other data

structures may be used for sensing data SDT if desired. Sensing receiver **56** may include post processing circuitry **60** that receives sensing data SDT from ADC **58**. Post processing circuitry **60** may process sensing data SDT to perform object detection on external objects **42**.
[0052] If desired, two or more of the antennas **30** used by sensing circuitry **28** may be integrated into a radar module (e.g., in an array such as a phased antenna array). Each antenna may transmit, receive, or transmit and receive sensing signals. Each of the antennas in the module may be synchronized in time, frequency, and phase (e.g., using the same LO distribution). The spacing between the antennas in the module may be uniform or non-uniform (e.g., in a MIMO radar arrangement). The module may have beamforming, monostatic, multi-static, and/or MIMO capabilities. The antennas may be arranged in a one-dimensional, two-dimensional, or three-dimensional pattern in the array. The antennas may share a local oscillator, waveform synthesizer (e.g., sensing transmitter **44**), control and timing units, memory, and/or processing circuitry (e.g., sensing receiver **56**).
[0053] In implementations where sensing signal SIGTX is a chirp waveform (e.g., under an FCMW architecture), the chirp waveform may periodically sweep (e.g., linearly ramp) up or down in frequency across the bandwidth of the chirp as a function of time. In these implementations, the reflected (back-scattered) signals are a delayed and attenuated version of the transmitted signal that are then mixed with the transmitted signal at de-chirp mixer **54**.
[0054] As an example, when external object **42** is at a range of R(τ)=R.sub.0+ΔR(τ), where τ is the roundtrip time delay of the transmitted and reflected signal (e.g., where R=c*τ/2 and c is the speed of light), beat signal SIGB may be given by the equation x(t,τ)≅exp(−j*(4*π/λ)*R(τ))*exp(−j*2*π*f.sub.b(τ)*t), where the first exponential term specifies the phase, the second exponential term specifies the frequency, k is the carrier wavelength, and f.sub.B is the beat frequency having a resolution determined by the chirp bandwidth (e.g., where f.sub.B≅k*(2*R.sub.0/c) and k is the slope of the transmitted chirp signal).
[0055] In this example, the accuracy for the estimation of target range R through estimation of beat signal SIGB at frequency f.sub.B is determined by the Rayleigh resolution limit R.sub.res, which is inversely proportional to the bandwidth B of the chirp signal (e.g., R.sub.res=c/(2*B)). For example, a bandwidth of B=1 GHz may provide a range resolution of approximately 15 cm. This may be suitable for detecting the overall location of the target and/or to separate the objects/reflectors located at different ranges. At the same time, the sensitivity for the estimation of the phase of beat signal SIGB is inversely proportional to the wavelength of the RF carrier (e.g., where phase Δϕ=(4*π/k)*ΔR), which makes phase detection suitable for fine-grain estimation of variations in the range of the target. For example, when the carrier frequency is 60 GHz (corresponding to a wavelength of approximately 5 mm), the detectable target range variation ΔR=1.25 mm leads to a 180 degree phase rotation of beat signal SIGB. These examples are illustrative and non-limiting and, in general, sensing circuitry **28** may implement any desired radio-frequency sensing scheme. While sensing circuitry **28** is illustrated in FIG. **2** as implementing a continuous wave (CW) architecture, sensing circuitry **28** may implement any desired spatial ranging and/or radar architecture.
[0056] If desired, sensing circuitry **28** may use signals **34** and **36** to detect and spatially map the surroundings or environment of device **10**. This process is sometimes referred to herein environment mapping, environmental mapping, or room mapping. When performing environment mapping, device **10** may generate an environment map based on signals **34** and **36** (e.g., based on external objects **42** that are detected using signals **34** and **36**). The environment map identifies the spatial locations of the different objects detected around device **10**. If desired, environment mapping may also include the identification or detection of spatial boundaries within the environment map and around device **10**.
[0057] FIG. **3** is a top view of an illustrative environment in which device **10** may perform environment mapping. As shown in FIG. **3**, device **10** may be located in an environment **62**.

Environment **62** may be a geographic area or region, an outdoor space, an indoor space, a room, a corridor, a hallway, an apartment, a house, a campus, an office, a cubicle, and/or any other desired spatial area at, surrounding, and/or around the location of device **10**.

[0058] Environment **62** may include one or more external objects **42**. The external objects **42** in environment **62** may include one or more stationary objects **42**S and one or more moving objects **42**M. When device **10** is stationary within environment **62**, stationary objects **42**S generally remain at a fixed position (e.g., are non-moving) relative to device **10**. Stationary objects **42**S include inanimate objects and may, if desired, include one or more stationary animate objects. On the other hand, moving objects **42**M move, rotate, and/or change position and/or orientation relative to device **10** when device **10** is stationary within environment **62**. Moving objects **42**M may include moving animate objects (e.g., people, animals, etc.) and/or moving inanimate objects.

[0059] During wireless sensing, device **10** transmits sensing signals **34** into environment **62** and receives corresponding reflected signals **36** that have reflected off of external objects **42** in environment **62**. Device **10** may use the reflected signals **36** that are received at device **10** after reflection off moving objects **42**M to detect moving objects **42**M. While device **10** is stationary in environment **62**, moving objects **42**M may pass between device **10** and stationary objects **42**S. Stationary objects **42**S may contribute a background or clutter signal to the reflected signals **36** received at device **10**. Stationary objects **42**S are therefore sometimes also referred to herein as background objects **42**S, clutter objects **42**S, or clutter **42**S. Stationary objects **42**S may include, for example, walls, ceilings, floors, doors, furniture, windows, and/or other stationary objects and/or physical boundaries of environment **62**.

[0060] During environment mapping, the post processing circuitry **60** in sensing receiver **56** (FIG. **2**) on device **10** generates an environment map RCM that maps the spatial position(s) (e.g., location(s) and/or orientation(s)) of the stationary objects **42**S in environment **62**. In other words, environment map RCM maps the spatial position of background objects or clutter in environment **62** (e.g., by mapping the energies returned from stationary objects **42**S without including the spatial location of moving objects **42**M). Environment map RCM is therefore sometimes also referred to herein as room clutter map RCM, clutter map RCM, background map RCM, or background object map RCM.

[0061] Device **10** may perform any desired operations based on environment map RCM. For example, device **10** may use environment map RCM as an input to one or more software applications running on device **10** (e.g., as executed by an application processor). In some implementations that are described herein as an example, the room mapping performed by device **10** also involves using environment map RCM to identify the edges or boundaries of environment **62**. Device **10** may then perform any desired operations based on the identified boundaries of environment **62**.

[0062] As one example, device **10** may use the boundaries to identify when radio-frequency signals **63** are incident upon device **10** from a source or location located outside of the boundaries of environment **62**. These radio-frequency signals **63** may, for example, include wireless communications data and/or sensing signals transmitted by other devices located outside of environment **62** that are owned and/or operated by another user or entity, or may be signals transmitted by device **10** and reflected from an external object outside the boundaries. When device **10** identifies that radio-frequency signals **63** are incident upon device **10** from a source located outside of the identified boundaries of environment **62**, device **10** may filter out or mask radio-frequency signals **63** from being received, decoded, demodulated, and/or provided to the user of device **10**. This may, for example, help to preserve the privacy of the other users who may be operating the device(s) that produced radio-frequency signals **63**.

[0063] As another example, device **10** (e.g., one or more input-output devices **22** of FIG. **1**) may generate, produce, emit, alter, adjust, and/or modify a device output **61** based on the identified boundaries of environment **62**. Device output **61** may include a visual output, a haptic output, a wireless, and/or an audio output, as example. The visual output may include light emitted by one or more light sources on device **10** and/or image and/or video data displayed by one or more displays on device **10**. The visual output may include, for example, the generation and/or adjustment of virtual objects displayed by the display(s) on device **10** using a mapping, navigation, video playback, video streaming, gaming, augmented reality, mixed reality, and/or virtual reality application.

[0064] Consider an example in which device **10** includes an augmented and/or virtual reality display. In these examples, the display may display virtual content (e.g., virtual objects) to a user. The virtual content may include virtual content displayed or overlaid onto the detected boundaries of environment **62**, may include virtual content displayed or overlaid onto a particular spatial position relative to the detected boundaries of environment **62**, and/or may include virtual objects that represent the detected boundaries of environment **62** (e.g., virtual room boundaries) and that are placed into a displayed rendering environment **62** at the location of the detected boundaries of environment **62**, as examples. This may allow the virtual content to be displayed with greater accuracy than in implementations where device **10** uses infrared light to detect the boundaries of environment **62**. This is because depth sensing technology based on infrared light can have difficulty detecting glass walls or uniform-colored wall surfaces in environment **62**. However, since device **10** receives reflected signals **36** from stationary objects **42** that include glass walls or uniform-colored wall surfaces (e.g., because sensing signals **34** reflect off glass or other surfaces regardless of color), device **10** may still successfully map boundaries of environment **62** even when the boundaries include the glass walls or uniform-colored wall surfaces, despite the difficulty of detecting such boundaries using infrared light.

[0065] The audio output may include, for example, sound emitted by a speaker on device **10** and/or wirelessly coupled to device **10** (e.g., speakers on wireless headphones, wireless earbuds, or a wireless speaker paired with device **10**). The haptic output may include, for example, one or more vibrations produced by vibrators or other haptic devices on device **10**. The wireless output may include, for example, wireless signals transmitted to another device that identify the detected boundaries of environment **62**. In these implementations, the other device may emit output such as device output **61** based on the detected boundaries of environment **62**.

[0066] If desired, the audio, haptic, and/or wireless output may include navigation instructions, warnings, alerts, directions, and/or other output based on the detected boundaries of environment **62**. These outputs may, for example, help to describe to the user of device **10** where the boundaries of environment **62** are located and/or may alert the user when the user approaches or is near to one of the detected boundaries. These outputs may, for example, allow a vision-impaired user of device **10** to freely move through environment **62** without hitting the detected boundaries and without requiring the user to view the detected boundaries (e.g., stationary objects **42**S). These examples are illustrative and non-limiting and, in general, device **10** may perform any desired operations and/or may produce any desired output based on the boundaries detected based on environment map RCM as generated while performing room mapping.

[0067] In general, it is desirable for environment map RCM to exhibit as high a spatial resolution as possible. This may, for example, maximize the accuracy with which device **10** identifies the boundaries of environment **62**, thereby optimizing any later device operations performed based on the identified boundaries. In some implementations, a device with wireless sensing circuitry generates an environment map by directly measuring the distance between device **10** and each possible point on stationary objects **42**S by transmitting sensing signals **34** to and receiving reflected signals **36** from each of those points on stationary objects **42**S (e.g., by implementing beam steering arrangements in which a phased antenna array is used to transmit and/or receive sensing signals to/from each of the points). In these scenarios, increasing the number of antennas used to transmit/receive the sensing signals (e.g., the number of elements in the phased antenna array) reduces the minimum resolvable spacing between the points and thus the precision of the points, which serves to maximize the resolution of the environment map. For example, the environment map may exhibit an angular resolution of 9.6 degrees at boresight and 19.5 degrees at 60 degrees off boresight when the device generates the environment map using a uniform linear array of twelve antennas, but may exhibit a deteriorated angular resolution of 30 degrees at boresight and 90 degrees at 60 degrees off boresight when the device generates the environment map using a uniform linear array of four antennas.

[0068] On the other hand, space and resources are at a premium in compact devices such as device **10**. Performing wireless sensing using twelve or more antennas **30** can consume an excessive amount of space in device **10**, can cause device **10** to be excessively heavy or bulky, can cause device **10** to consume excessive chip space to support the antennas, can cause device **10** to consume excessive power, and/or can undesirably increase the cost of device **10**. It would therefore be desirable for device **10** to be able to generate environment map RCM with as high a resolution as possible while minimizing the number of antennas used to convey signals **34** and **36**. For example, it would be desirable for device **10** to be able to generate environment map RCM with fewer than twelve antennas **30** but with similar spatial resolution as when twelve or more antennas are used (e.g., 9.6 degrees or lower at boresight).

[0069] In implementations that are described herein as an example, device **10** mitigates these issues by performing motion-based environment mapping. Motion-based environment mapping is environment mapping based on the motion/movement of one or more moving objects **42**M between device **10** and stationary objects **42**S (e.g., as shown by arrow A of FIG. **3**), rather than by directly sensing reflections off each point on stationary objects **42**S. Such motion-based environment mapping may, for example, allow device **10** to generate environment map RCM with similar or higher resolution as when directly sensing stationary objects **42**S using a large array of antennas, but while using as few as only a single transmit antenna **30**TX and/or receive antenna **30**RX to convey signals **34** and **36**. The motion-based environment mapping may therefore allow device **10** to minimize its size, weight, cost, area consumption, and/or power consumption without sacrificing the accuracy with which it identifies the boundaries of environment **62**.

[0070] FIG. **4** is a schematic diagram of post processing circuitry **60** in sensing receiver **56** in implementations where device **10** performs motion-based environment mapping of environment **62**. As shown in FIG. **4**, post processing circuitry **60** may include a map generator such as map generator **64** and may include an environment boundary estimator such as environment boundary estimator **66**. The input of map generator **64** may receive sensing data SDT from ADC **58** (FIG. **2**). The output of map generator **64** may be coupled to the input of environment boundary estimator **66**.

[0071] The components and functions of map generator **64** and environment boundary estimator **66** may be implemented using hardware (e.g., digital circuitry, sets of digital logic gates, registers, switches, filters, clocking circuitry, memory, etc.), firmware, and/or software (e.g., logic implemented in software, software code executed by one or more processors, etc.). If desired, the hardware may be controlled or operated by processing circuitry **18** of FIG. **1** (e.g., one or more processors. Map generator **64** is sometimes also referred to herein as map generator circuitry **64**, map generator circuit **64**, map generator logic **64**, map generator engine **64**, or map generator block **64**. Environment boundary estimator **66** is sometimes also referred to herein as environment boundary estimator, identifier, or detector **66**, environment boundary estimator, identifier, or detection circuitry **66**, environment boundary estimator, identifier, or detector circuit **66**, environment boundary estimator, identifier, or detector logic **66**, environment boundary estimator, identifier, or detector engine **66**, or environment boundary estimator, identifier, or detector logic **66**.

[0072] While performing environment mapping, map generator **64** receives sensing data SDT (e.g., a stream of data samples from a series of one or more data cubes) from ADC **58** (FIG. **2**). Map generator **64** may generate environment map RCM based on the motion of one or more moving objects **42**M between device **10** and stationary objects **42**S as included or identified in the received sensing data SDT. For example, when a moving object **42**M (e.g., a human, pet, cleaning robot, etc.) moves between device **10** and different points on stationary objects **42**S (as shown by arrow A of FIG. **3**), the moving object temporarily blocks or occludes device **10** from different points on stationary objects **42**S (e.g., blocks line of sight paths between device **10** and the different points on stationary objects **42**S). This motion of moving object **42**M to block and/or unblock stationary objects **42**S may perturb the reflected signals **26** as reflected off of stationary objects **42**S and received at device **10**. Device **10** may use the motion associated with this temporary blockage (e.g., perturbations or changes to the reflected signals from stationary objects **42**S due to moving object **42**M moving into and/or out of the foreground between device **10** and stationary objects **42**S) to detect the distance between device **10** and each of the different points on stationary objects **42**S (and thus the location of stationary objects **42**S).

[0073] Sensing data SDT includes sensing data produced from reflected signals **36** received after reflection off of stationary objects **42**S. This portion of sensing data SDT is sometimes also referred to herein as the stationary signal or stationary sensing data of sensing data SDT. Motion of moving object **42**M between device **10** and points on stationary objects **42**S will cause some of the sensing data produced from reflection off stationary objects **42**S (e.g., stationary sensor data) to exhibit a corresponding change or perturbation, while other portions of the stationary sensor data produced by reflection off points on stationary objects **42**S that are not blocked by moving object **42**M do not exhibit such changes or perturbations. Map generator **64** may include a moving target indicator (MTI) filter that passes only the portion of the received sensing data SDT that was produced by reflection off of stationary objects **42**S (e.g., the stationary sensing data) and that includes changes or perturbations produced by motion of moving object **42**M into and/or out of the foreground between device **10** and stationary objects **42**S, while filtering out other portions of the sensing data without such changes or perturbations. When no movement exists between device **10** and stationary objects **42**S (e.g., in the absence of moving objects **42**M), all of the stationary sensing data is free of changes or perturbations from the motion of moving objects **42**M between device **10** and stationary objects **42**S, and therefore no signal is produced at the output of the MTI filter.

[0074] Put differently, when a moving object **42**M moves through environment **62**, the moving object will perturb the line of sight between device **10** and portions or points on stationary objects **42**S. This motion and blockage perturbs the reflected signal **36** received at device **10** from portions of stationary objects **42**S that are blocked by moving object **42**M, which perturbs or changes that portion of the stationary sensing data as a function of time in sensing data SDT. This part of the stationary sensing data is not filtered out and is instead passed by the MTI filter. At the same time, the portions of the stationary sensing data produced from reflected signals received from other (non-occluded) portions of stationary objects **42**S do not include the same perturbations or changes over time and are instead filtered out by the MTI filter. Therefore, the local clutter signal and thus the location of stationary objects **42**S can be resolved from nearby competing signals. As the motion/trajectory of moving objects **42**M progresses and covers different areas of stationary objects **42**S from the perspective of device **10**, map generator **64** may detect and accumulate the signal from different stationary objects **42**S or different portions of stationary objects **42**S into environment map RCM.

[0075] This type of motion-based environment mapping may, for example, serve to provide even higher spatial resolution than what is intrinsically produced by a phased antenna array having a large number of antennas that directly sense reflections from all portions of stationary objects **42**S to map environment **62**. This type of motion-based environment mapping may also, for example, allow device **10** to detect stationary objects **42**S in far less time and with greater accuracy than simply detecting moving objects **42**M (e.g., reflected signals **36** that have reflected off moving objects **42**M) over time and then inferring the presence of stationary objects **42**S as the locations where moving objects **42**M have not traveled over a statistically significant time period (e.g., so-called “no-go” regions).

[0076] Environment boundary estimator **66** may estimate the edges or boundaries of environment **62** based on environment map RCM. Environment boundary estimator **66** may, for example, generate and output boundary information BINFO based on environment map RCM. Boundary information BINFO may include or identify, based on environment map RCM, the positions(s) (e.g., location(s) and/or orientation(s)) of stationary objects **42**S, which may itself represent or identify the spatial boundaries of environment **62**. Sensing receiver **56** may provide boundary information BINFO to other circuitry in device **10** (e.g., control circuitry **14** of FIG. **1**) for further processing.

[0077] FIG. **5** is a schematic circuit diagram of map generator **64**. As shown in FIG. **5**, map generator **64** may include MTI filter circuitry such as MTI filter **68**, Fourier transform circuitry such as a first Fourier transform **70** and a second Fourier transform **72**, integrator circuitry such as a first integrator **74** and a second integrator **76**, constant false alarm rate (CFAR) detection circuitry such as CFAR detector **78**, signal classification circuitry such as signal classifier **80**, and detection accumulation circuitry such as detection accumulator **82**.

[0078] The sensing data SDT (FIG. **4**) received from ADC **58** (FIG. **2**) may include baseline sensing data SDT**0** and real-time sensing data SDTX. Baseline sensing data SDT**0** may include sensing data that is generated by sensing circuitry **28** when device **10** is stationary in environment **62** and when environment **62** is free from moving objects **42**M. Baseline sensing data SDT**0** may, for example, include one or more data cubes collected by sensing circuitry **28** when there are no moving objects **42**M within environment **62**. Baseline sensing data SDT**0** may be generated at an initial time and/or may be updated over time if desired. Baseline sensing data SDT**0** may be stored at storage circuitry on device **10** until processing by map generator **64**. On the other hand, real-time sensing data SDTX includes sensing data for use in mapping environment **62** based on the motion of moving objects **42**M between device **10** and stationary objects **42**S. Real-time sensing data SDTX may be generated by sensing circuitry **28** after generation of baseline sensing data SDT**0** (e.g., when one or more moving objects **42**M are present and moving around environment **62**). Map generator **64** may generate environment map RCM based on real-time sensing data SDTX and baseline sensing data SDT**0**.

[0079] MTI filter **68** may have an input that receives real-time sensing data SDTX. The output of MTI filter **68** may be coupled to the input of Fourier transform **70**. The output of Fourier transform **70** may be coupled to the input of integrator **74**. Alternatively, the location of MTI filter **68** and Fourier transform **70** may be reversed (e.g., the output of Fourier transform **70** may be coupled to the input of MTI filter **68**). The output of integrator **74** may be coupled to the input of CFAR **78** and a first input of signal classifier **80**. The output of CFAR **78** may be coupled to a second input of signal classifier **80**. Fourier transform **72** may have an input that receives baseline sensing data SDT**0**. The output of Fourier transform **72** may be coupled to integrator **76**. The output of integrator **76** may be coupled to a third input of signal classifier **80**. The output of signal classifier **80** may be coupled to the input of detection accumulator **82**. Detection accumulator **82** may output environment map RCM (e.g., for subsequent processing by environment boundary estimator **66**).

[0080] During environment mapping, MTI filter **68** receives real-time sensing data SDTX and applies an MTI or high pass filter to real-time sensing data SDTX. The MTI filter passes a dynamic (e.g., changing or perturbed) portion of stationary sensing data in real-time sensing data SDTX (e.g., time samples of the signal produced by reflection off stationary objects **42**S with a signal magnitude that changes at a rate having an absolute value exceeding a threshold rate). At the same time, the MTI filter blocks or filters out a static portion of the signal in real-time sensing data SDTX (e.g., a remainder of the time samples of the stationary sensing data, with a signal magnitude that changes at a rate having an absolute value less than or equal to the threshold rate). This may serve to filter out a first portion of the stationary sensing data produced by reflection of the sensing signals off stationary objects **42**S that are not blocked by moving objects **42**M while passing, to Fourier transform **70**, only a second portion of the stationary sensing data having changes and/or perturbations over time produced by motion of a moving object **42**M into and/or away from a position that occludes a corresponding point or location on stationary objects **42**S.

[0081] FIG. **6** is a diagram showing how moving object **42**M may produce a signal in real-time sensing data SDTX that passes through MTI filter **68** to Fourier transform **70**. Portion **88** of FIG. **6** illustrates the position of moving object **42**M between stationary objects **42**S and device **10** over time (e.g., while device **10** is stationary). As shown by portion **88** of FIG. **6**, moving object **42**M may be at an initial position **86**A at a first time TA. Moving object **42**M may be in motion in the direction of arrow **84** over time, such that moving object **42**M arrives at position **86**B at a second time TB after time TA. During environment mapping operations, device **10** may transmit sensing signals **34** and may receive corresponding reflected signals **36** from point P on stationary objects P (e.g., a reflected version of the transmitted sensing signals **34** that have reflected off stationary objects P). While illustrated as a point for the sake of clarity, point P has a finite width or point spread in practice.

[0082] Curve **92** of plot **90** in FIG. **6** plots the local signal amplitude (magnitude) in the stationary sensing data of the real-time sensing data SDT (e.g., coming from point P) received at MTI filter **68** as a function of time. Prior to time TA and after time TB, moving object **42**M does not block or occlude point P from device **10**. As shown by curve **92**, the real-time sensing data SDTX produced from reflection off stationary objects **42**S therefore exhibits a relatively constant magnitude (e.g., a rate of change with an absolute value less than a threshold level) prior to time TA and after time TB. Curve **94** of plot **90** plots the signal amplitude as output by MTI filter **68**. The amplitude of curve **94** may correspond to the magnitude of the rate of change of curve **92** over time. As shown by curve **94**, the output of MTI filter **68** is relatively low prior to time TA and after time TB because the signal magnitude associated with curve **92** is relatively constant before time TA and time TB.

[0083] Between time TA and time TB, moving object **42**M moves into a position that occludes point P from device **10** and then moves out of the position that occludes point P from device **10**. This motion of moving object **42**M produces a change or perturbation (e.g., a reduction and then an increase) in magnitude between times TA and time TB (e.g., by a rate having an absolute value exceeding the threshold level), as shown by curve **92**. However, the change in magnitude produced by motion of moving object **42**M through the position blocking point P causes MTI filter **68** to output this portion of the signal with a relatively high magnitude, as shown by the peak in curve **94** between times TA and TB. MTI filter **68** may output or pass the portion of the signal exceeding a detection threshold TH (sometimes referred to herein as filtered sensor data or filtered data) to Fourier transform **70** while blocking the rest of the stationary sensor data from passing to Fourier transform **70**. As such, Fourier transform **70** will only receive the portion (samples) of the signal output by MTI filter **68** having an amplitude that exceeds detection threshold TH (e.g., the portion of the signal in real-time sensor data SDTX received during time range TR between times TA and TB). These samples correspond to times when the amplitude associated with curve **92** exhibited a rate of change having an absolute value exceeding a threshold rate of change. In this way, MTI filter **68** passes only the portion of real-time sensor data SDTX that exhibits a change due to foreground moving object **42**M moving in front of a background stationary object **42**S, while filtering out the rest of the real-time sensor data including portions of the sensing data produced by reflected signals from portions of stationary objects **42**S that are not blocked by moving objects **42**M.

[0084] Fourier transform **70** may receive the filtered sensor data from MTI filter **68** (e.g., real-time sensor data SDTX that is output or passed through MTI filter **68**). Fourier transform **70** may apply one or more discrete Fourier transforms (DFTs) to the filtered sensor data received from MTI filter **68** (e.g., over the fast time and spatial dimensions (axes) of the data cube in the real-time sensor data SDTX that passed MTI filter **68**). This may, for example, convert the filtered sensor data from the time domain into the spatial domain (e.g., range and azimuth coordinates). Fourier transform **70** may output the converted filtered sensor data to integrator **74**.

[0085] Integrator **74** may perform non-coherent integration (e.g., over the slow time dimension) on the filtered sensor data received from Fourier transform **70**. This may produce a real-time range-azimuth power spectrum RAPSX (sometimes also referred to herein as real-time range and azimuth power spectrum data RAPSX). Integrator **74** may transmit real-time range-azimuth power spectrum RAPSX to CFAR **78** and to signal classifier **80** for subsequent processing. Integrator **74** may, for example, integrate forever without end or may include an averager that averages over a certain amount of chirps.

[0086] At the same time, Fourier transform **72** may apply one or more DFTs to baseline sensor data SDT**0** to convert the baseline sensor data to range and azimuth coordinates. Integrator **76** may perform non-coherent integration (e.g., over the slow time dimension) on the converted baseline sensor data received from Fourier transform **72**. This may produce a baseline range-azimuth power spectrum RAPS**0** (sometimes also referred to herein as baseline range and power spectrum data RAPS**0**). Integrator **76** may transmit baseline range-azimuth power spectrum RAPS**0** to signal classifier **80** for subsequent processing.

[0087] Diagram **83** of FIG. **5** shows one example of real-time range-azimuth power spectrum RAPSX output by integrator **74** (e.g., in range and azimuth coordinates). The horizontal axis of diagram **83** plots increasing azimuth angle. The vertical axis of diagram **83** plots increasing range angle. Each cell of diagram **83** represents a different spatial position relative to device **10** (e.g., a different combination or bin of range and azimuth values). Each cell of diagram **83** has a corresponding data/signal value or level (not shown in FIG. **5** for the sake of clarity) that corresponds to or represents the signal power or power density received by device **10** at the corresponding combination of range and azimuth. In general, range corresponds to radial distance from device **10** and azimuth corresponds to an angle within a plane orthogonal to the boresight direction of the antenna(s) **30** used by device **10** to transmit and/or receive signals **34** and **36**. Since the stationary signal produced by signal reflection off stationary objects **42**S are filtered out of the real-time sensor data by MTI filter **68**, the power represented by each cell in diagram **83** corresponds only to the signal produced by the movement of a moving object **42** into and/or out of a position between device **10** and different combinations of range and azimuth with respect to device **10**.

[0088] CFAR **78** may apply a constant false alarm rate algorithm to real-time range-azimuth power spectrum RAPSX in a manner that maintains an overall constant false alarm rate (e.g., where a false alarm is produced by the false detection of a given object). For a given test cell **79** (sometimes also referred to as cell under test (CUT) **79**) at a corresponding test range R**0** and test azimuth Y**0**, CFAR **78** may compare the value of test cell **79** to a combination of the values within a set of nearby reference cells **81** around test cell **79**. CFAR **78** may output a detection signal (e.g., as detection data DETS) associated with test cell **79** when the value of test cell **79** exceeds the combination of values from the set of reference cells **81**. The detection signal may be indicative of the detection of an object at the range and azimuth of the test cell (e.g., test range R**0** and test azimuth Y**0**) while allowing for the detection to exhibit an overall constant false detection rate. The combination of values compared to the value of test cell **79** may, for example, be given by the sum of the values from the set of reference cells **81** multiplied by a constant factor that is selected to set the overall constant false alarm rate of detection signals output by CFAR **78**. Implementations in which map generator **64** includes a CFAR detector such as CFAR **78** are illustrative and non-limiting. In general, CFAR **78** may be replaced with other false alarm rate detectors or other types of detectors.

[0089] To optimize the performance of CFAR **78** and thus the generated environment map RCM, the set of reference cells **81** may, for example, include at least two reference cells **81** at the same test range R**0** as test cell **79** but at azimuth(s) greater than test azimuth Y**0** and azimuth(s) less than test azimuth Y**0**. The set of reference cells **79** may also include at least one reference cell **81** at the same test azimuth Y**0** as test cell **79** but at range(s) that are closer than test range R**0** (e.g., cells at farther ranges may be omitted from the set of reference cells given that the signal from moving object **42**M may raise the detection threshold and prevent the detection of the stationary object). If desired, the nearest cells to test cell **79** may be omitted from the set of reference cells **81**.

[0090] CFAR **78** may perform the CFAR algorithm across each of the cells in real time range-azimuth power spectrum RAPSX to output corresponding detection data DETS (e.g., where each cell forms a test cell **79** that is compared to a corresponding set of reference cells **81**). Detection data DETS may include or identify the cells in real time range-azimuth power spectrum RAPSX that produced a detection signal when compared to its corresponding set of reference cells **81**. Each cell or data value of detection data DETS may, for example, identify the spatial position relative to device **10** where motion of moving object **42**M produced reflected power that exceeds the combination of values from its corresponding set of reference cells **81**. CFAR **78** may pass detection data DETS to signal classifier **80**.

[0091] Signal classifier **80** may use baseline range-azimuth power spectrum RAPS**0**, real-time range-azimuth power spectrum RAPSX, and detection data DETS to identify, determine, detect, and/or classify which cells or data from detection data DETS are associated with the spatial position (e.g., range-azimuth combinations) of stationary object(s) **42**S, which cells or data from detection data DETS are associated with the spatial position of moving object(s) **42**M, and which cells or data from detection data DETS are associated with multipath detections of moving object(s) **42**M. Signal classifier **80** may filter out or remove the cells or data from detection data DETS that are associated with the spatial position of moving object(s) **42**M and the cells or data from detection data DETS that are associated with multipath detections of moving object(s) **42**M, leaving only the cells or data from detection data DETS that are associated with the spatial position of stationary object(s) **42**S.

[0092] Signal classifier **80** may output stationary object detection information BGDETS and may provide stationary object detection information BGDETS to detection accumulator **82**. Stationary object detection information BGDETS may identify or include the cells or data of detection data DETS that are associated with the spatial position of stationary object(s) **42**S. Stationary object detection information BGDETS may thereby include or identify the spatial position (e.g., range and azimuth) of each point on stationary object(s) **42**S that was blocked by motion of moving object **42**M when producing real-time sensing data SDTX. Stationary object detection information BGDETS may also identify the value (e.g., power level or density) of the cells or data of detection data DETS received at signal classifier **80**.

[0093] This process may be repeated as moving object(s) **42**M continue to move around environment **62** over time. Sensing circuitry **28** may continue to generate sets of real-time sensing data SDTX (e.g., frames, data cubes, etc.) as moving object(s) **42**M move around environment **62** over time. Detection accumulator **82** may generate environment map RCM by accumulating the stationary object detection information BGDETS generated from each set of real-time sensing data SDTX. As moving object(s) **42**M move between device **10** and each of the different possible points or locations on stationary objects **42**S in environment **62** over time, detection accumulator **82** will generate an environment map RCM that accurately and precisely maps as many points on stationary objects **42**S as possible, forming an environment map RCM that exhibits high spatial resolution. These stationary objects may form boundaries of environment **62** that are then detected by environment boundary estimator **66** (FIG. **4**).

[0094] FIG. **7** is a diagram showing how device **10** may map different points on stationary objects **42**S as moving object **42**M moves between device **10** and stationary objects **42**S. As shown in FIG. **7**, moving object **42**M may move through N positions **86** over time (e.g., from position **86-1** to position **86-2** and so on until position **86-**N). Moving object **42**M may block or occlude a different respective point or location **96** on stationary objects **42**S at each of its N positions **86** (e.g., may block location **96-1** while at position **86-1**, may block location **96-2** while at position **86-2**, may block position **96**-N while at position **86**-N, etc.).

[0095] Device **10** may generate stationary object detection information BGDETS from the motion of moving object **42**M into and/or away from each position **86**, from position **86-1** to position **86**-N (e.g., where map generator **64** receives N different sets of real-time sensor data SDTX, one corresponding to each position **86** of moving object **42**M, and generates a different set of stationary object detection information BGDETS for each set of real-time sensor data SDTX). Each set of stationary object detection information BGDETS may, for example, identify the spatial position of at least the corresponding location **96** on stationary objects **42**S. For example, the stationary object detection information BGDETS generated while moving object **42**M moved into and/or away from position **86-1** may identify the range and azimuth from device **10** to location **96-1** on stationary object **42**S, the stationary object detection information BGDETS generated while moving object **42**M moved into and/or away from position **86-2** may identify the range and azimuth from device **10** to location **96-2** on stationary object **42**S, the stationary object detection information BGDETS generated while moving object **42**M moved into and/or away from position **86**-N may identify the range and azimuth from device **10** to location **96-1** on stationary object **42**S, etc.

[0096] By accumulating stationary object detection information BGDETS over time as one or more moving objects **42**M moves around environment **62** between device **10** and different locations **96** on stationary objects **42**S, device **10** may accumulate an environment map RCM that identifies as many locations **96** on stationary objects **42**S as possible. Map generator **64** may, for example, generate an environment map RCM that identifies all stationary objects **42**S around device **10** within environment **62** or within the field of view of device **10**. Application of MTI filter **68** configures the object detections identified by the environment map RCM output by map generator **64** to only include data generated from moving object **42**M changing/perturbing the stationary sensor data generated by reflection off points P on stationary objects **42**S, rather than data generated by reflection off portions of the stationary objects **42**S not perturbed by intervening moving objects.

[0097] In this way, map generator **64** may detect different locations **96** on stationary objects **42**S over time based on perturbations or changes in the stationary sensor data caused by motion of moving object(s) **42**M into and/or away from different points between those locations **96** and device **10** (e.g., perturbations or changes that pass the MTI filter), rather than by measuring reflections directly off of those locations **96** on stationary objects **42**S. This may allow device **10** to implement as few as a single transmit antenna **30**TX and/or a single receive antenna **30**RX in mapping all of locations **96**, thereby minimizing device resources, while allowing map generator **64** to generate environment map RCM with a spatial resolution that is as high or greater than would otherwise be achievable using a large array of antenna elements that measures reflections directly off of stationary objects **42**S. In addition, map generator **64** may generate environment map RCM in less time and potentially with greater resolution and/or accuracy than in implementations where device **10** tracks the position of moving objects **42**M over time and merely infers the presence of stationary objects **42**S as locations where moving objects **42**M do not travel (e.g., no-go zones) over a statistically significant amount of time.

[0098] FIG. **8** is a three-dimensional plot of a spatial power spectrum that may be generated by map generator **64** while performing motion-based environment mapping. The axes of FIG. **8** are three-dimensional Cartesian axes for the sake of illustration. Device **10** is located at the origin (point **112**). In the example of FIG. **8**, device **10** has a field of view facing the +Z, +Y, and −X directions. This is illustrative and, in general, any desired coordinate systems may be used to illustrate the spatial power spectrum and device **10** may have any desired field of view.

[0099] The spatial power spectrum of FIG. **8** is taken after MTI filtering at map generator **64** and therefore only includes signal contributions produced by the motion of a moving object **42**M in front of stationary objects **42**S. Signal reflections off stationary objects **42**S without an intervening moving object **42**M are filtered out by MTI filter **68**. The spatial power spectrum of FIG. **8** may, for example, represent detection signal DETS (FIG. **5**) prior to classification by signal classifier **80**. Points **100** and **102** of FIG. **8** correspond to spatial locations from which the local signal received at device **10** (e.g., in real-time sensor data SDTX) has a power exceeding a threshold level.

[0100] The real-time sensor data SDTX corresponding to a moving object **42**M moving into and/or away from position **86-1** (FIG. **7**) may cause the power spectrum to include a first point **100-1**. The spatial coordinates of point **100-1** may correspond to the spatial coordinates of position **86-1** (e.g., from signal reflection off moving object **42**M). At the same time, the real-time sensor data SDTX corresponding to the moving object moving into and/or away from position **86-1** may cause the power spectrum to include a second point **102-1** behind point **100-1** from the perspective of device **10**. The peak in power spectrum associated with point **102-1** is produced by a stationary object **42**S behind moving object **42**M while moving object **42**M moves to block and then to unblock the stationary object over time. The spatial coordinates of point **102-1** may correspond to the spatial coordinates of position **96-1** of FIG. **7**.

[0101] Similarly, real-time sensor data SDTX corresponding to moving object **42**M moving into and/or away from position **86-2** (FIG. **7**) may cause the power spectrum to include a second point **100-2**. The spatial coordinates of point **100-2** may correspond to the spatial coordinates of position **86-2** (e.g., from signal reflection off moving object **42**M). At the same time, the real-time sensor data SDTX corresponding to the moving object **42**M moving into and/or away from position **86-2** may cause the power spectrum to include a second point **102-2** behind point **100-2** from the perspective of device **10**. The peak in power spectrum associated with point **102-2** is produced by a stationary object **42**S behind moving object **42**M as moving object **42**M moves in front of the stationary object over time. The spatial coordinates of point **102-2** may correspond to the spatial coordinates of locations **96-2** of FIG. **7**.

[0102] This process may continue as moving object **42**M moves through different points **86** and thus in front of different locations **96** on stationary object **42** over time (e.g., along arrow A in FIG. **7**). As moving object **42**M moves over time, different points **100** are produced in the spatial power spectrum along a first sphere **110** (e.g., in the direction of arrow **104**) due to signal reflection off moving object **42**M. At the same time, different points **102** are produced in the spatial power spectrum along a second sphere **108** having a greater radius than sphere **100** due to the motion of moving object **42**M into and/or away from positions blocking different locations **96** along stationary objects **42**S (e.g., due to perturbations or changes in the stationary sensor data produced by moving object **42**M). In other words, each point **100** may correspond to one of the N positions **86** of FIG. **7** and each point **102** may correspond to one of the N locations **96** of FIG. **7**.

[0103] Signal classifier **80** (FIG. **5**) may compare the power spectrum of FIG. **8** to baseline range-azimuth power spectrum RAPS**0** and/or real-time range-azimuth power spectrum RAPSX to identify that points **100** are associated with reflection off of moving object **42**M rather than the spatial location of stationary objects **42**S. Signal classifier **80** may then remove or filter out points **100** associated with direct reflection off moving object **42**M, leaving only points **102** associated with the spatial position of stationary objects **42**S (e.g., stationary object detection information BGDETS of FIG. **5** may include points **102** but not points **100**).

[0104] Detection accumulator **82** may continue to accumulate points **102** in this way over time to generate environment map RCM (e.g., environment map RCM may include one or more sets of points **102** as shown in FIG. **8** for different locations of stationary objects **42**S in environment **62** as moving objects **42**M continue to move around device **10**). The overall number of accumulated points **102** and the spacing between adjacent accumulated points **102** correspond to the spatial resolution of environment map RCM. By leveraging the motion of moving objects **42**M to occlude different locations **96** on stationary objects **42**S, map generator **64** may maximize the number of points **102** accumulated in environment map RCM (e.g., minimizing the spacing between adjacent points **102**) and thus the spatial resolution of environment map RCM using as few as only a single transmit antenna **30**TX and/or a single receive antenna **30**RX, thereby minimizing resource consumption, space consumption, and cost at device **10**.

[0105] FIG. **9** is a schematic circuit diagram of environment boundary estimator **66**. As shown in FIG. **9**, environment boundary estimator **66** may include filter circuitry such as filter **120**, value normalizer circuitry such as value normalizer **122**, data augmenter circuitry such as data augmenter **124**, spatial normalizer circuitry such as spatial normalizer **126**, model fitting circuitry such as model fitter **130**, and one or more environment models **128**. Environment models **128** may be stored on storage circuitry in device **10**, for example.

[0106] The output of filter **120** may be coupled to the input of value normalizer **122**. The output of value normalizer **122** may be coupled to the input of data augmenter **124**. The output of data augmenter **124** may be coupled to the input of spatial normalizer **126**. The output of spatial normalizer **126** may be coupled to a first input of model fitter **130**. Model fitter **130** may have a second input that receives one or more of environment models **128**.

[0107] Filter **120** may receive environment map RCM from map generator **64**. Environment map RCM may include a set of accumulated points **102** (FIG. **8**) having corresponding spatial coordinates and power values. If desired, filter **120** may filter out contributions to environment map RCM (e.g., points **102**) from relatively small reflectors in stationary objects **42**S such as furniture. Environment map RCM is sometimes described and/or shown herein in two dimensions but, in general, environment map RCM may be a three-dimensional map or a one-dimensional map.

[0108] Value normalizer **122** may adjust the number of detections (e.g., points **102**) in environment map RCM to mitigate bias due to particular situations such as target trajectory, radar orientation, etc. Data augmenter **124** may, if desired, use environment map RCM to sample other detections based on waveform properties (e.g., angular resolution, etc.). Spatial normalizer **126** may modify the format or coordinates of the data in environment map RCM (e.g., by normalizing the spatial coordinates to values between 0 and 1, thereby optimizing the subsequent model fitting procedure by model **130**).

[0109] Model fitter **130** may compare different environment models **128** to environment map RCM to identify a best-fitting environment model **128** for the remaining points in the environment map (e.g., using any desired performance or optimization function that outputs the best parameterized environment model). Model fitter **130** may output environment boundary information BINFO based on environment map RCM and environment models **128**. Environment boundary information BINFO may, for example, identify the environment model **128** that best fits the points in environment map RCM. The best-fitting environment model **128** may include a model of the edges or boundaries of environment **62** (e.g., one or more walls, the floor, the ceiling, etc.). Environment boundary information BINFO may identify the best-fitting environment model **128** using any desired data or parameters (e.g., equations defining the surfaces and/or lines that define the edges or boundaries of environment **62** as formed by the detected stationary objects **42**S). Model fitter **130** may output environment boundary information BINFO for subsequent processing by control circuitry **14** (FIG. **1**).

[0110] FIG. **10** is a diagram showing how model fitter **130** may identify different best-fitting environment models **128** for different environment maps RCM. FIG. **10** plots a two-dimensional example of a first environment map RCM-**1** and a second environment map RCM-**2** that may be generated by map generator **64** (e.g., for different environments **62**). This is illustrative and, if desired, environment maps RCM may be three-dimensional and/or may use any desired coordinate system.

[0111] As shown in FIG. **10**, the points **132** of environment map RCM-**1** each correspond to a respective point **102** (FIG. **7**) that passed filter **120**, value normalizer **122**, data augmenter **124**, and spatial normalizer **126** of FIG. **9**. Each point **132** has a different respective spatial location. Model fitter **130** may attempt to fit a set of different environment models **128** to the points **132** of environment map RCM-**1**. Model fitter **130** may, for example, identify a best-fitting environment model **134** that best fits the points **132** of environment map RCM-**1**. In this example, the points **132** of environment map RCM-**1** may be produced by a stationary object **42**S such as a straight wall. The best-fitting environment model **134** may be a line or plane that estimates or approximates the edge or boundary of environment **62** (e.g., the straight wall) and that passes through points **132** (e.g., while minimizing a cost function or any other desired fitting function associated with fitting points **132** with different mathematical models for an edge or boundary of environment **62**).

[0112] Turning to environment map RCM-**1**, the points **132** of environment map RCM-**1** each correspond to a respective point **102** (FIG. **7**) that passed filter **120**, value normalizer **122**, data augmenter **124**, and spatial normalizer **126** of FIG. **9**. Each point **132** has a different respective spatial location. Model fitter **130** may attempt to fit a set of different environment models **128** to the points **132** of environment map RCM-**2**. Model fitter **130** may, for example, identify a best-fitting environment model **136** that best fits the points **132** of environment map RCM-**2**. In this example, the points **132** of environment map RCM-**1** may be produced by stationary objects **42**S such as two straight walls that intersect at the corner of environment **62** (e.g., a cornered wall). The best-fitting environment model **136** may be intersecting lines or planes that estimate or approximate the edge or boundary of environment **62** and that pass through points **132** (e.g., while minimizing a cost function or any other desired fitting function associated with fitting points **132** with different mathematical models for an edge or boundary of environment **62**). Best-fitting environment models **134** and **136** are sometimes also referred to herein as environment boundary models or simply as boundary models.

[0113] As shown by environment maps RCM-**1** and RCM-**2** of FIG. **10**, environment model **136** may be the best fitting model for environment map RCM-**2** but is not a satisfactory fit for the points **132** in environment map RCM-**1**. Similarly, environment model **134** may be the best fitting model for environment map RCM-**1** but is not a satisfactory fit for the points **132** in environment map RCM-**2**. Model fitter **130** may iterate over or test different environment models **128** until the best fitting environment model for a given environment map RCM is found. Model fitter **130** may identify or include the best-fitting model and thus the boundary or boundaries of environment **62** in output environment boundary information BINFO. In this way, sensing circuitry **28** may identify the boundaries of environment **62** with high resolution and using a minimal number of antennas **30**.

[0114] FIG. **11** is a flow chart of operations that may be processed by sensing circuitry **28** (FIG. **2**) to perform motion-based environment mapping (e.g., to map environment **62** and its boundaries/edges as defined by stationary objects **42**S based on one or more moving objects **42**M). At operation **140**, sensing circuitry **28** may begin transmitting sensing signals **34** and receiving corresponding reflected signals **36**. ADC **58** in sensing receiver **56** may generate sets of sensing data SDT based on reflected signals **36** as the reflected signals are received over time. Sensing circuitry **28** may continue to transmit sensing signals **34** and receive reflected signals **36** while processing the remaining operations of FIG. **11**.

[0115] At operation **142**, map generator **64** may generate (e.g., produce, output, calculate, compute, compile, accumulate, identify, detect, etc.) environment map RCM based on the transmitted sensing signals **34**, the received reflected signals **36** (e.g., sensing data SDT), and the motion of one or more moving objects **42**M through different positions **86** (FIG. **9**) between device **10** and different locations **96** on stationary objects **42**S (e.g., perturbations in stationary sensing data in sensing data SDT as caused by moving objects **42**M). Map generator **64** may accumulate the data or values in environment map RCM (e.g., points **102** of FIG. **8**) as the moving objects **42**M move around environment **62** over time to temporarily occlude or block different locations **96** on stationary objects **42**S from the perspective of device **10** (e.g., as a series of sets of sensing data SDT is received). Leveraging the motion of moving objects **42**M into and out of occlusion between stationary objects **42**S and device **10** may allow environment map RCM to be generated with relatively high resolution using as few antennas **30** in device **10** as possible.

[0116] At operation **144**, environment boundary estimator **66** may generate (e.g., produce, output, calculate, compute, compile, accumulate, identify, detect, etc.) environment boundary information

BINFO based on environment map RCM and one or more parametrizable environment models **128** (sometimes also referred to herein as environment boundary models **128** or simply as boundary models **128**). Environment boundary information BINFO may, for example, identify or include the best-fitting environment model **128** for the points in environment map RCM (e.g., model **134** for environment map RCM-**1** of FIG. **10**, model **136** for environment map RCM-**2** of FIG. **10**, etc.).

[0117] At operation **146**, control circuitry **14** may perform any desired actions or operations based on environment boundary information BINFO (e.g., based on the boundaries of environment **62** as detected or identified by environment boundary estimator **66**). As one example, device **10** may use the identified boundaries to identify when radio-frequency signals **63** (FIG. **3**) are incident upon device **10** from a source or location located outside of the identified boundaries of environment **62** and may filter out or mask the radio-frequency signals from being received, decoded, demodulated, and/or provided to the user of device **10**. This may, for example, help to preserve the privacy of the other users who may be operating the device(s) that produced radio-frequency signals **63**.

[0118] As another example, device **10** (e.g., one or more input-output devices **22** of FIG. **1**) may generate, produce, emit, alter, adjust, and/or modify a device output **61** (FIG. **3**) based on the identified boundaries of environment **62**. Device output **61** may include a visual output, a haptic output, a wireless, and/or an audio output. The visual output may include light emitted by one or more light sources on device **10** and/or image or video data displayed by one or more displays on device **10** (e.g., the visual output may include generation and/or adjustment of one or more virtual objects displayed by a virtual and/or augmented reality display on device **10**). As another example, the audio, haptic, and/or wireless output may include navigation instructions, warnings, alerts, directions, and/or other output based on the detected boundaries of environment **62**. These outputs may, for example, help to describe to the user of device **10** where the boundaries of environment **62** are located and/or may alert the user when the user approaches or is near to one of the detected boundaries (e.g., using an accessibility or vision impairment assistance application). These outputs may, for example, allow a vision-impaired user of device **10** to freely move through environment **62** without hitting the detected boundaries and without requiring the user to view the detected boundaries (e.g., stationary objects **42**S). These examples are illustrative and non-limiting and, in general, device **10** may perform any desired operations and/or may produce any desired output based on the boundaries detected based on environment map RCM as generated while performing room mapping.

[0119] FIG. **12** is a flow chart of operations that may be performed by map generator **64** (FIG. **5**) to generate environment map RCM. At operation **150**, map generator **64** may receive baseline sensing data SDT**0** associated with the absence of moving objects within the field of view of device **10**. Map generator **64** may store baseline sensing data SDT**0** for subsequent processing.

[0120] At operation **152**, map generator **64** may receive a set of real-time sensing data SDTX from ADC **58** (FIG. **2**). Real-time sensing data SDTX may include stationary sensor data produced from reflected signals **36** received by device **10** after reflection off different points on stationary objects **42**S.

[0121] At operation **154**, MTI filter **68** may generate filtered data by applying an MTI filter to the set of real-time sensing data SDTX. This may filter out stationary sensor data produced from signal reflection off points on stationary objects **42**S that are not blocked by moving objects **42**M (e.g., portions of the stationary sensor data that are not changed or perturbed by moving objects **42**M), leaving (as filtered data) stationary sensor data having changes or perturbations over time caused by motion of moving object(s) **42**M through positions **86** that occlude corresponding points on stationary object(s) **42**S from device **10**.

[0122] Operations **156-160** may be performed concurrently with operations **162** and/or **164**. Alternatively, operations **162** and **164** may be performed prior to operation **156**. At operation **162**, Fourier transform **72** may convert the set of baseline sensing data SDT**0** into spatial dimensions (e.g., range and azimuth).

[0123] At operation **164**, integrator **76** may generate baseline range-power spectrum RAPS**0** based on the set of baseline sensing data SDT**0** in spatial dimensions (e.g., range and azimuth). Integrator **76** may pass baseline range-power spectrum RAPS**0** to signal classifier **80**.
[0124] At operation **156**, Fourier transform **70** may convert the filtered data output by MTI filter **68** into spatial dimensions (e.g., range and azimuth).
[0125] At operation **158**, integrator **74** may generate real-time range-power spectrum RAPSX based on the filtered data in spatial dimensions (e.g., range and azimuth). Integrator **74** may pass real-time range-power spectrum RAPSX to signal classifier **80** and CFAR **78**.
[0126] At operation **160**, CFAR **78** may perform a CFAR algorithm on real-time range-power spectrum RAPSX (e.g., as shown by diagram **83** of FIG. **5**) to generate detection information DETS (e.g., as illustrated by points **102** and **100** of FIG. **8**).
[0127] At operation **166**, signal classifier **80** may extract (e.g., generate, identify, compute, calculate, produce, output, etc.) stationary object detection information BGDETS (e.g., as illustrated by points **102** but not points **100** of FIG. **8**) from detection information DETS based on real-time range-power spectrum RAPSX and baseline range-power spectrum RAPS**0** (e.g., filtering out detections associated with reflection off moving objects **42**M and/or multipath detections).
[0128] At operation **168**, detection accumulator **82** may accumulate the stationary object detection information BGDETS generated by map generator **64** from previous sets of real-time sensing data SDTX to generate environment map RCM. Processing may loop back to operation **152** via path **170** as additional sets of real-time sensing data SDTX are received (e.g., as moving objects **42**M move around environment **62** to block different points on stationary objects **42**S from the perspective of device **10**). Map generator **64** may iterate over operations **152-168** a predetermined number of times, for a predetermined time period, until the accumulated environment map RCM exhibits at least a threshold resolution, or until detection of any desired trigger condition.
[0129] FIG. **13** is a flow chart of operations that may be performed by environment boundary estimator **66** (FIG. **9**) to generate boundary information BINFO based on environment map RCM and environment models **128**. At operation **172**, filter **120** may receive environment map RCM from map generator **64**.
[0130] At operation **174**, filter **120** may filter environment map RCM (e.g., to remove detections or points **102** of FIG. **8** that were produced by relatively small reflectors in stationary objects **42**S such as furniture). Operation **174** may be omitted if desired.
[0131] At operation **176**, value normalizer **122** may adjust the number of detections in environment map RCM (e.g., points **102** of FIG. **8**) to mitigate potential biases (e.g., to compensate for the trajectory of moving object **42**M, antenna orientation on device **10**, etc.). Operation **176** may be omitted if desired.
[0132] At operation **178**, data augmenter **124** may sample other detections in environment map RCM (e.g., angular resolution) based on various waveform properties. Operation **178** may be omitted if desired.
[0133] At operation **180**, spatial normalizer **126** may re-map the data in environment map RCM (e.g., points **102** of FIG. **8**) to a normalized coordinate system for subsequent processing (e.g., a coordinate system having values between 0 and 1). Operation **180** may be omitted if desired.
[0134] At operation **182**, model fitter **130** may fit a set of one or more parametrizable environment models **128** to the remaining points **132** in environment map RCM (FIG. **10**). Model fitter **130** may identify (e.g., calculate, compute, generate, output, produce, estimate, detect, etc.) a best-fitting of environment models **128** for the points **132** in environment map RCM. Model fitter **130** may include or identify the best-fitting environment model **128** in boundary information BINFO (e.g., as a best fitting boundary model for environment map RCM). Models **128** may be static or may be adjustable (e.g., parametrizable).
[0135] The examples of FIGS. **5-13** are illustrative and non-limiting. If desired, MTI filter **68** may be coupled between Fourier transform **70** and integrator **74** (FIG. **5**). MTI filter **68** may effectively

perform high pass filtering on the signal received by map generator **64**. Alternatively, MTI filter **68** may be omitted from map generator **64**. In these implementations, Fourier transform **70** may itself perform high pass filtering on the signal received by map generator **64**. As a first example, Fourier transform **70** may ignore or filter out zero-Doppler bins of the signal, causing Fourier transform **70** to output a Fourier transformed (e.g., spatial domain) signal without or free from zero-Doppler bins. In this example, subsequent processing is performed by the rest of map generator **64** only on non-zero-Doppler bins of the signal received by map generator **64**. As a second example, map generator **64** may include a subtractor (e.g., subtraction circuitry or logic) coupled to input of Fourier transform **70**. In this example, the subtractor may subtract, from the signal received by map generator **70**, an average of the chirps (e.g., over slow time) in the signal received by map generator **64**. This may produce a difference signal that is output by the subtractor and input to Fourier transform **70**. The operations of FIG. **12** may be adapted to accommodate these examples in which MTI filter **68** is omitted from map generator **64** (e.g., where operation **154** is omitted and zero-Doppler bins are discarded at operations **156** and/or **162**, where operation **154** is replaced with the subtraction of the average of sensing data SDTX over slow time from sensing data SDTX, etc.).

[0136] As used herein, the term “concurrent” means at least partially overlapping in time. In other words, first and second events are referred to herein as being “concurrent” with each other if at least some of the first event occurs at the same time as at least some of the second event (e.g., if at least some of the first event occurs during, while, or when at least some of the second event occurs). First and second events can be concurrent if the first and second events are simultaneous (e.g., if the entire duration of the first event overlaps the entire duration of the second event in time) but can also be concurrent if the first and second events are non-simultaneous (e.g., if the first event starts before or after the start of the second event, if the first event ends before or after the end of the second event, or if the first and second events are partially non-overlapping in time). As used herein, the term “while” is synonymous with “concurrent.”

[0137] As described above, one aspect of the present technology is the gathering and use of information such as biometric information or sensor information. The present disclosure contemplates that in some instances, this gathered data may include personal information data that uniquely identifies or can be used to contact or locate a specific person. Such personal information data can include demographic data, location-based data, telephone numbers, email addresses, twitter ID's, home addresses, data or records relating to a user's health or level of fitness (e.g., vital signs measurements, medication information, exercise information), date of birth, eyeglasses prescription, username, password, biometric information, or any other identifying or personal information.

[0138] The present disclosure recognizes that the use of such personal information, in the present technology, can be used to the benefit of users. For example, the personal information data can be used to deliver targeted content that is of greater interest to the user. Accordingly, use of such personal information data enables users to calculated control of the delivered content. Further, other uses for personal information data that benefit the user are also contemplated by the present disclosure. For instance, health and fitness data may be used to provide insights into a user's general wellness, or may be used as positive feedback to individuals using technology to pursue wellness goals.

[0139] The present disclosure contemplates that the entities responsible for the collection, analysis, disclosure, transfer, storage, or other use of such personal information data will comply with well-established privacy policies and/or privacy practices. In particular, such entities should implement and consistently use privacy policies and practices that are generally recognized as meeting or exceeding industry or governmental requirements for maintaining personal information data private and secure. Such policies should be easily accessible by users, and should be updated as the collection and/or use of data changes. Personal information from users should be collected for legitimate and reasonable uses of the entity and not shared or sold outside of those legitimate uses.

Further, such collection/sharing should occur after receiving the informed consent of the users. Additionally, such entities should consider taking any needed steps for safeguarding and securing access to such personal information data and ensuring that others with access to the personal information data adhere to their privacy policies and procedures. Further, such entities can subject themselves to evaluation by third parties to certify their adherence to widely accepted privacy policies and practices. In addition, policies and practices should be adapted for the particular types of personal information data being collected and/or accessed and adapted to applicable laws and standards, including jurisdiction-specific considerations. For instance, in the United States, collection of or access to certain health data may be governed by federal and/or state laws, such as the Health Insurance Portability and Accountability Act (HIPAA), whereas health data in other countries may be subject to other regulations and policies and should be handled accordingly. Hence different privacy practices should be maintained for different personal data types in each country.

[0140] Despite the foregoing, the present disclosure also contemplates embodiments in which users selectively block the use of, or access to, personal information data. That is, the present disclosure contemplates that hardware and/or software elements can be provided to prevent or block access to such personal information data. For example, the present technology can be configured to allow users to select to “opt in” or “opt out” of participation in the collection of personal information data during registration for services or anytime thereafter. In another example, users can select not to provide certain types of user data. In yet another example, users can select to limit the length of time user-specific data is maintained. In addition to providing “opt in” and “opt out” options, the present disclosure contemplates providing notifications relating to the access or use of personal information. For instance, a user may be notified upon downloading an application (“app”) that their personal information data will be accessed and then reminded again just before personal information data is accessed by the app.

[0141] Moreover, it is the intent of the present disclosure that personal information data should be managed and handled in a way to minimize risks of unintentional or unauthorized access or use. Risk can be minimized by limiting the collection of data and deleting data once it is no longer needed. In addition, and when applicable, including in certain health related applications, data de-identification can be used to protect a user's privacy. De-identification may be facilitated, when appropriate, by removing specific identifiers (e.g., date of birth, etc.), controlling the amount or specificity of data stored (e.g., collecting location data at a city level rather than at an address level), controlling how data is stored (e.g., aggregating data across users), and/or other methods.

[0142] Therefore, although the present disclosure broadly covers use of personal information data to implement one or more various disclosed embodiments, the present disclosure also contemplates that the various embodiments can also be implemented without the need for accessing such personal information data. That is, the various embodiments of the present technology are not rendered inoperable due to the lack of all or a portion of such personal information data.

[0143] If desired, an apparatus may be provided that includes means to perform one or more elements or any combination of elements of one or more methods or processes described herein.

[0144] If desired, one or more non-transitory computer-readable media may be provided that include instructions to cause an electronic device, upon execution of the instructions by one or more processors of the electronic device, to perform one or more elements or any combination of elements of one or more methods or processes described herein.

[0145] If desired, an apparatus may be provided that includes logic, modules, or circuitry to perform one or more elements or any combination of elements of one or more methods or processes described herein.

[0146] If desired, an apparatus may be provided that includes one or more processors and one or more non-transitory computer-readable storage media comprising instructions that, when executed by the one or more processors, cause the one or more processors to perform one or more elements

or any combination of elements of one or more methods or processes described herein.
[0147] If desired, a signal (e.g., a signal encoded with data), datagram, information element (IE), packet, frame, segment, PDU, or message may be provided that includes or performs one or more elements or any combination of elements of one or more methods or processes described herein.
[0148] If desired, an electromagnetic signal may be provided that carries computer-readable instructions, where execution of the computer-readable instructions by one or more processors causes the one or more processors to perform one or more elements or any combination of elements of one or more methods or processes described herein.
[0149] If desired, a computer program may be provided that includes instructions, where execution of the program by a processing element causes the processing element to carry out one or more elements or any combination of elements of one or more methods or processes described herein.
[0150] The foregoing is merely illustrative and various modifications can be made to the described embodiments. The foregoing embodiments may be implemented individually or in any combination.

Claims

1. A method of operating an electronic device comprising: transmitting, using one or more antennas, radio-frequency signals into an environment that contains a moving object and a stationary object; receiving, using the one or more antennas, reflected radio-frequency signals from the environment; and estimating, using one or more processors, a boundary of the environment based on a motion, as identified from the reflected radio-frequency signals, of the moving object into a position between the electronic device and the stationary object.
2. The method of claim 1, wherein the boundary comprises a point on the stationary object that is blocked by the moving object while the moving object is at the position.
3. The method of claim 1, further comprising: generating, using an analog-to-digital converter (ADC), sensor data based on the reflected radio-frequency signals received by the one or more antennas, wherein estimating the boundary comprises estimating the boundary based on the sensor data.
4. The method of claim 3, further comprising: generating, using the one or more processors, filtered data by applying a moving target indicator (MTI) filter to the sensor data, wherein estimating the boundary comprises estimating the boundary based on the filtered data.
5. The method of claim 4, further comprising: generating, using the one or more processors, a range-azimuth power spectrum by integrating the filtered data over a slow time axis of the sensing data, wherein estimating the boundary comprises estimating the boundary based on the range-azimuth power spectrum.
6. The method of claim 5, further comprising: generating, using the one or more processors, a detection signal by applying a constant false alarm rate (CFAR) algorithm to the range-azimuth power spectrum; and accumulating, using the one or more processors, a map of different spatial locations in the environment based on the detection signal, wherein estimating the boundary comprises estimating the boundary based on the map.
7. The method of claim 6, wherein estimating the boundary comprises fitting the map to different environment boundary models and outputting, as the estimated boundary, a best-fitting of the different environment boundary models.
8. The method of claim 1, further comprising: displaying, using a display, an image based on the estimated boundary.
9. The method of claim 1, further comprising: outputting, using a speaker, audio based on the estimated boundary.
10. An electronic device comprising: one or more antennas configured to transmit radio-frequency signals into an environment and configured to receive reflected signals from one or more stationary

objects in the environment; and one or more processors configured to accumulate a map of the one or more stationary objects in the environment based on changes in the reflected signals produced by movement of one or more moving objects through different positions between the electronic device and the one or more stationary objects over time, and estimate a boundary of the environment based on the accumulated map of stationary objects.

11. The electronic device of claim 10, further comprising: an analog-to-digital converter configured to generate sensing data based on the reflected signals received by the one or more antennas, the one or more processors being further configured to generate filtered data by applying a moving target indicator (MTI) filter to the sensing data, and accumulate the map of stationary objects based on the filtered data, wherein the map of stationary objects identifies portions of the filtered data at different spatial locations in the environment.

12. The electronic device of claim 10, further comprising: an analog-to-digital converter configured to generate sensing data based on the reflected signals received by the one or more antennas, the one or more processors being further configured to apply a Fourier transform to the sensing data to generate a spatial domain signal, discard zero-Doppler bins from the spatial domain signal, and accumulate the map of stationary objects based on non-zero-Doppler bins of the spatial domain signal.

13. The electronic device of claim 10, further comprising: an analog-to-digital converter configured to generate sensing data based on the reflected signals received by the one or more antennas, the one or more processors being further configured to subtract, from the sensing data, an average of the sensing data over a slow time axis to generate a difference signal, apply a Fourier transform to the difference signal to generate a spatial domain signal, and accumulate the map of stationary objects based on the spatial domain signal.

14. A method of operating an electronic device comprising: transmitting, using one or more antennas, sensing signals into an environment that contains a moving object and a stationary object; receiving, using the one or more antennas, reflected signals corresponding to the sensing signals, the reflected signals having reflected off the stationary object; generating, using an analog-to-digital converter (ADC), sensing data based on the reflected signals; generating, using one or more processors, filtered data by applying a moving target indicator (MTI) filter to the sensing signals, wherein the filtered data is indicative of a movement of the moving object through a position between the electronic device and the stationary object; and detecting, using the one or more processors, a location on the stationary object based on the filtered data.

15. The method of claim 14, wherein the moving object occludes the location on the stationary object from the electronic device while the moving object is at the position.

16. The method of claim 14, further comprising: generating, using the one or more processors, a spatial power spectrum based on the filtered data, wherein detecting the location comprises detecting the location based on the spatial power spectrum.

17. The method of claim 16, further comprising: filtering, using the one or more processors, a signal contribution from the spatial power spectrum that was produced by reflection of the sensing signals off the moving object.

18. The method of claim 16, wherein detecting the location comprises comparing the spatial power spectrum to an additional spatial power spectrum that is generated by the one or more processors while moving objects are absent from the environment.

19. The method of claim 14, wherein the filtered data is indicative of an additional movement of the moving object through an additional position between the electronic device and the stationary object, the method further comprising: detecting, using the one or more processors, an additional location on the stationary object based on the additional movement of the moving object through the additional position between the electronic device and the stationary object; and generating, using the one or more processors, a spatial map of the environment that identifies the location and the additional location.

20. The method of claim 19, further comprising: identifying, using the one or more processors, a boundary of the environment based on the location and the additional location.