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(54) METHODS AND SYSTEMS FOR SYNCHRONIZING DATA RECEIVED FROM MULTIPLE SENSORS OF A DEVICE

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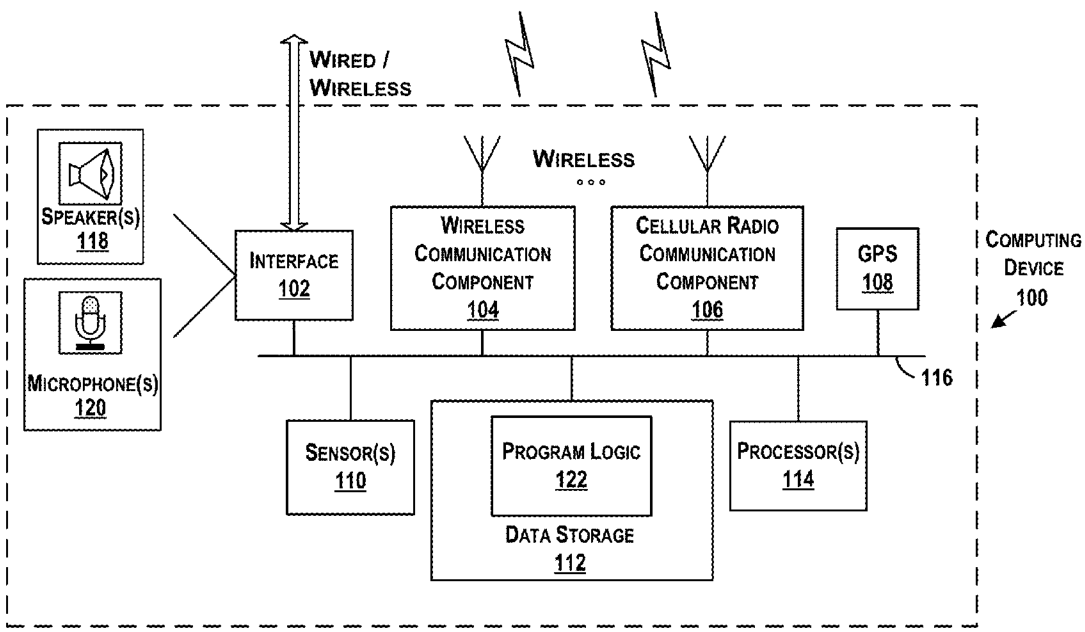
(57) ABSTRACT

Example methods and systems for synchronizing data received from multiple sensors of a device are provided. A method may be performed by a device having an application processor configured to function based on an operating system and a co-processor configured to receive data from sensors of the device. The method may comprise determining an interrupt by a sensor of the device, and providing, by the co-processor, a timestamp of the interrupt that is indicative of a time that the sensor has data for output. The method also comprises receiving the data for output from the sensor, associating the timestamp of the interrupt by the sensor with the received data, associating together data received from multiple sensors into data structures based on timestamps of the data, and providing the data structures to the application processor in sequence based on the timestamps of the data.



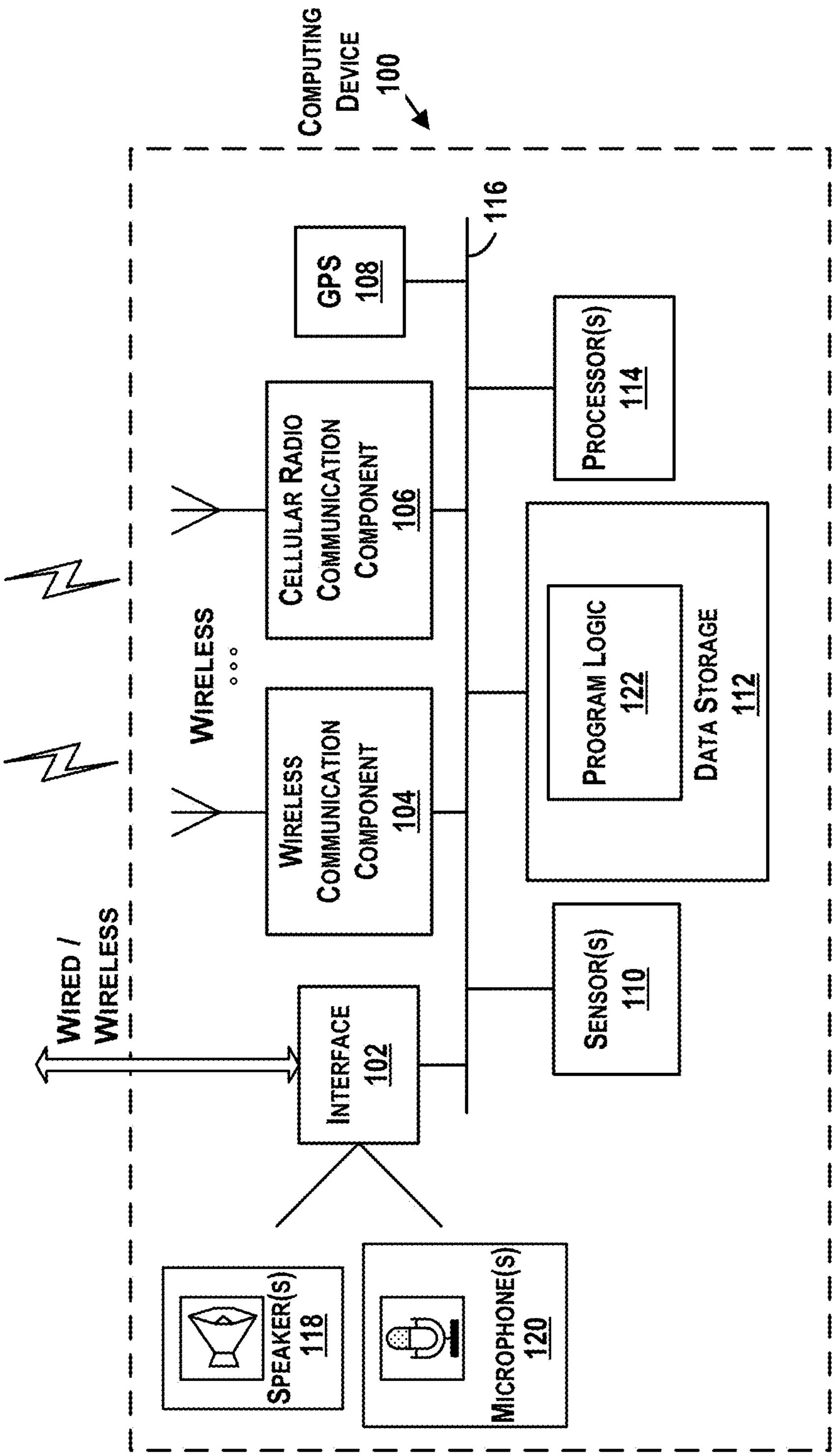

COMPUTING DEVICE 100
WIRED / WIRELESS
INTERFACE 102
WIRELESS
WIRELESS COMMUNICATION COMPONENT 104
CELLULAR RADIO COMMUNICATION COMPONENT 106
GPS 108
116
SENSOR(S) 110
PROGRAM LOGIC 122
DATA STORAGE 112
PROCESSOR(S) 114
SPEAKER(S) 118
MICROPHONE(S) 120

FIG. 1

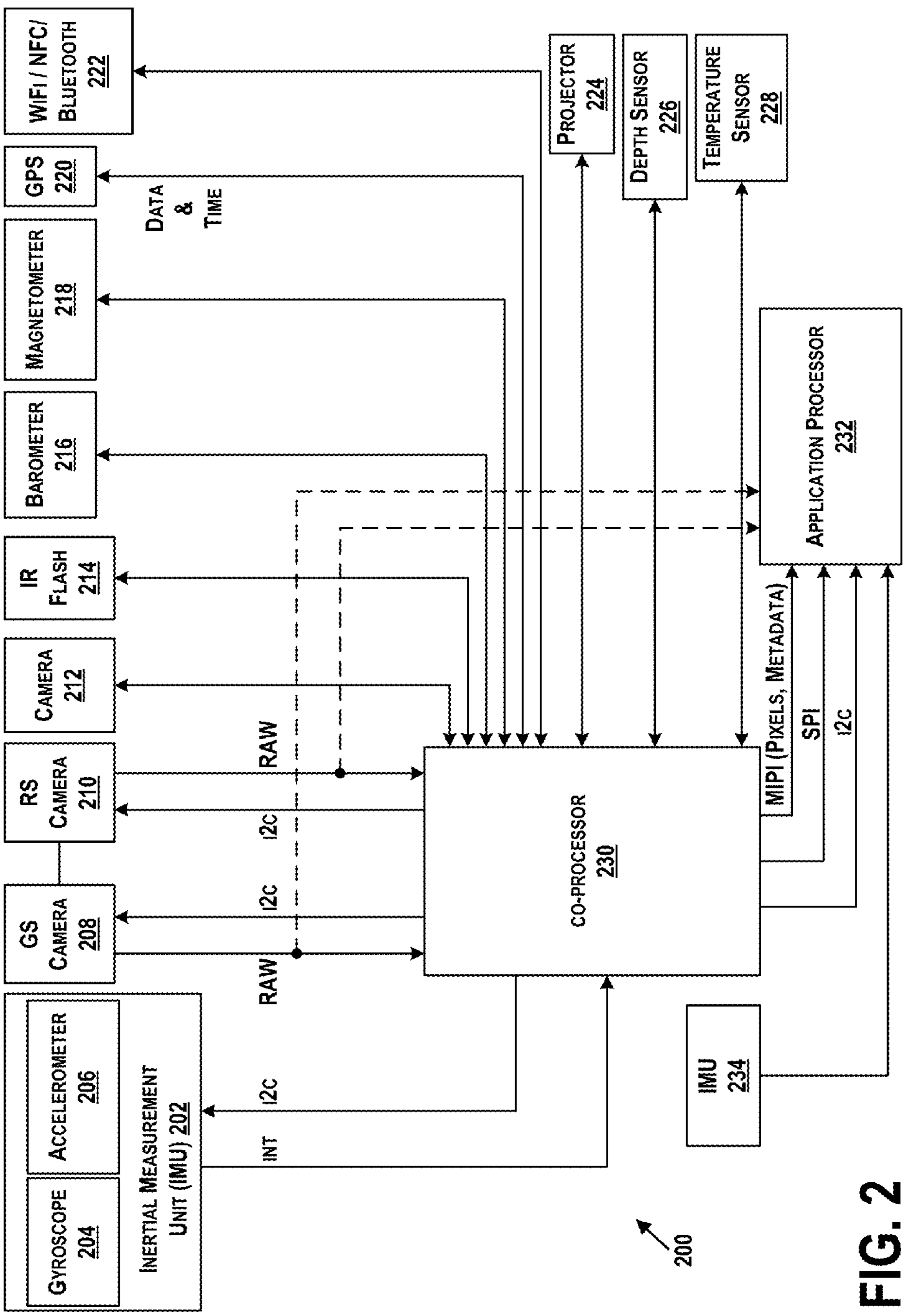

GYROSCOPE 204
ACCELEROMETER 206
INERTIAL MEASUREMENT UNIT (IMU) 202
GS CAMERA 208
RS CAMERA 210
CAMERA 212
IR FLASH 214
BAROMETER 216
MAGNETOMETER 218
GPS 220
WIFI / NFC/ BLUETOOTH 222
PROJECTOR 224
DEPTH SENSOR 226
TEMPERATURE SENSOR 228
CO-PROCESSOR 230
APPLICATION PROCESSOR 232
IMU 234
DATA & TIME
RAW
I2C
RAW
I2C
I2C
INT
MIPI (PIXELS, METADATA)
SPI
I2C
200

FIG. 2

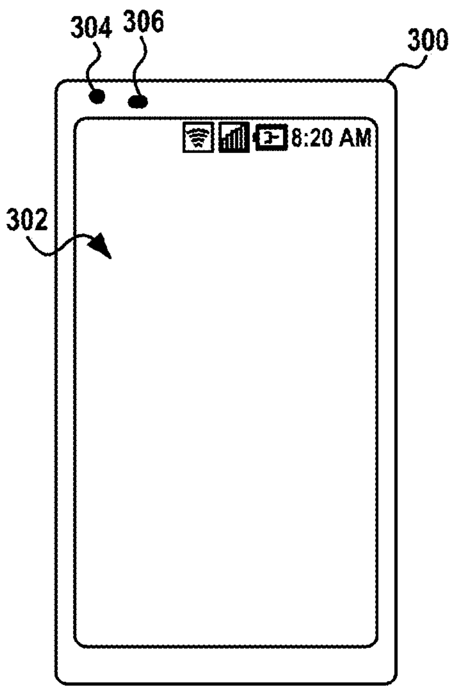


FIG. 3A

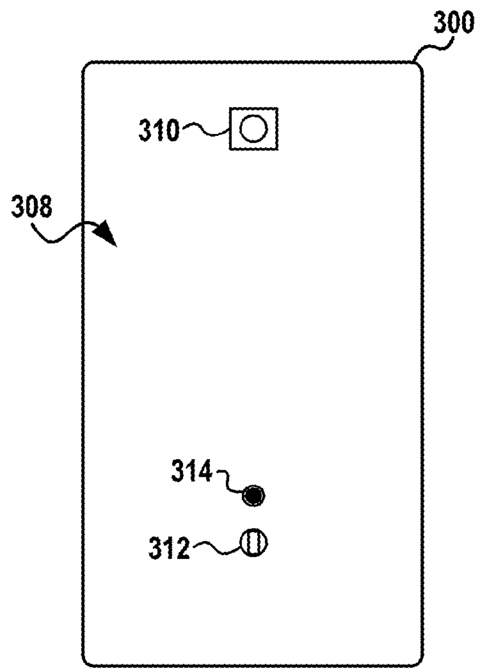


FIG. 3B

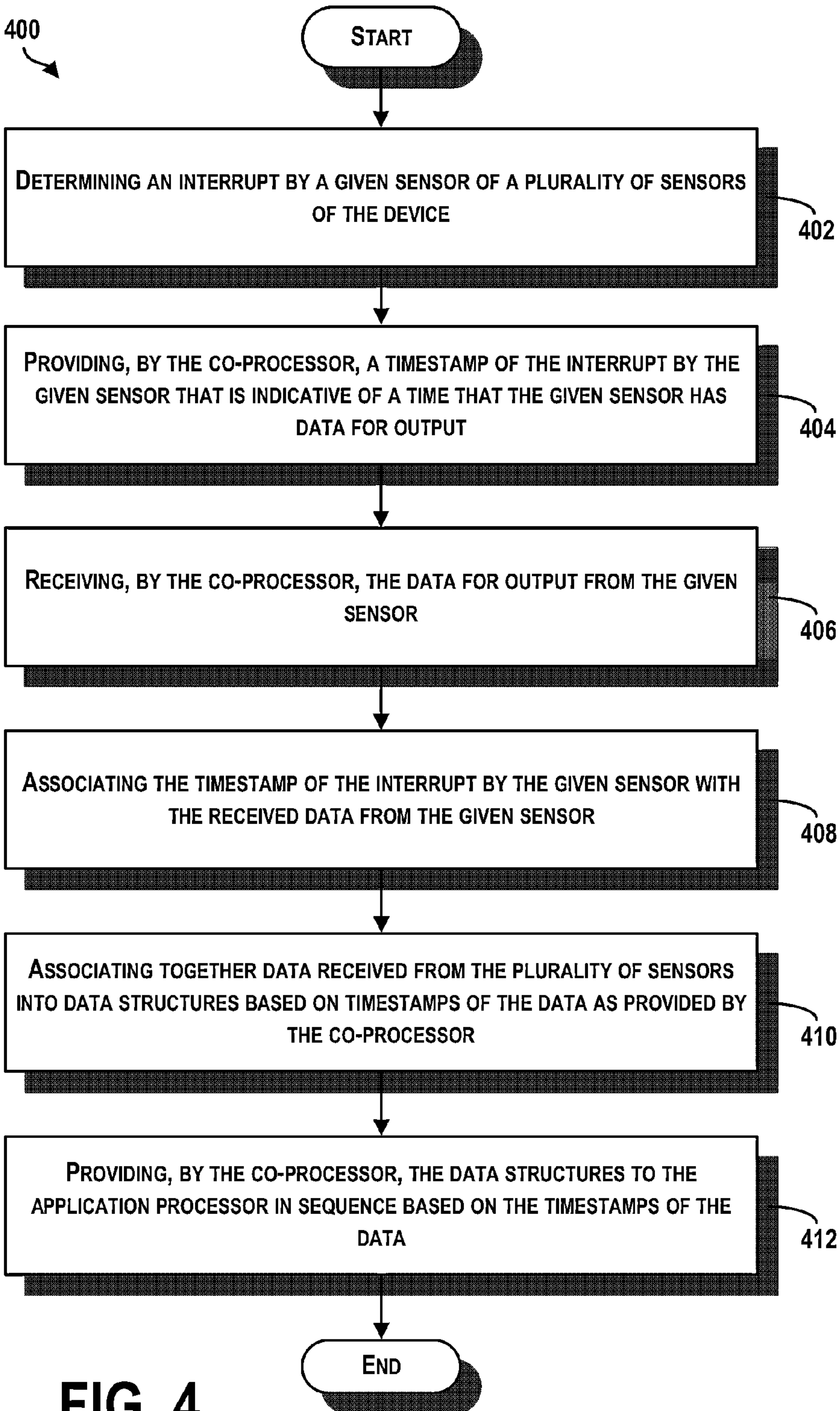

400
START
DETERMINING AN INTERRUPT BY A GIVEN SENSOR OF A PLURALITY OF SENSORS OF THE DEVICE
402
PROVIDING, BY THE CO-PROCESSOR, A TIMESTAMP OF THE INTERRUPT BY THE GIVEN SENSOR THAT IS INDICATIVE OF A TIME THAT THE GIVEN SENSOR HAS DATA FOR OUTPUT
404
RECEIVING, BY THE CO-PROCESSOR, THE DATA FOR OUTPUT FROM THE GIVEN SENSOR
406
ASSOCIATING THE TIMESTAMP OF THE INTERRUPT BY THE GIVEN SENSOR WITH THE RECEIVED DATA FROM THE GIVEN SENSOR
408
ASSOCIATING TOGETHER DATA RECEIVED FROM THE PLURALITY OF SENSORS INTO DATA STRUCTURES BASED ON TIMESTAMPS OF THE DATA AS PROVIDED BY THE CO-PROCESSOR
410
PROVIDING, BY THE CO-PROCESSOR, THE DATA STRUCTURES TO THE APPLICATION PROCESSOR IN SEQUENCE BASED ON THE TIMESTAMPS OF THE DATA
412
END

FIG. 4

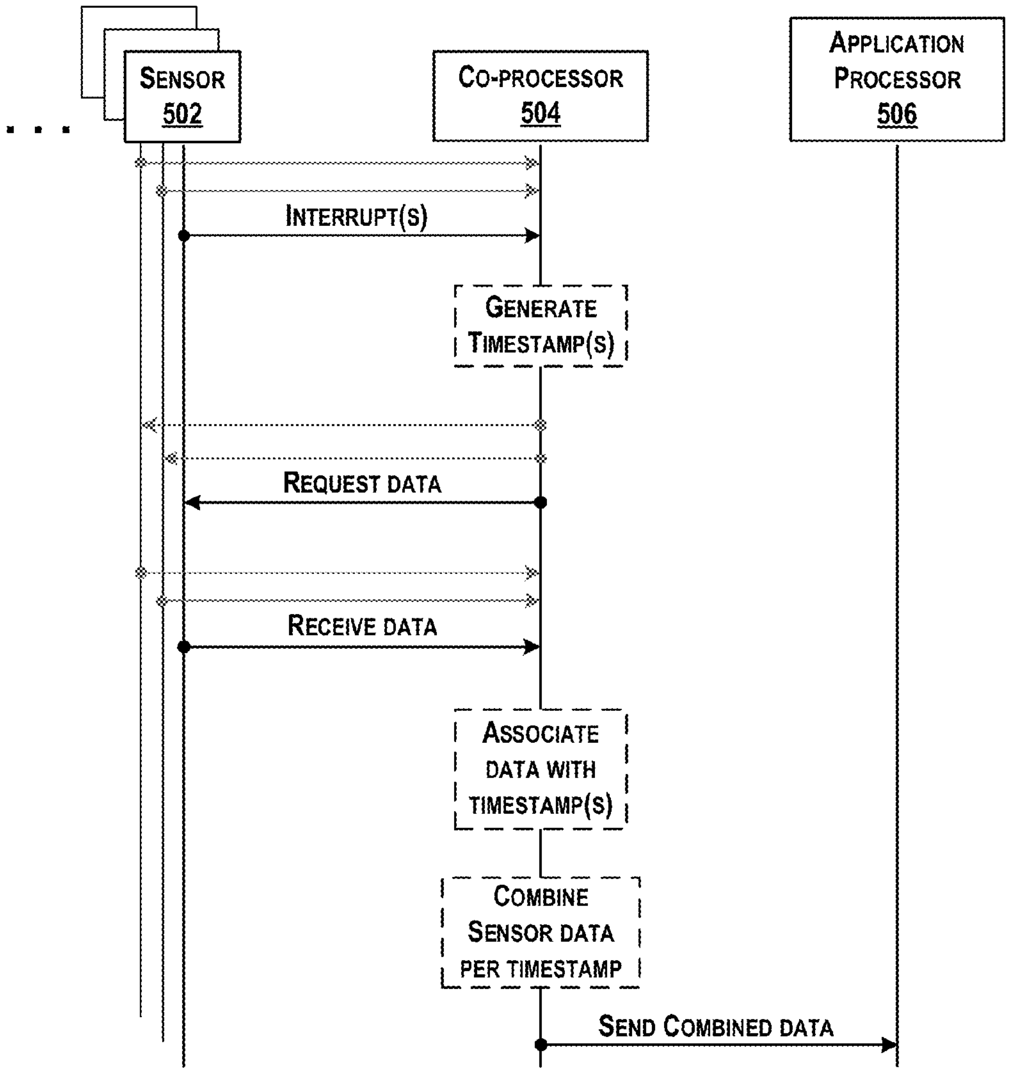

SENSOR
502
CO-PROCESSOR
504
APPLICATION
PROCESSOR
506
INTERRUPT(S)
GENERATE
TIMESTAMP(S)
REQUEST DATA
RECEIVE DATA
ASSOCIATE
DATA WITH
TIMESTAMP(S)
COMBINE
SENSOR DATA
PER TIMESTAMP
SEND COMBINED DATA

FIG. 5A

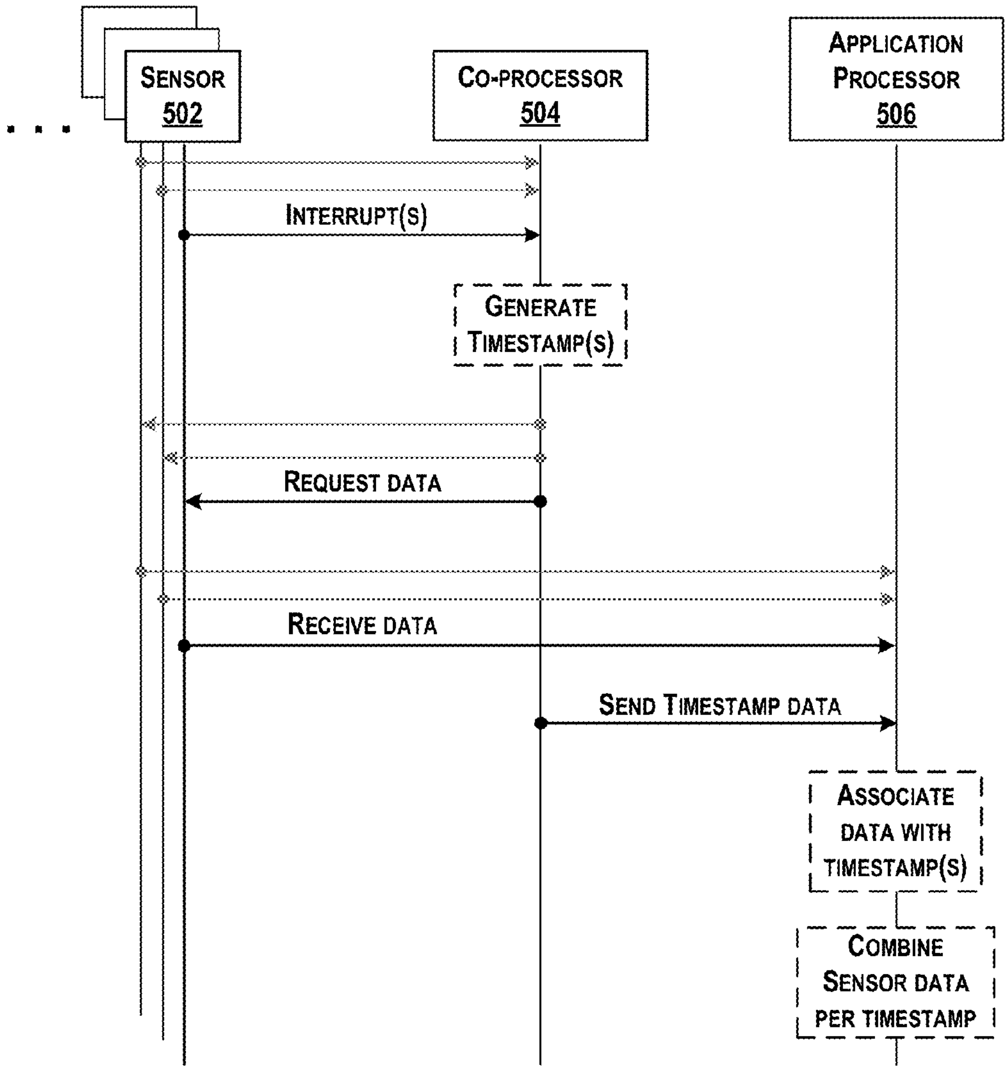

SENSOR
502
CO-PROCESSOR
504
APPLICATION
PROCESSOR
506
INTERRUPT(S)
GENERATE
TIMESTAMP(S)
REQUEST DATA
RECEIVE DATA
SEND TIMESTAMP DATA
ASSOCIATE
DATA WITH
TIMESTAMP(S)
COMBINE
SENSOR DATA
PER TIMESTAMP

FIG. 5B

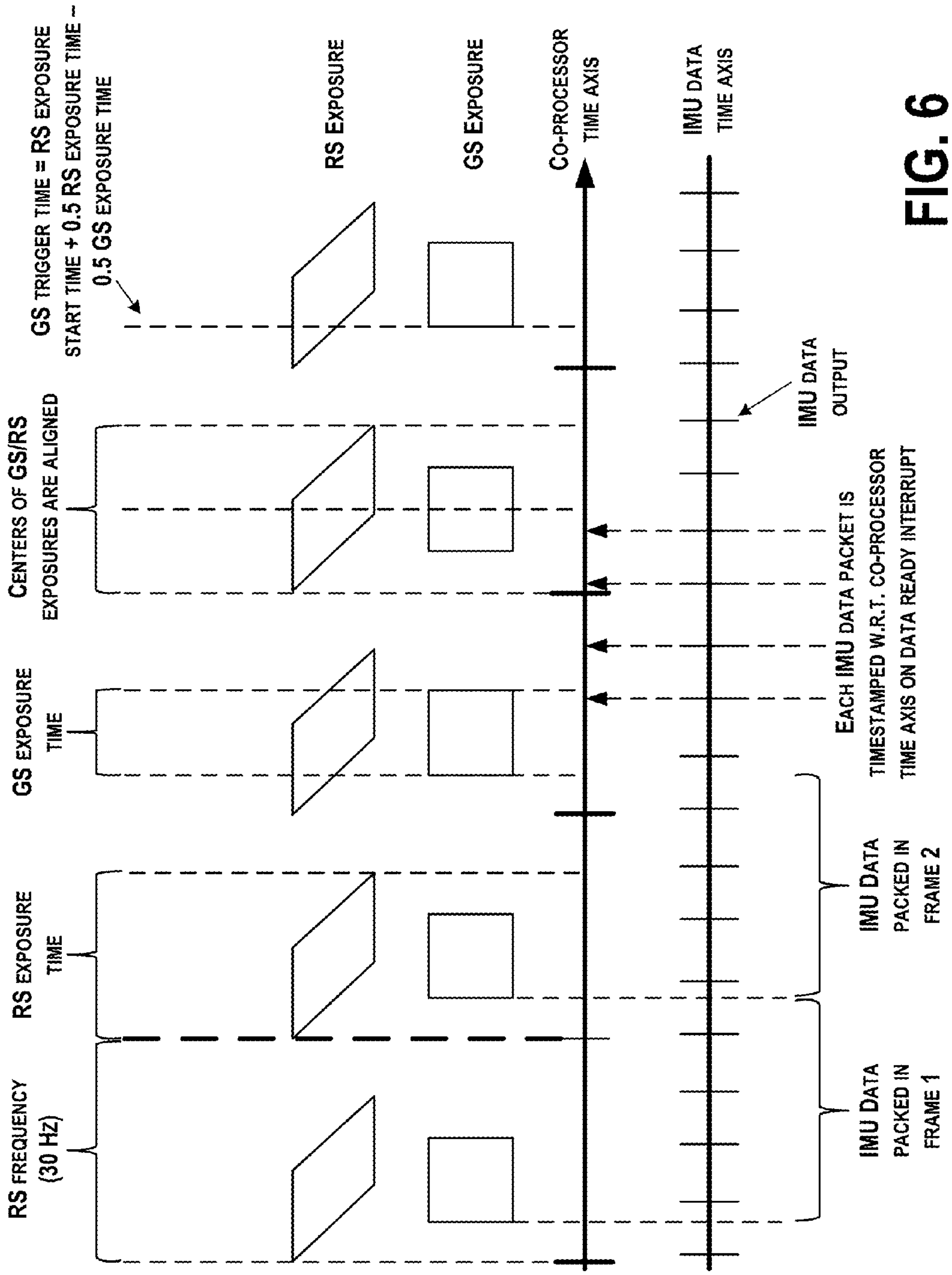

GS TRIGGER TIME = RS EXPOSURE START TIME + 0.5 RS EXPOSURE TIME – 0.5 GS EXPOSURE TIME
RS EXPOSURE
GS EXPOSURE
CO-PROCESSOR TIME AXIS
IMU DATA TIME AXIS
CENTERS OF GS/RS EXPOSURES ARE ALIGNED
IMU DATA OUTPUT
GS EXPOSURE TIME
EACH IMU DATA PACKET IS TIMESTAMPED W.R.T. CO-PROCESSOR TIME AXIS ON DATA READY INTERRUPT
RS EXPOSURE TIME
RS FREQUENCY (30 Hz)
IMU DATA PACKED IN FRAME 2
IMU DATA PACKED IN FRAME 1

FIG. 6

METHODS AND SYSTEMS FOR SYNCHRONIZING DATA RECEIVED FROM MULTIPLE SENSORS OF A DEVICE

BACKGROUND

[0001] Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

[0002] Sensor fusion includes combining sensor data or data derived from sensory data from independent sources such that resulting information is more complete. Data sources for a fusion process may include multiple distinct sensors. Each sensor may provide different information about the same object in an environment, or about the same location in an environment, for example. By combining the sensor data, a more complete depiction of the object or location can be provided. As an example, one sensor may include a camera to capture an image of an object, and another sensor may include location detection capabilities to determine a location of a device used to capture the image. By combining the sensor data, specific location information for the image data is provided.

SUMMARY

[0003] In one example, a method performed by a device having an application processor configured to function based on an operating system and a co-processor configured to receive data from a plurality of sensors of the device is provided. The method comprises determining an interrupt by a given sensor of the plurality of sensors of the device, and the interrupt is indicative of the given sensor having data for output. The method also comprises providing, by the co-processor, a timestamp of the interrupt by the given sensor that is indicative of a time that the given sensor has data for output, and receiving, by the co-processor, the data for output from the given sensor. The method also comprises associating the timestamp of the interrupt by the given sensor with the received data from the given sensor, associating together data received from the plurality of sensors into data structures based on timestamps of the data as provided by the co-processor, and providing, by the co-processor, the data structures to the application processor in sequence based on the timestamps of the data.

[0004] In another example, a computer readable memory configured to store instructions that, when executed by a device having an application processor configured to function based on an operating system and a co-processor configured to receive data from a plurality of sensors of the device, cause the device to perform functions is provided. The functions comprise determining an interrupt by a given sensor of the plurality of sensors of the device, and the interrupt is indicative of the given sensor having data for output. The functions also comprise providing, by the co-processor, a timestamp of the interrupt by the given sensor that is indicative of a time that the given sensor has data for output, and receiving, by the co-processor, the data for output from the given sensor. The functions also comprise associating the timestamp of the interrupt by the given sensor with the received data from the given sensor, associating together data received from the plurality of sensors into data structures based on timestamps of the data as provided by the co-processor, and providing, by the co-processor, the data structures to the application processor in sequence based on the timestamps of the data.

[0005] In another example, a device is provided that comprises an application processor configured to function based on an operating system, a plurality of sensors, and a co-processor configured to receive data from the plurality of sensors and configured to perform functions. The functions comprise determine an interrupt by a given sensor of the plurality of sensors, and the interrupt is indicative of the given sensor having data for output. The functions also comprise provide a timestamp of the interrupt by the given sensor that is indicative of a time that the given sensor has data for output, receive the data for output from the given sensor, associate the timestamp of the interrupt by the given sensor with the received data from the given sensor, associate together data received from the plurality of sensors into data structures based on timestamps of the data as provided by the co-processor, and provide the data structures to the application processor in sequence based on the timestamps of the data.

[0006] These as well as other aspects, advantages, and alternatives, will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying figures.

BRIEF DESCRIPTION OF THE FIGURES

[0007] FIG. **1** illustrates an example computing device.

[0008] FIG. **2** illustrates another example computing device.

[0009] FIGS. **3**A-**3**B are conceptual illustrations of a computing device that show a configuration of some sensors of the computing device in FIG. **2**.

[0010] FIG. **4** is a block diagram of an example method for synchronizing data received from multiple sensors of a device, in accordance with at least some embodiments described herein.

[0011] FIG. **5**A is an example timing diagram conceptually illustrating synchronizing data received from multiple sensors of a device.

[0012] FIG. **5**B is another example timing diagram conceptually illustrating synchronizing data received from multiple sensors of a device.

[0013] FIG. **6** is another example timing diagram conceptually illustrating synchronizing data received from multiple sensors of a device.

DETAILED DESCRIPTION

[0014] The following detailed description describes various features and functions of the disclosed systems and methods with reference to the accompanying figures. In the figures, similar symbols identify similar components, unless context dictates otherwise. The illustrative system and method embodiments described herein are not meant to be limiting. It may be readily understood that certain aspects of the disclosed systems and methods can be arranged and combined in a wide variety of different configurations, all of which are contemplated herein.

[0015] Within examples, methods and systems for synchronizing data received from multiple sensors of a device are described. Example methods may be performed by a device having an application processor configured to function based on an operating system and a co-processor configured to receive data from a plurality of sensors of the device. An example method includes determining an interrupt by a given sensor of a plurality of sensors of the device, and the interrupt is indicative of the given sensor having data for output. The method also includes providing, by a co-processor, a timestamp of the interrupt by the given sensor that is indicative of a time that the given sensor has data for output, and receiving, by the co-processor, the data for output from the given sensor. The method also includes associating the timestamp of the interrupt by the given sensor with the received data from the given sensor, and associating together data received from the plurality of sensors into data structures based on timestamps of the data as provided by the co-processor. The method also includes providing, by the co-processor, the data structures to the application processor in sequence based on the timestamps of the data.

[0016] In some existing devices, sensor data is provided to an application processor and the sensor data receives a timestamp from software executed by the application processor. However, some time elapses between data collection and data timestamp by the software due to transmission of the data over a communication bus between the sensor and the application processor or due to buffering or queuing of data, and thus, timestamps may be inaccurate or not synchronized across all data received from multiple sensors. Within examples presented herein, the co-processor may be configured to provide hardware based timestamps for all sensor data of the device to capture accurate and precise timestamps for data collected or measured by the sensors.

[0017] Referring now to the figures, FIG. **1** illustrates an example computing device **100**. In some examples, components illustrated in FIG. **1** may be distributed across multiple computing devices. However, for the sake of example, the components are shown and described as part of one example computing device **100**. The computing device **100** may be or include a mobile device (such as a mobile phone), desktop computer, laptop computer, email/messaging device, tablet computer, or similar device that may be configured to perform the functions described herein. Generally, the computing device **100** may be any type of computing device or transmitter that is configured to transmit data or receive data in accordance with methods and functions described herein.

[0018] The computing device **100** may include an interface **102**, a wireless communication component **104**, a cellular radio communication component **106**, a global position system (GPS) receiver **108**, sensor(s) **110**, data storage **112**, and processor(s) **114**. Components illustrated in FIG. **1** may be linked together by a communication link **116**. The computing device **100** may also include hardware to enable communication within the computing device **100** and between the computing device **100** and other computing devices (not shown), such as a server entity. The hardware may include transmitters, receivers, and antennas, for example.

[0019] The interface **102** may be configured to allow the computing device **100** to communicate with other computing devices (not shown), such as a server. Thus, the interface **102** may be configured to receive input data from one or more computing devices, and may also be configured to send output data to the one or more computing devices. The interface **102** may be configured to function according to a wired or wireless communication protocol. In some examples, the interface **102** may include buttons, a keyboard, a touchscreen, speaker(s) **118**, microphone(s) **120**, and/or any other elements for receiving inputs, as well as one or more displays, and/or any other elements for communicating outputs.

[0020] The wireless communication component **104** may be a communication interface that is configured to facilitate wireless data communication for the computing device **100** according to one or more wireless communication standards. For example, the wireless communication component **104** may include a Wi-Fi communication component that is configured to facilitate wireless data communication according to one or more IEEE 802.11 standards. As another example, the wireless communication component **104** may include a Bluetooth communication component that is configured to facilitate wireless data communication according to one or more Bluetooth standards. Other examples are also possible.

[0021] The cellular radio communication component **106** may be a communication interface that is configured to facilitate wireless communication (voice and/or data) with a cellular wireless base station to provide mobile connectivity to a network. The cellular radio communication component **106** may be configured to connect to a base station of a cell in which the computing device **100** is located, for example.

[0022] The GPS receiver **108** may be configured to estimate a location of the computing device **100** by precisely timing signals sent by GPS satellites.

[0023] The sensor(s) **110** may include one or more sensors, or may represent one or more sensors included within the computing device **100**. Example sensors include an accelerometer, gyroscope, pedometer, light sensors, microphone, camera(s), infrared flash, barometer, magnetometer, GPS, WiFi, near field communication (NFC), Bluetooth, projector, depth sensor, temperature sensors, or other location and/or context-aware sensors.

[0024] The data storage **112** may store program logic **122** that can be accessed and executed by the processor(s) **114**. The data storage **112** may also store data collected by the sensor(s) **110**, or data collected by any of the wireless communication component **104**, the cellular radio communication component **106**, and the GPS receiver **108**.

[0025] The processor(s) **114** may be configured to receive data collected by any of sensor(s) **110** and perform any number of functions based on the data. As an example, the processor(s) **114** may be configured to determine one or more geographical location estimates of the computing device **100** using one or more location-determination components, such as the wireless communication component **104**, the cellular radio communication component **106**, or the GPS receiver **108**. The processor(s) **114** may use a location-determination algorithm to determine a location of the computing device **100** based on a presence and/or location of one or more known wireless access points within a wireless range of the computing device **100**. In one example, the wireless location component **104** may determine the identity of one or more wireless access points (e.g., a MAC address) and measure an intensity of signals received (e.g., received signal strength indication) from each of the one or more wireless access points. The received signal strength indication (RSSI) from each unique wireless access point may be used to determine a distance from each wireless access point. The distances may then be compared to a database that stores information regarding where each unique wireless access point is located. Based on the distance from each wireless access point, and the known location of each of the wireless access points, a location estimate of the computing device **100** may be determined.

[0026] In another instance, the processor(s) **114** may use a location-determination algorithm to determine a location of the computing device **100** based on nearby cellular base stations. For example, the cellular radio communication component **106** may be configured to identify a cell from which the computing device **100** is receiving, or last received, signal from a cellular network. The cellular radio communication component **106** may also be configured to measure a round trip time (RTT) to a base station providing the signal, and combine this information with the identified cell to determine a location estimate. In another example, the cellular communication component **106** may be configured to use observed time difference of arrival (OTDOA) from three or more base stations to estimate the location of the computing device **100**.

[0027] In some implementations, the computing device **100** may include a device platform (not shown), which may be configured as a multi-layered Linux platform. The device platform may include different applications and an application framework, as well as various kernels, libraries, and runtime entities. In other examples, other formats or operating systems may operate the computing g device **100** as well.

[0028] The communication link **116** is illustrated as a wired connection; however, wireless connections may also be used. For example, the communication link **116** may be a wired serial bus such as a universal serial bus or a parallel bus, or a wireless connection using, e.g., short-range wireless radio technology, or communication protocols described in IEEE 802.11 (including any IEEE 802.11 revisions), among other possibilities.

[0029] The computing device **100** may include more or fewer components. Further, example methods described herein may be performed individually by components of the computing device **100**, or in combination by one or all of the components of the computing device **100**.

[0030] FIG. **2** illustrates another example computing device **200**. The computing device **200** in FIG. **2** may be representative of a portion of the computing device **100** shown in FIG. **1**. In FIG. **2**, the computing device **200** is shown to include a number of sensors such as an inertial measurement unit (IMU) **202** including a gyroscope **204** and an accelerometer **206**, a global shutter (GS) camera **208**, a rolling shutter (RS) camera **210**, a front facing camera **212**, an infrared (IR) flash **214**, a barometer **216**, a magnetometer **218**, a GPS receiver **220**, a WiFi/NFC/Bluetooth sensor **222**, a projector **224**, a depth sensor **226**, and a temperature sensor **228**, each of which outputs to a co-processor **230**. The co-processor **230** receives input from and outputs to an application processor **232**. The computing device **200** may further include a second IMU **234** that outputs directly to the application processor **232**.

[0031] The IMU **202** may be configured to determine a velocity, orientation, and gravitational forces of the computing device **200** based on outputs of the gyroscope **204** and the accelerometer **206**.

[0032] The GS camera **208** may be configured on the computing device **200** to be a rear facing camera, so as to face away from a front of the computing device **200**. The GS camera **208** may be configured to read outputs of all pixels of the camera **208** simultaneously. The GS camera **208** may be configured to have about a 120-170 degree field of view, such as a fish eye sensor, for wide-angle viewing.

[0033] The RS camera **210** may be configured to read outputs of pixels from a top of the pixel display to a bottom of the pixel display. As one example, the RS camera **210** may be a red/green/blue (RGB) infrared (IR) 4 megapixel image sensor, although other sensors are possible as well. The RS camera **210** may have a fast exposure so as to operate with a minimum readout time of about 5.5 ms, for example. Like the GS camera **208**, the RS camera **210** may be a rear facing camera.

[0034] The camera **212** may be an additional camera in the computing device **200** that is configured as a front facing camera, or in a direction facing opposite of the GS camera **208** and the RS camera **210**. The camera **212** may be configured to capture images of a first viewpoint of the computing device **200** and the GS camera **208** and the RS camera **210** may be configured to capture images of a second viewpoint of the device that is opposite the first viewpoint. The camera **212** may be a wide angle camera, and may have about a 120-170 degree field of view for wide angle viewing, for example.

[0035] The IR flash **214** may provide a light source for the computing device **200**, and may be configured to output light in a direction toward a rear of the computing device **200** so as to provide light for the GS camera **208** and RS camera **210**, for example. In some examples, the IR flash **214** may be configured to flash at a low duty cycle, such as 5 Hz, or in a non-continuous manner as directed by the co-processor **230** or application processor **232**. The IR flash **214** may include an LED light source configured for use in mobile devices, for example.

[0036] FIGS. **3A-3B** are conceptual illustrations of a computing device **300** that show a configuration of some sensors of the computing device **200** in FIG. **2**. In FIGS. **3A-3B**, the computing device **300** is shown as a mobile phone. The computing device **300** may be similar to either of computing device **100** in FIG. **1** or computing device **200** in FIG. **2**. FIG. **3A** illustrates a front of the computing device **300** in which a display **302** is provided, along with a front facing camera **304**, and a P/L sensor opening **306** (e.g., a proximity or light sensor). The front facing camera **304** may be the camera **212** as described in FIG. **2**.

[0037] FIG. **3B** illustrates a back **308** of the computing device **300** in which a rear camera **310** and another rear camera **314** are provided. The rear camera **310** may be the RS camera **210** and the rear camera **312** may be the GS camera **208**, as described in the computing device **200** in FIG. **2**. The back **308** of the computing device **300** also includes an IR-flash **314**, which may be the IR flash **214** or the projector **224** as described in the computing device **200** in FIG. **2**. In one example, the IR flash **214** and the projector **224** may be one in the same. For instance, a single IR flash may be used to perform the functions of the IR flash **214** and the projector **224**. In another example, the computing device **300** may include a second flash (e.g., an LED flash) located near the rear camera **310** (not shown). A configuration and placement of the sensors may be helpful to provide desired functionality of the computing device **300**, for example, however other configurations are possible as well.

[0038] Referring back to FIG. **2**, the barometer **216** may include a pressure sensor, and may be configured to determine air pressures and altitude changes.

[0039] The magnetometer **218** may be configured to provide roll, yaw, and pitch measurements of the computing device **200**, and can be configured to operate as an internal compass, for example. In some examples, the magnetometer **218** may be a component of the IMU **202** (not shown).

[0040] The GPS receiver **220** may be similar to the GPS receiver **108** described in the computing device **100** of FIG. **1**. In further examples, the GPS **220** may also output timing signals as received from GPS satellites or other network entities. Such timing signals may be used to synchronize collected data from sensors across multiple devices that include the same satellite timestamps.

[0041] The WiFi/NFC/Bluetooth sensor **222** may include wireless communication components configured to operate according to WiFi and Bluetooth standards, as discussed above with the computing device **100** of FIG. **1**, and according to NFC standards to establish wireless communication with another device via contact or coming into close proximity with the other device.

[0042] The projector **224** may be or include a structured light projector that has a laser with a pattern generator to produce a dot pattern in an environment. The projector **224** may be configured to operate in conjunction with the RS camera **210** to recover information regarding depth of objects in the environment, such as three-dimensional (3D) characteristics of the objects. For example, the separate depth sensor **226** may be configured to capture video data of the dot pattern in 3D under ambient light conditions to sense a range of objects in the environment. The projector **224** and/or depth sensor **226** may be configured to determine shapes of objects based on the projected dot pattern. By way of example, the depth sensor **226** may be configured to cause the projector **224** to produce a dot pattern and cause the RS camera **210** to capture an image of the dot pattern. The depth sensor **226** may then process the image of the dot pattern, use various algorithms to triangulate and extract 3D data, and output a depth image to the co-processor **230**.

[0043] The temperature sensor **228** may be configured to measure a temperature or temperature gradient, such as a change in temperature, for example, of an ambient environment of the computing device **200**.

[0044] The co-processor **230** may be configured to control all sensors on the computing device **200**. In examples, the co-processor **230** may control exposure times of any of cameras **208**, **210**, and **212** to match the IR flash **214**, control the projector **224** pulse sync, duration, and intensity, and in general, control data capture or collection times of the sensors. The co-processor **230** may also be configured to process data from any of the sensors into an appropriate format for the application processor **232**. In some examples, the co-processor **230** merges all data from any of the sensors that corresponds to a same timestamp or data collection time (or time period) into a single data structure to be provided to the application processor **232**.

[0045] The application processor **232** may be configured to control other functionality of the computing device **200**, such as to control the computing device **200** to operate according to an operating system or any number of software applications stored on the computing device **200**. The application processor **232** may use the data collected by the sensors and received from the co-processor to perform any number of types of functionality. The application processor **232** may receive outputs of the co-processor **230**, and in some examples, the application processor **232** may receive raw data outputs from other sensors as well, including the GS camera **208** and the RS camera **210**.

[0046] The second IMU **234** may output collected data directly to the application processor **232**, which may be received by the application processor **232** and used to trigger other sensors to begin collecting data. As an example, outputs of the second IMU **234** may be indicative of motion of the computing device **200**, and when the computing device **200** is in motion, it may be desired to collect image data, GPS data, etc. Thus, the application processor **232** can trigger other sensors through communication signaling on common buses to collect data at the times at which the outputs of the IMU **234** indicate motion.

[0047] The computing device **200** shown in FIG. **2** may include a number of communication buses between each of the sensors and processors. For example, the co-processor **230** may communicate with each of the IMU **202**, the GS camera **208**, and the RS camera **212** over an inter-integrated circuit (I2C) bus that includes a multi-master serial single-ended bus for communication. The co-processor **230** may receive raw data collected, measured, or detected by each of the IMU **202**, the GS camera **208**, and the RS camera **212** over the same I2C bus or a separate communication bus. The co-processor **230** may communicate with the application processor **232** over a number of communication buses including a serial peripheral interface (SPI) bus that includes a synchronous serial data link that may operate in full duplex mode, the I2C bus, and a mobile industry processor interface (MIPI) that includes a serial interface configured for communicating camera or pixel information. Use of various buses may be determined based on need of speed of communication of data as well as bandwidth provided by the respective communication bus, for example.

[0048] FIG. **4** is a block diagram of an example method for synchronizing data received from multiple sensors of a device, in accordance with at least some embodiments described herein. Method **400** shown in FIG. **4** presents an embodiment of a method that, for example, could be used with the computing device **100** in FIG. **1**, the computing device **200** in FIG. **2**, or the computing device **300** in FIG. **3**, for example, or may be performed by a combination of any components of the computing device **100** in FIG. **1**, the computing device **200** in FIG. **2**, or the computing device **300** in FIG. **3**. Method **400** may include one or more operations, functions, or actions as illustrated by one or more of blocks **402-412**. Although the blocks are illustrated in a sequential order, these blocks may in some instances be performed in parallel, and/or in a different order than those described herein. Also, the various blocks may be combined into fewer blocks, divided into additional blocks, and/or removed based upon the desired implementation.

[0049] In addition, for the method **400** and other processes and methods disclosed herein, the flowchart shows functionality and operation of one possible implementation of present embodiments. In this regard, each block may represent a module, a segment, or a portion of program code, which includes one or more instructions executable by a processor for implementing specific logical functions or steps in the process. The program code may be stored on any type of computer readable medium, for example, such as a storage device including a disk or hard drive. The computer readable medium may include a non-transitory computer readable medium, for example, such as computer-readable media that stores data for short periods of time like register memory, processor cache and Random Access Memory (RAM). The computer readable medium may also include other non-transitory media, such as secondary or persistent long term storage, like read only memory (ROM), optical or magnetic disks, compact-disc read only memory (CD-ROM), for example. The computer readable media may also be any other volatile or non-volatile storage systems. The computer readable medium may be considered a computer readable storage medium, a tangible storage device, or other article of manufacture, for example. The program code (or data for the code) may also be stored or provided on other media including communication media, such as a wireless communication media, for example.

[0050] In addition, for the method **400** and other processes and methods disclosed herein, each block in FIG. **4** may represent circuitry that is wired to perform the specific logical functions in the process.

[0051] Functions of the method **400** may be fully performed by a computing device, or may be distributed across multiple computing devices and/or a server. In some examples, the computing device may receive information from sensors of the computing device, or where the computing device is a server the information can be received from another device that collects the information. The computing device could further communicate with a server to receive information from sensors of other devices, for example. The method **400** may further be performed by a device that has an application processor configured to function based on an operating system and a co-processor configured to receive data from a plurality of sensors of the device. The sensors may include any sensors as described above in any of FIG. **1**, FIG. **2**, or FIGS. **3**A-**3**B, for example, including an IMU, a global shutter camera, a rolling shutter camera, a structured light projector, a depth camera, an infrared flash, a barometer, a magnetometer, and a temperature sensor.

[0052] At block **402**, the method **400** includes determining an interrupt by a given sensor of the plurality of sensors of the device. The interrupt is indicative of the given sensor having data for output. As an example, the co-processor may receive a signal from the sensor indicating the interrupt, such as a signal including a flag set to true. The sensor may send the signal once the sensor has data for output, for example, after performing a sensing function. A sensor may have data for output based on the sensor performing data collection internally, or based on being triggered to perform a data collection.

[0053] At block **404**, the method **400** includes providing, by the co-processor, a timestamp of the interrupt by the given sensor that is indicative of a time that the given sensor has data for output. For instance, at the time the co-processor determines the interrupt, the co-processor generates a timestamp for the interrupt, and stores the timestamp with the interrupt, and with other metadata indicating the sensor providing the interrupt. In this way, the co-processor marks an exact time at which the sensor collected data.

[0054] As another example, for cameras, an image capture may not occur at a discrete point in time due to image capture requiring time to expose an image. It may be desired to determine a timestamp of the image that corresponds to a beginning, middle, or ending of the exposure. For an RS camera, for example, which exposes from top to bottom, a top portion of the image occurs earlier in time than a bottom portion of the image, and the image may be associated with only one timestamp, and so the co-processor can generate a timestamp at a center exposure time to minimize a time difference between a top and bottom portion of the image. The co-processor may know an exposure time of the camera and can generate the timestamp to be at a center exposure time based on an average of exposure times of the camera once triggered to capture an image, for example.

[0055] At block **406**, the method **400** includes receiving, by the co-processor, the data for output from the given sensor. Thus, after generating the timestamp, the co-processor can retrieve the data from the sensor. The data may be provided from the sensor to the co-processor along any number of communication buses within the computing device. The data transmission can occur over a time period, e.g., about 10-30 ms. Thus, the co-processor can request the data from the sensor that corresponds to the interrupt. Timestamping and data retrieval are performed separately because a query for sensor data may be slow and take time, and accurate timestamps may be required for data processing. Thus, the interrupt is used as a flag to generate the timestamp, and then a data fetch is subsequently performed.

[0056] At block **408**, the method **400** includes associating the timestamp of the interrupt by the given sensor with the received data from the given sensor. In this manner, the co-processor can associate a time at which the data was collected by the sensor with the data, rather than associating a time of receipt of the data at the co-processor as the data collection time. Since the data transmission from the sensor to the co-processor consumes some time, an exact timestamp at time of data collection by the sensor is provided based on the timestamp of the previously received interrupt.

[0057] At block **410**, the method **400** includes associating together data received from the plurality of sensors into data structures based on timestamps of the data as provided by the co-processor. For example, the co-processor may receive data from many sensors of the device, and the data can be organized based on timestamps generated for interrupts as provided by the co-processor. For data received by the co-processor from sensors and associated with an interrupt timestamp of the same time, such data can be associated together or formatted together into one data structure.

[0058] The data can be formatted into any number of types of data structures. In one example, the data may be stored into one file indicating a type of data, a sensor that collected the data, and a timestamp for the data. In another example, the data can be formatted into an image frame format data structure, where data is stored as pixel values for the given timestamp. The image frame format may take the form of a transport datatype of "RGB" or "YUV" for traditional transmission across a camera interface.

[0059] At block **412**, the method **400** includes providing, by the co-processor, the data structures to the application processor in sequence based on the timestamps of the data. The application processor may then receive the data in sequence as the data is collected.

[0060] Within examples, using the method **400** in FIG. **4**, accurate timing of data collection by sensors is provided based on timestamps provided by the co-processor that is dedicated to timestamp/synchronize all sensor data. Functionality performed based on the synchronized sensor data may be performed by the application processor. All sensor data is synchronized based on the same time clock since all data is timestamped by the same co-processor that runs according to a master clock so as to provide a hardware level time synchronization. In addition, the timestamp is generated based on the interrupt, and so the timestamp is the time of data collection by the sensor rather than the time of data receipt at the co-processor.

[0061] In some examples, the method **400** may further include providing, by the co-processor, data received from an IMU to the application processor prior to associating together the data received from the plurality of sensors into the data structures, and subsequently providing the data structures to the application processor. An IMU may collect data at a higher frequency than other sensors, and the IMU data may be more useful to the application processor than other data. Thus, the co-processor can generate timestamps for IMU data, retrieve the IMU data, and immediately provide the IMU data to the application processor ahead of other data associated with the same timestamp so that the application processor can have the data to perform time-sensitive functions.

[0062] The computing device may include a bus for communication between the application processor and the co-processor, and another bus for communication between the co-processor and the sensors that has a latency less than communication on between the application processor and the co-processor. In some instances, the co-processor may receive data from the IMU and provide the data to the application processor on the same bus so as to provide the data more quickly to the application processor. The bus may be an SPI bus as a fast low-latency communication channel for IMU data. The data structures, which are a larger amount of data, can then be assembled and provided to application processor on the I2C bus, for example, which allows for larger bandwidths of data transmission. The application processor may benefit by receiving the IMU data alone quickly, for example.

[0063] In further examples, the device may include multiple cameras the co-processor may provide a trigger signal to a first camera requesting data output from the first camera. The trigger signal can be received by other cameras of the device via the first camera, so as to cause capture of images in synchrony. As examples, one camera may be an RS camera and another camera may be a GS camera. The trigger signal can be provided to the GS camera at about a center exposure time of the RS camera so as to cause exposure of the GS camera at about the center exposure time of the RS camera.

[0064] The sensors may also include a red-green-blue (RGB) camera and an infrared (IR) sensor. The IR sensor may be configured to output data at a frequency that is less than an output frequency of the RGB camera. Thus, when associating together data form the sensors, data output by the IR sensor can be interleaved within data output by the RGB camera based on timestamps of the respective data as provided by the co-processor. As an example, about four frames of image data may be received from the camera for every one frame of depth data from the IR sensor.

[0065] In further examples, sensors may output data at a first frequency data can be associated together by the co-processor into data structures at a second frequency that is less than the first frequency. For example, data may be output by the sensors faster than a camera framerate used to transmit data, and thus, the co-processor may provide most recent IMU data samples (which may be configured to run at 120 Hz) within the data structure at a slower frequency so as to provide multiple samples of IMU data within one data structure.

[0066] In some examples, the sensors may include a buffer to store recently collected data, and the sensors may provide current data collected as well as previous data for output to the co-processor. The previous data may be redundant data received for error correction, since the previous data was likely received previously by the co-processor. For instance, the IMU may have a running buffer of redundant IMU data, and instead of just pulling latest data from the IMU, the co-processor can collect all data from the buffer to receive a most recent X number of samples from the IMU. If a frame of data is ever missed or corrupted during data transmission, the redundant data received by the co-processor received in a next frame of data can be used to fill in missing data. As an example, if the computing device were rotating 30 degrees per second, and a frame of data was missed, an exact location and orientation of the computing device may not be known (i.e., the location/orientation estimate may be now a few degrees off from where the device is actually located). By providing redundant data, lost or missing data from the IMU can be identified to make corrections to any location/orientation estimates of the device.

[0067] FIG. **5**A is an example timing diagram conceptually illustrating synchronizing data received from multiple sensors of a device. As shown, a sensor **502** may provide an interrupt to a co-processor **504**, at which time the co-processor **504** will generate a timestamp. A number of sensors may provide interrupts to the co-processor **504** simultaneously or at various intervals, and upon receipt of an interrupt, the co-processor **504** will generate an associated timestamp. The co-processor **504** may then request the data from the sensor **502** corresponding to the interrupt, and subsequently receive the data from the sensor **502**. In other examples, the co-processor **504** may not need to request the data from the sensor **502** as the sensor **502** will provide the data after providing an interrupt. Upon receipt of the sensor data, the co-processor may associate the timestamp with the respective data by matching interrupt timestamps to corresponding sensor data, and then combine sensor data per timestamp into a single data structure per timestamp. The co-processor **504** may subsequently provide the data structures to an application processor **506** in sequence.

[0068] FIG. **5**B is another example timing diagram conceptually illustrating synchronizing data received from multiple sensors of a device. In FIG. **5**B, the sensor **502** may provide an interrupt to the co-processor **504**, at which time the co-processor **504** will generate a timestamp. A number of sensors may provide interrupts to the co-processor **504** simultaneously or at various intervals, and upon receipt of an interrupt, the co-processor **504** will generate an associated timestamp. The co-processor **504** may then request the data from the sensor **502** corresponding to the interrupt, and subsequently the sensor **502** may forward the data to the application processor **508**. The co-processor **504** may then send the timestamp data to the application processor **508**. Upon receipt of the data, the application processor **508** may associate the timestamp with the respective data by matching interrupt timestamps to corresponding sensor data, and then combine sensor data per timestamp into a single data structure per timestamp.

[0069] FIG. **6** is another example timing diagram conceptually illustrating synchronizing data received from multiple sensors of a device. In FIG. **6**, two timelines are shown that correspond to a timeline of data output by an IMU, and a time axis of a co-processor. The IMU may output data at intervals as shown along the IMU data time axis. Each IMU data packet is timestamped with respect to the co-processor time axis based on a data ready interrupt provided by the IMU to the co-processor.

[0070] Example RS exposure and GS exposure times for an RS camera and GS camera are shown along the co-processor time axis as well. Since the RS exposure occurs from a top to a bottom of the image, the exposure is over a longer time period than exposure of the GS camera. The RS camera may operate at a frequency of 30 Hz, for example. A GS camera trigger time is set to coincide with an exposure of the center scanline of the RS camera so that centers of the GS camera and RS camera exposures are time aligned. For example, the RS camera may require 30 ms to capture an image, and the GS camera may only require 20 ms, and thus, the GS trigger time can be set to be 5 ms after the RS exposure time so that the centers of the GS camera and RS camera exposure times are aligned. The trigger time for the GS camera may then be as follows

$$GS\text{ Trigger time}=RS\text{ exposure start time}+\tfrac{1}{2}\,RS\text{ exposure time}-\tfrac{1}{2}\,GS\text{ exposure time}$$

[0071] The center scanline of the cameras is the timestamp produced for the camera images by the co-processor as determined from a timestamped end of a camera readout and subtracting a deterministic readout and exposure time for the frame, for example.

[0072] The co-processor captures data from both cameras and IMU in a synchronized manner, and then combines the data into a data structure to be provided to an application processor. The data structures may be in an image frame format. FIG. **6** illustrates that a single frame includes an image from the RS camera, an image from the GS camera, and about four to five outputs from the IMU. Since the IMU runs faster than the cameras, the IMU data will be accumulated more quickly and can be provided separately to the application processor for immediate use, for example.

[0073] Thus, IMU data may be recorded as soon as a packet is ready and time stamped at a frame rate of the IMU (i.e., if the IMU is set at 100 Hz mode, then IMU packets may be read-out at 100 Hz, and corresponding co-processor timestamps on the IMU packets can occur at 100 Hz). The IMU data may then be time-aligned with an image frame in which the IMU data is packed. In examples, a first IMU data packet in a frame corresponds with an image trigger time of the GS camera. In other examples, the table below shows a sample set of images and IMU data packed into frames when the camera is running at 30 Hz (approximated as 33 ms delta t in the table), and the IMU is running at 120 Hz (approximated as 8 ms delta t in the table).

Image frame 1 (GS): ts 0 ms	Image frame 2 (GS): ts 33 ms	Image frame 3 (GS): ts 66 ms	Image frame 4 (GS): ts 99 ms
IMU pkt 1: ts 3 ms	IMU pkt 5: ts 35 ms	IMU pkt 9: ts 67 ms	IMU pkt 13: ts 99 ms
IMU pkt 2: ts 11 ms	IMU pkt 6: ts 43 ms	IMU pkt 10: ts 75 ms	IMU pkt 14: ts 107 ms
IMU pkt 3: ts 19 ms	IMU pkt 7: ts 51 ms	IMU pkt 11: ts 83 ms	IMU pkt 15: ts 115 ms
IMU pkt 4: ts 27 ms	IMU pkt 8: ts 59 ms	IMU pkt 12: ts 91 ms	IMU pkt 16: ts 123 ms

[0074] Both the RS camera and the GS camera may be time stamped with respect to the co-processor time axis at a beginning of their respective exposure. Both the RS camera and the GS camera exposure times are also recorded to compute a beginning, middle, and end of exposure.

[0075] In further examples, image frames may include additional data as well, such as data from previous frames. As an example, frame **2** may include all data for frame **2** as well as all data within frame **1**, and the redundancy of resending data from frame **1** within frame **2** can be used for error correction or data verifications.

[0076] Within examples described herein, data output from sensors can be associated with an exact timestamp of the data corresponding to the time the data was collected by the sensors, and data from multiple sensors can be synchronized into data structures. In some examples, this enables synchronization of data indicating motion of the device (e.g., data output by a gyroscope) with camera images. Sensor data from all sensors of a device can be accurately synchronized to take a readout of the sensors and match data from all sensors that was collected at the same time together into a data structure without any software timestamp delays or inaccuracies, for example.

[0077] It should be understood that arrangements described herein are for purposes of example only. As such, those skilled in the art will appreciate that other arrangements and other elements (e.g. machines, interfaces, functions, orders, and groupings of functions, etc.) can be used instead, and some elements may be omitted altogether according to the desired results. Further, many of the elements that are described are functional entities that may be implemented as discrete or distributed components or in conjunction with other components, in any suitable combination and location, or other structural elements described as independent structures may be combined.

[0078] While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope being indicated by the following claims, along with the full scope of equivalents to which such claims are entitled. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting.

What is claimed is:

1. A method performed by a device having an application processor configured to function based on an operating system and a co-processor configured to receive data from a plurality of sensors of the device, the method comprising:

determining an interrupt by a given sensor of the plurality of sensors of the device, wherein the interrupt is indicative of the given sensor having data for output;

providing, by the co-processor, a timestamp of the interrupt by the given sensor that is indicative of a time that the given sensor has data for output;

receiving, by the co-processor, the data for output from the given sensor;

associating the timestamp of the interrupt by the given sensor with the received data from the given sensor;

associating together data received from the plurality of sensors into data structures based on timestamps of the data as provided by the co-processor; and

providing, by the co-processor, the data structures to the application processor in sequence based on the timestamps of the data.

2. The method of claim **1**, further comprising wherein the data structures comprise an image frame format.

3. The method of claim **1**, wherein one of the plurality of sensors comprises an inertial measurement unit (IMU), and wherein the method further comprises:

providing, by the co-processor, data received from the IMU to the application processor prior to associating together the data received from the plurality of sensors into the data structures; and

subsequently providing the data structures to the application processor.

4. The method of claim **1**, wherein the device includes a first bus for communication between the application processor and the co-processor, and a second bus for communication between the co-processor and the plurality of sensors, wherein the second bus is configured for communication having a latency less than communication on the first bus, and wherein the method further comprises:

providing, by the co-processor, data received from an inertial measurement unit (IMU) of the plurality of sensors to the application processor via the second bus; and

providing, by the co-processor, the data structures to the application processor via the first bus.

5. The method of claim **1**, further comprising receiving previous data for output by the given sensor from a buffer of the given sensor in addition to the data for output from the given sensor, wherein the previous data is redundant data received for error correction.

6. The method of claim **5**, wherein the given sensor is configured to output data at a first frequency, and the method further comprises:

associating together, by the co-processor, data received from the plurality of sensors into data structures at a second frequency, wherein the first frequency is greater than the second frequency; and

providing the received previous data for output from the buffer of the given sensor in the data structures.

7. The method of claim **1**, wherein the plurality of sensors of the device includes multiple cameras, and wherein the method further comprises:

providing, by the co-processor, a trigger signal to a first camera of the multiple cameras, wherein the trigger signal requests data output from the first camera, wherein the trigger signal is received by other cameras of the multiple cameras via the first camera, so as to cause capture of images in synchrony.

8. The method of claim **7**, wherein the first camera is a rolling shutter camera and a second camera is a global shutter camera, and the method further comprises:

providing the trigger signal to the second camera at about a center exposure time of the first camera so as to cause exposure of the second camera at about the center exposure time of the first camera.

9. The method of claim **1**, wherein the plurality of sensors include a red-green-blue (RGB) camera and an infrared (IR) sensor, and wherein the RGB camera is configured to output data at a first frequency and the IR sensor is configured to output data at a second frequency that is less than the first frequency, and the method further comprises:

interleaving data output by the IR sensor within data output by the RGB camera based on timestamps of the respective data as provided by the co-processor.

10. The method of claim **1**, wherein the plurality of sensors include an inertial measurement unit (IMU), a global shutter camera, a rolling shutter camera, a structured light projector, a depth camera, an infrared flash, a barometer, a magnetometer, and a temperature sensor.

11. The method of claim **1**, wherein the plurality of sensors includes three cameras, wherein a first camera is a front facing camera, and a second camera and a third camera are each rear facing cameras, wherein the front facing camera is configured to capture images of a first viewpoint of the device and the rear facing cameras are configured to capture images of a second viewpoint of the device that is opposite the first viewpoint.

12. The method of claim **1**, wherein the given sensor includes a GPS sensor configured to output data indicative of a location of the device and a timestamp of the location as received from network entity, and the method further comprising:

associating the location and the timestamp into a given data structure based on the timestamp of the location as received from the network entity.

13. A computer readable memory configured to store instructions that, when executed by a device having an application processor configured to function based on an operating system and a co-processor configured to receive data from a plurality of sensors of the device, cause the device to perform functions comprising:

determining an interrupt by a given sensor of the plurality of sensors of the device, wherein the interrupt is indicative of the given sensor having data for output;

providing, by the co-processor, a timestamp of the interrupt by the given sensor that is indicative of a time that the given sensor has data for output;

receiving, by the co-processor, the data for output from the given sensor;

associating the timestamp of the interrupt by the given sensor with the received data from the given sensor;

associating together data received from the plurality of sensors into data structures based on timestamps of the data as provided by the co-processor; and

providing, by the co-processor, the data structures to the application processor in sequence based on the timestamps of the data.

14. The computer readable memory of claim **13**, wherein one of the plurality of sensors comprises an inertial measurement unit (IMU), and wherein the function further comprise:

providing, by the co-processor, data received from the IMU to the application processor prior to associating together the data received from the plurality of sensors into the data structures; and

subsequently providing the data structures to the application processor.

15. The computer readable memory of claim **13**, wherein the functions further comprise:

receiving previous data for output by the given sensor from a buffer of the given sensor in addition to the data for output from the given sensor, wherein the previous data is redundant data received for error correction; and

associating together, by the co-processor, the received previous data for output from the buffer of the given sensor in the data structures.

16. The computer readable memory of claim **13**, wherein the plurality of sensors of the device includes a rolling shutter camera and a global shutter camera, and the functions further comprise:

providing, by the co-processor, a trigger signal to the rolling shutter camera at about a center exposure time of the rolling shutter camera, wherein the trigger signal requests data output from the rolling shutter camera,

wherein the trigger signal is received by the global shutter camera via the rolling shutter camera so as to cause capture of images by the rolling shutter camera and the global shutter camera at about the center exposure time of the rolling shutter camera.

17. The computer readable memory of claim **13**, wherein the plurality of sensors include a red-green-blue (RGB) camera and an infrared (IR) sensor, and wherein the RGB camera is configured to output data at a first frequency and the IR sensor is configured to output data at a second frequency that is less than the first frequency, and the functions further comprise:

interleaving data output by the IR sensor within data output by the RGB camera based on timestamps of the respective data as provided by the co-processor.

18. A device comprising:

an application processor configured to function based on an operating system;

a plurality of sensors; and

a co-processor configured to receive data from the plurality of sensors, and wherein the co-processor is configured to perform functions comprising:

determine an interrupt by a given sensor of the plurality of sensors, wherein the interrupt is indicative of the given sensor having data for output;

provide a timestamp of the interrupt by the given sensor that is indicative of a time that the given sensor has data for output;

receive the data for output from the given sensor;

associate the timestamp of the interrupt by the given sensor with the received data from the given sensor;

associate together data received from the plurality of sensors into data structures based on timestamps of the data as provided by the co-processor; and

provide the data structures to the application processor in sequence based on the timestamps of the data.

19. The device of claim **18**, wherein the co-processor is configured to associate together the data received from the plurality of sensors into the data structures having an image frame format.

20. The device of claim **18**, wherein one of the plurality of sensors comprises an inertial measurement unit (IMU), and wherein the co-processor is further configured to:

provide data received from the IMU to the application processor prior to associating together the data received from the plurality of sensors into the data structures; and

subsequently providing the data structures to the application processor.

21. The device of claim **18**, further comprising:

a first bus for communication between the application processor and the co-processor; and

a second bus for communication between the co-processor and the plurality of sensors, wherein the second bus is configured for communication having a latency less than communication on the first bus, and

wherein the co-processor is configured to provide data received from an inertial measurement unit (IMU) of the plurality of sensors to the application processor via the second bus and provide the data structures to the application processor via the first bus.

22. A method performed by a device having an application processor configured to function based on an operating system and a co-processor configured to receive data from a plurality of sensors of the device, the method comprising:

determining an interrupt by a given sensor of the plurality of sensors of the device, wherein the interrupt is indicative of the given sensor having data for output;

providing, by the co-processor, a timestamp of the interrupt by the given sensor that is indicative of a time that the given sensor has data for output;

providing, by the co-processor, the timestamp to the application processor;

receiving, by the application -processor, the data for output from the given sensor;

associating the timestamp of the interrupt by the given sensor with the received data from the given sensor; and

associating together data received from the plurality of sensors into data structures based on timestamps of the data as provided by the co-processor.

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