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(54) **WEB SERVICES FOR SMART ENTITY MANAGEMENT FOR SENSOR SYSTEMS**

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None
See application file for complete search history.

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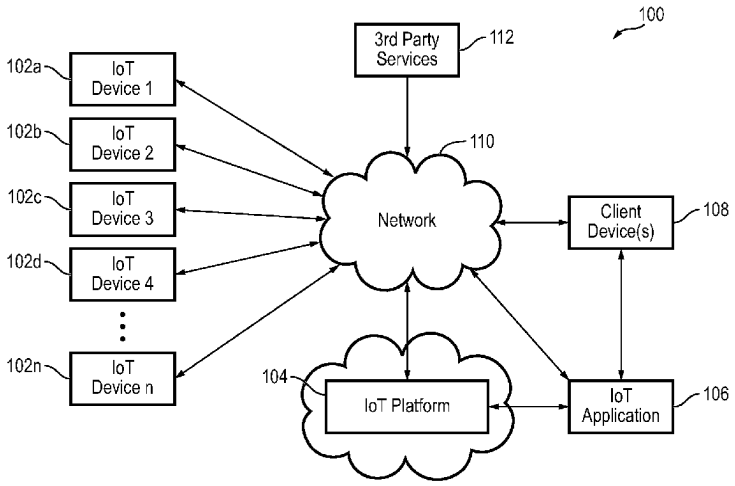
(57) **ABSTRACT**

One or more non-transitory computer readable media contain program instructions that, when executed by one or more processors, cause the one or more processors to perform operations including generating a database of interconnected smart entities. The smart entities include sensor object entities representing each of the plurality of sensors and data entities representing measurements received from the sensors. The smart entities are interconnected by relational objects indicating relationships between the smart entities. The instructions cause the one or more processors to receive a new measurement from a first sensor, identify a first data entity from a relational object for the first sensor, the first data entity including a plurality of past measurements received from the first sensor, and modify the first data entity within the database of smart entities to include the new measurement received from the first sensor.

19 Claims, 8 Drawing Sheets



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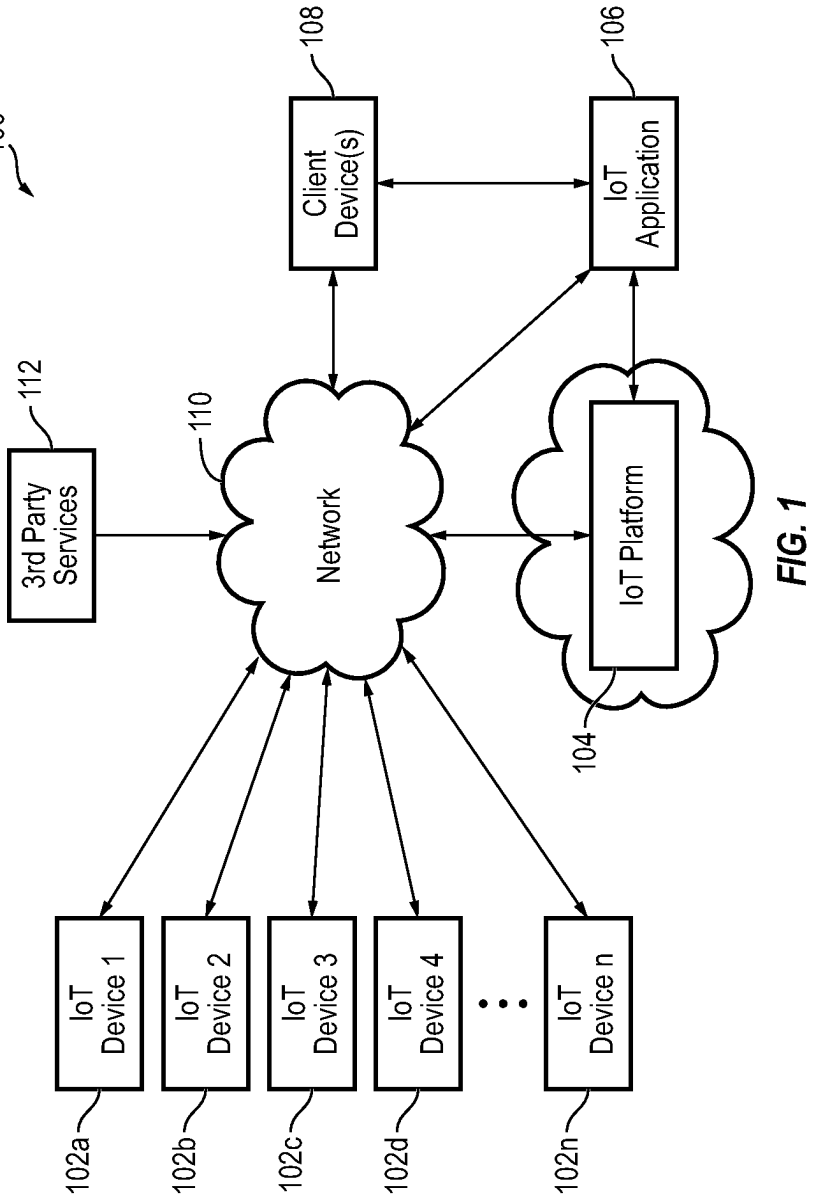
100
108
Client Device(s)
106
IoT Application
112
3rd Party Services
110
Network
IoT Platform
104
IoT Device 1
IoT Device 2
IoT Device 3
IoT Device 4
IoT Device n
102a
102b
102c
102d
102n

FIG. 1

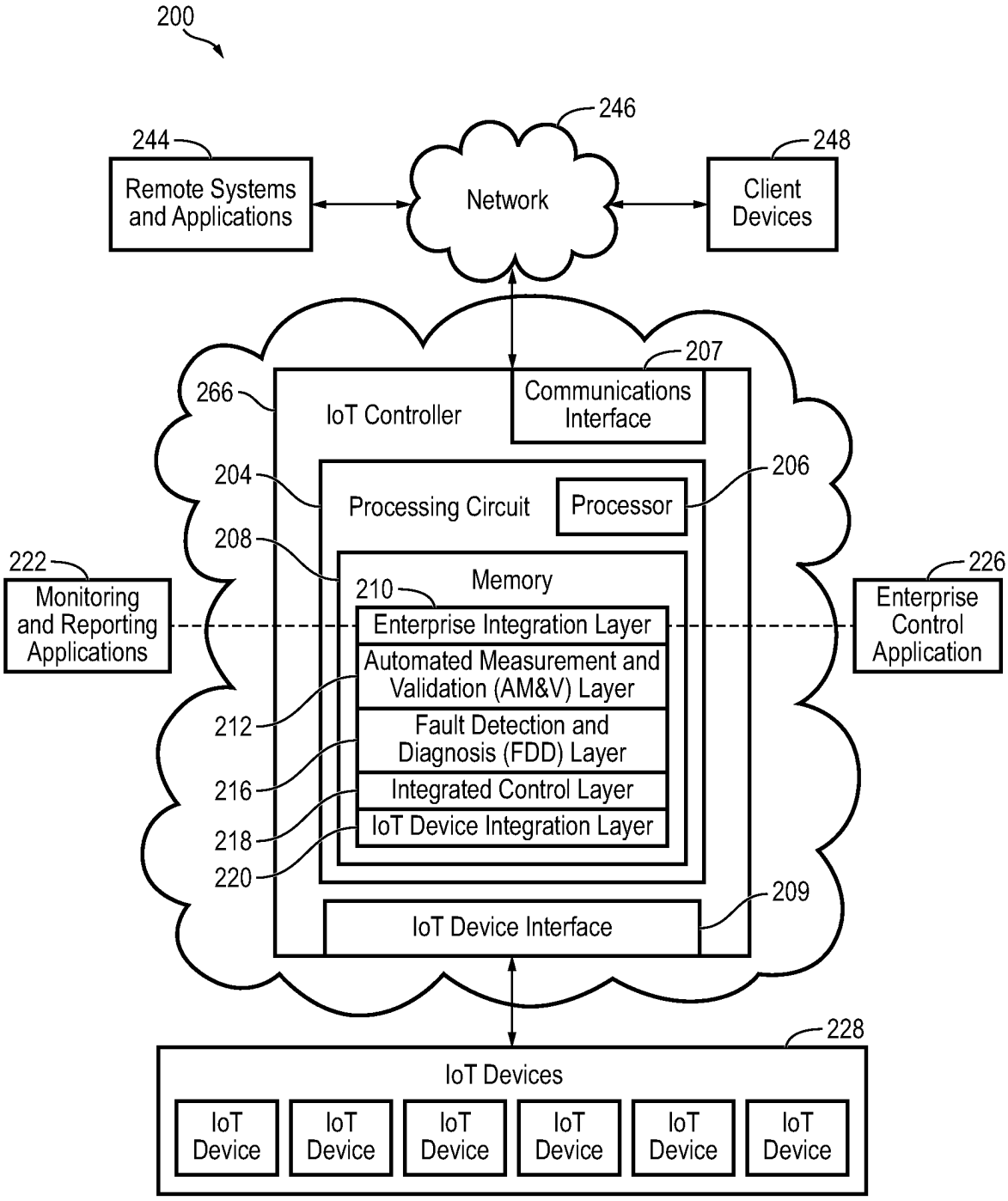
200
246
244
Remote Systems and Applications
Network
248
Client Devices
207
266
IoT Controller
Communications Interface
204
Processing Circuit
Processor
206
208
222
Monitoring and Reporting Applications
Memory
210
226
Enterprise Control Application
Enterprise Integration Layer
Automated Measurement and Validation (AM&V) Layer
212
Fault Detection and Diagnosis (FDD) Layer
216
Integrated Control Layer
218
IoT Device Integration Layer
220
209
IoT Device Interface
228
IoT Devices
IoT Device
IoT Device
IoT Device
IoT Device
IoT Device
IoT Device

FIG. 2

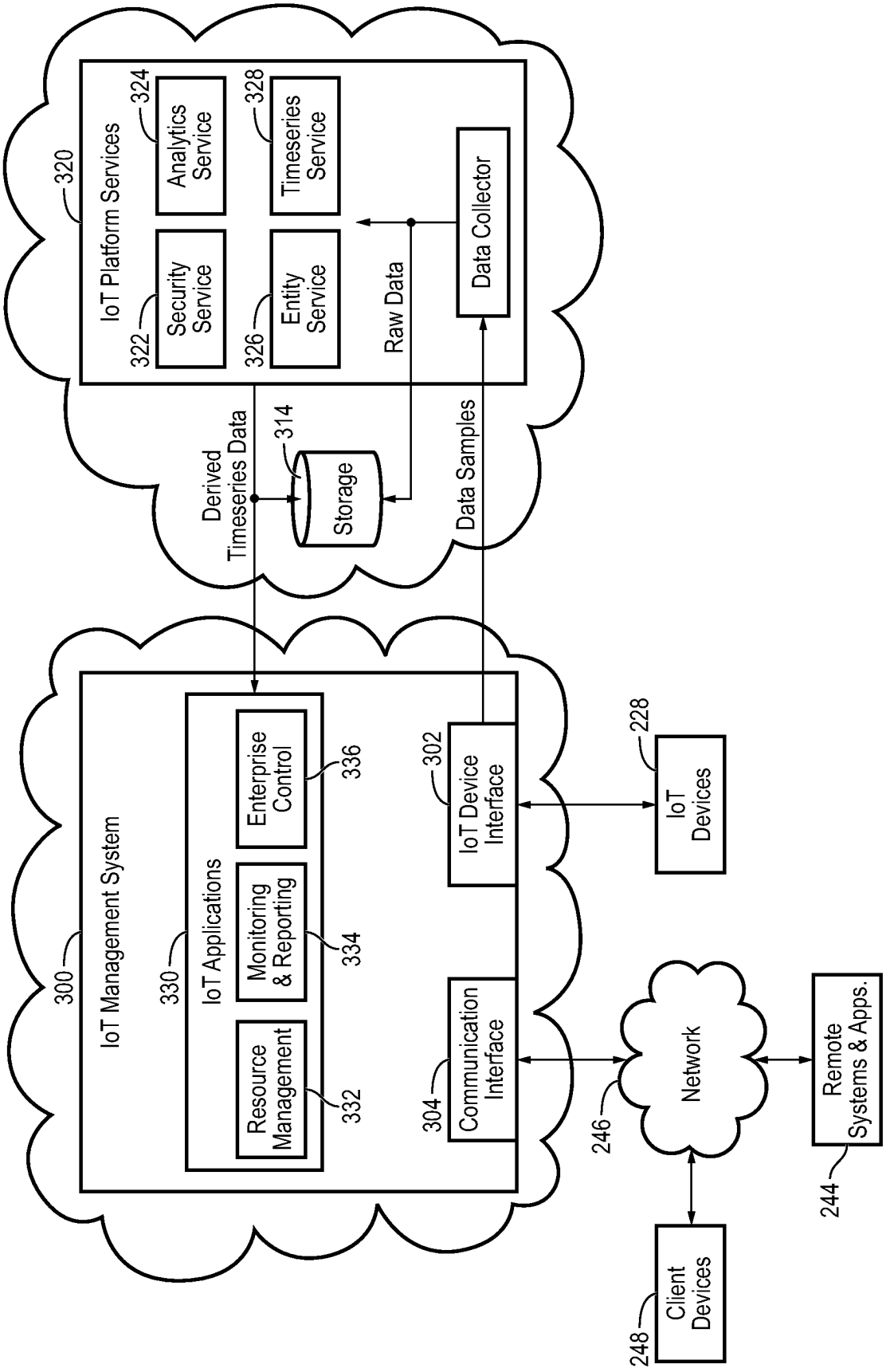
IoT Platform Services
320
Analytics Service
324
Timeseries Service
328
Security Service
322
Entity Service
326
Raw Data
Data Collector
Derived Timeseries Data
314
Storage
Data Samples
IoT Management System
300
IoT Applications
330
Enterprise Control
336
Monitoring & Reporting
334
Resource Management
332
IoT Device Interface
302
IoT Devices
228
Communication Interface
304
Network
246
Remote Systems & Apps.
244
Client Devices
248

FIG. 3

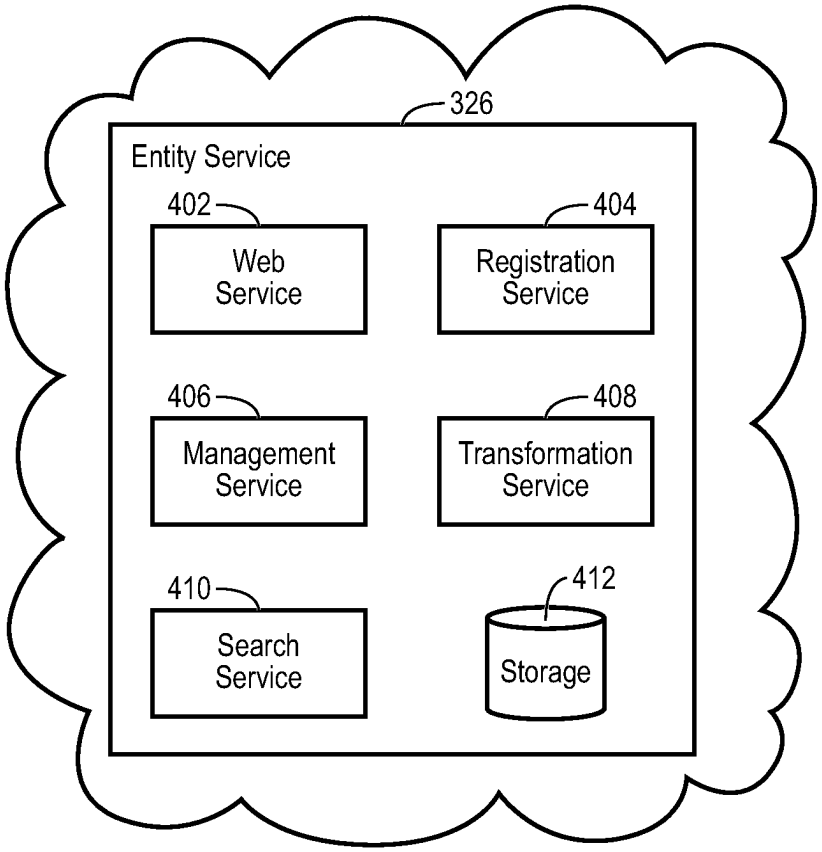
326
Entity Service
402
Web Service
404
Registration Service
406
Management Service
408
Transformation Service
410
Search Service
412
Storage

FIG. 4

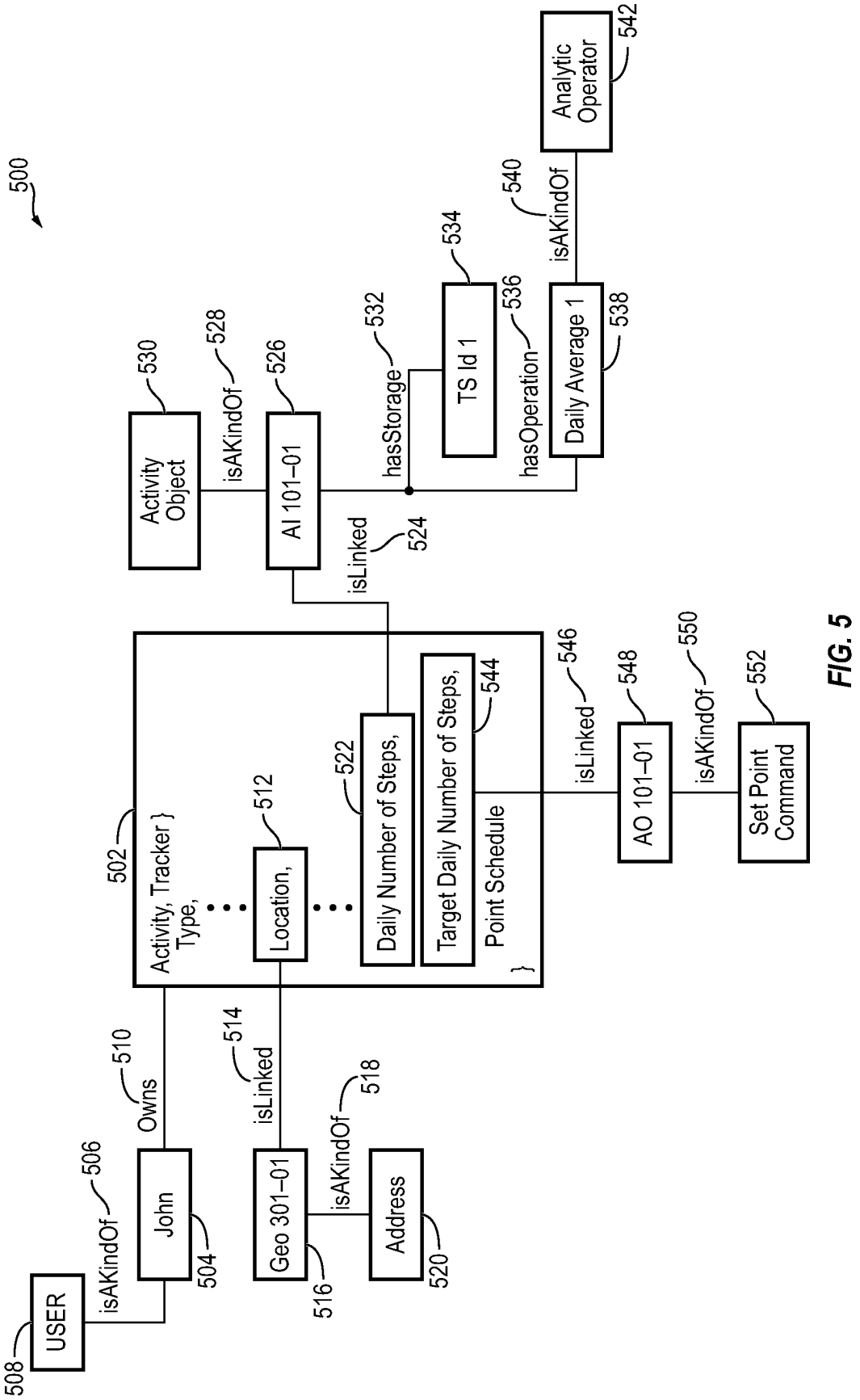
500
Analytic Operator
542
isAKindOf
540
534
TS Id 1
536
hasOperation
Daily Average 1
538
532
hasStorage
Activity Object
530
isAKindOf
528
AI 101–01
526
isLinked
524
Activity, Tracker }
Type,
Location,
Daily Number of Steps,
Target Daily Number of Steps,
Point Schedule
}
502
512
522
544
546
isLinked
AO 101–01
548
isAKindOf
550
Set Point Command
552
Owns
510
514
isLinked
isAKindOf
518
USER
isAKindOf
506
John
504
Geo 301–01
516
Address
520
508

FIG. 5

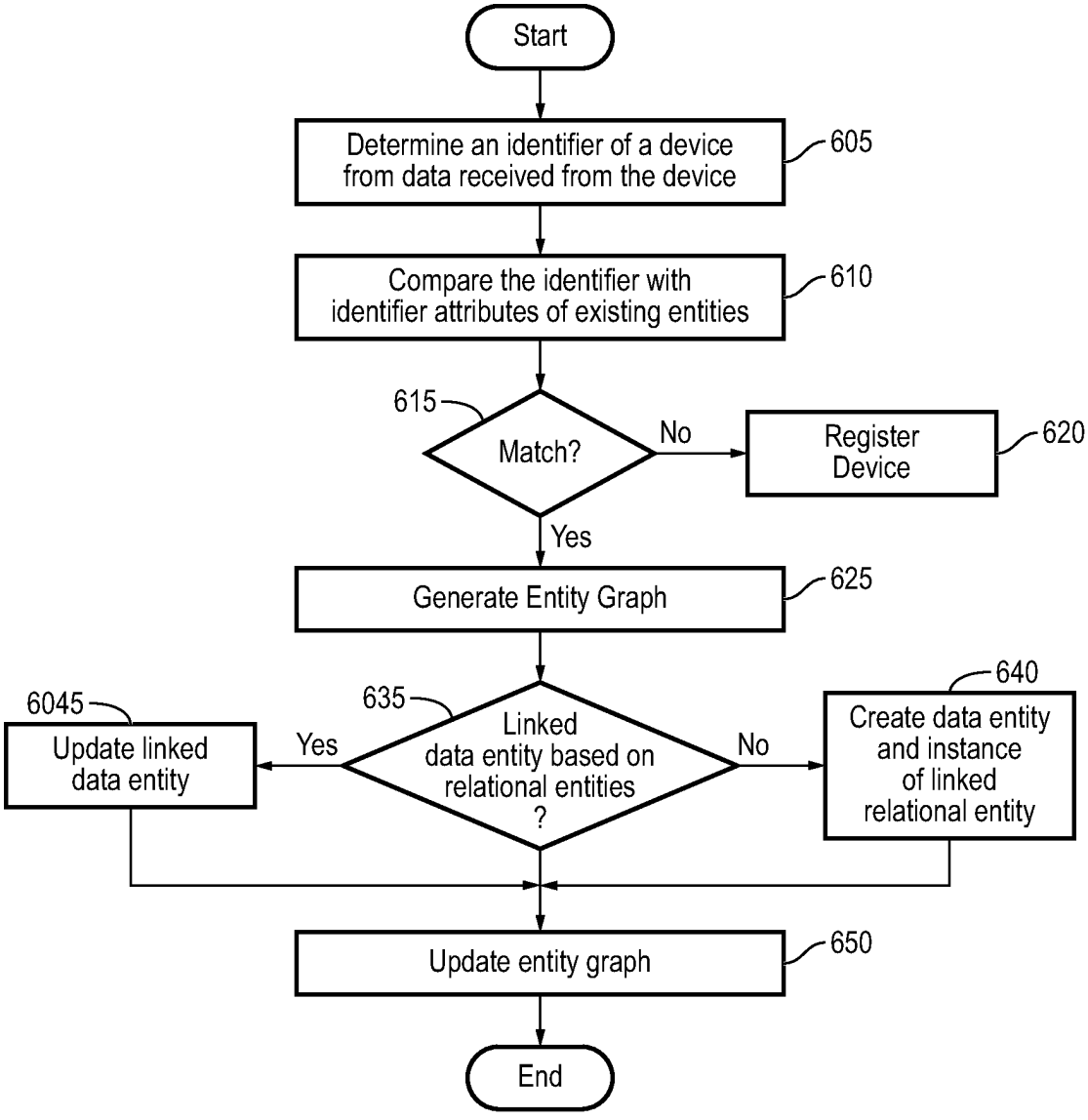
Start
Determine an identifier of a device from data received from the device
605
Compare the identifier with identifier attributes of existing entities
610
615
Match?
No
Register Device
620
Yes
Generate Entity Graph
625
640
6045
635
Update linked data entity
Yes
Linked data entity based on relational entities ?
No
Create data entity and instance of linked relational entity
Update entity graph
650
End

FIG. 6

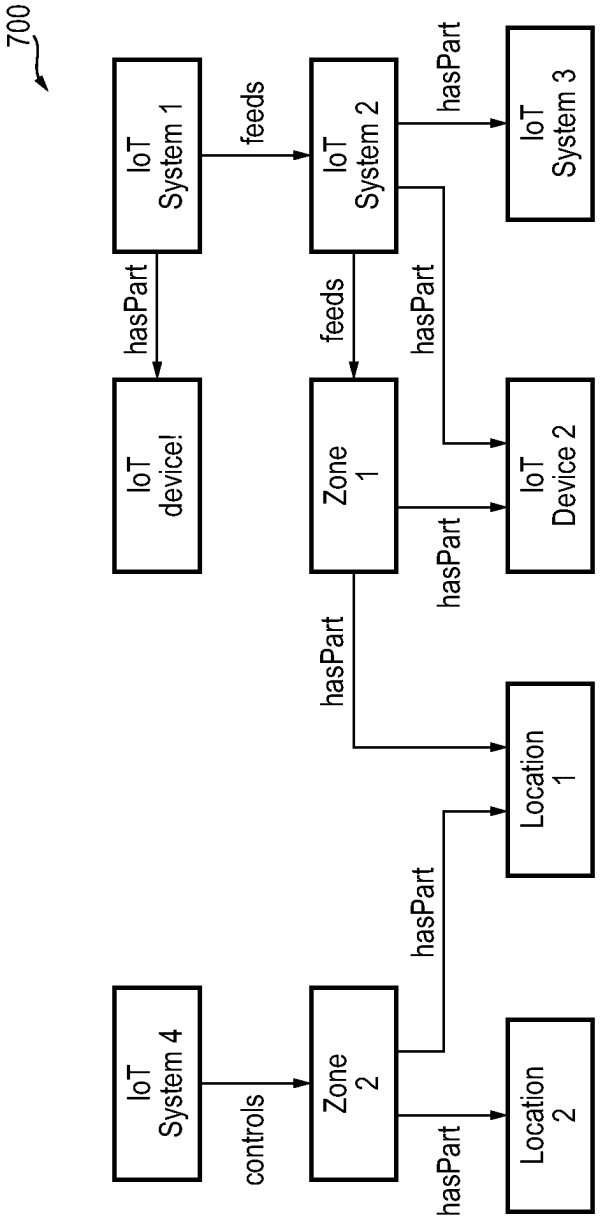
700
IoT System 1
feeds
IoT System 2
hasPart
IoT System 3
hasPart
feeds
hasPart
IoT device!
Zone 1
IoT Device 2
hasPart
hasPart
Location 1
hasPart
IoT System 4
Zone 2
controls
hasPart
Location 2

FIG. 7

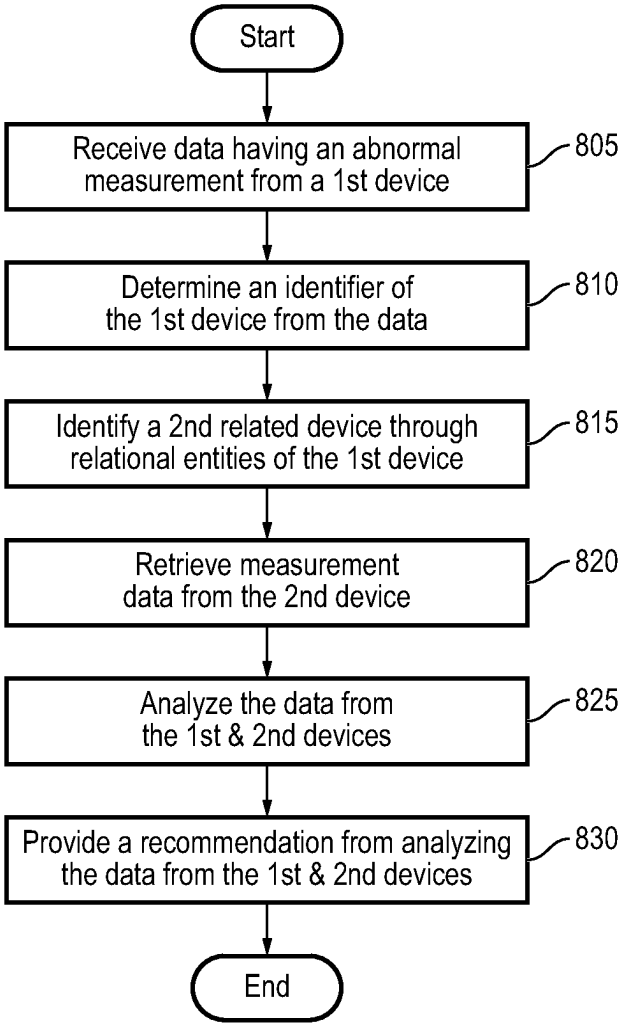
Start
Receive data having an abnormal measurement from a 1st device
805
Determine an identifier of the 1st device from the data
810
Identify a 2nd related device through relational entities of the 1st device
815
Retrieve measurement data from the 2nd device
820
Analyze the data from the 1st & 2nd devices
825
Provide a recommendation from analyzing the data from the 1st & 2nd devices
830
End

FIG. 8

WEB SERVICES FOR SMART ENTITY MANAGEMENT FOR SENSOR SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 16/143,164 filed Sep. 26, 2018, which claims the benefit of and priority to U.S. Provisional Patent Application No. 62/564,247 filed Sep. 27, 2017, U.S. Provisional Patent Application No. 62/588,179 filed Nov. 17, 2017, U.S. Provisional Patent Application No. 62/588,190 filed Nov. 17, 2017, U.S. Provisional Patent Application No. 62/588,114 filed Nov. 17, 2017, and U.S. Provisional Patent Application No. 62/611,962 filed Dec. 29, 2017. The entire disclosure of each of these patent applications is incorporated by reference herein.

BACKGROUND

One or more aspects of example embodiments of the present disclosure generally relate to creation and maintenance of smart entities. One or more aspects of example embodiments of the present disclosure relate to a system and method for defining relationships between smart entities. One or more aspects of example embodiments of the present disclosure relate to a system and method for correlating data produced by related smart entities.

The Internet of Things (IoT) is a network of interconnected objects (or Things), hereinafter referred to as IoT devices, that produce data through interaction with the environment and/or are controlled over a network. An IoT platform is used by application developers to produce IoT applications for the IoT devices. Generally, IoT platforms are utilized by developers to register and manage the IoT devices, gather and analyze data produced by the IoT devices, and provide recommendations or results based on the collected data. As the number of IoT devices used in various sectors increases, the amount of data being produced and collected has been increasing exponentially. Accordingly, effective analysis of a plethora of collected data is desired.

SUMMARY

One implementation of the present disclosure is an entity management cloud computing system for managing data relating to a plurality of sensors connected to one or more electronic communications networks. The system includes one or more processors and one or more computer-readable storage media communicably coupled to the one or more processors having instructions stored thereon. When executed by the one or more processors, the instructions cause the one or more processors to generate a database of interconnected smart entities. The smart entities include sensor object entities representing each of the plurality of sensors and data entities representing measurements received from the sensors, the smart entities being interconnected by relational objects indicating relationships between the sensor object entities and the data entities. The instructions cause the one or more processors to receive a new measurement from a first sensor of the plurality of sensors, identify a first data entity from a relational object for the first sensor, the first data entity including a plurality of past measurements received from the first sensor, and modify the first data entity within the database of smart entities to include the new measurement received from the first sensor.

In some embodiments, the instructions cause the one or more processors to periodically receive new measurements from the first sensor and update the first data entity each time a new measurement from the first sensor is received.

In some embodiments, the first sensor is configured to send the new measurement to the cloud computing system in response to detecting an event. The instructions may cause the one or more processors to update the first data entity to include a data value representative of the event.

In some embodiments, the new measurement from the first sensor is received in a first protocol or format. The instructions further cause the one or more processors to receive another new measurement from a second sensor of the plurality of sensors. The new measurement from the second sensor is received in a second protocol or format. The instructions further cause the one or more processors to convert the new measurement from the first sensor from the first protocol or format into a third protocol or format and convert the new measurement from the second sensor from the second protocol or format into the third protocol or format.

In some embodiments, each of the sensor object entities includes a static attribute identifying a physical sensor represented by the sensor object entity and a dynamic attribute storing a most recent measurement received from the physical sensor.

In some embodiments, the first data entity includes a static attribute identifying the first sensor and a dynamic attribute storing a most recent measurement received from the first sensor.

In some embodiments, each of the relational objects includes a first attribute identifying one of the sensor object entities and a second attribute identifying one of the data entities.

In some embodiments, modifying the first data entity includes using an attribute of the new measurement received from the first sensor to identify a first sensor object entity associated with the first sensor, identifying a first relational object connecting the first sensor object entity to the first data entity, and storing a value of the new measurement received from the first sensor in the first data entity identified by the first relational object.

In some embodiments, the instructions further cause the one or more processors to create a shadow entity to store the plurality of past measurements received from the first sensor. In some embodiments, the instructions further cause the one or more processors to calculate an average value from the plurality of past measurements stored in the shadow entity. In some embodiments, the instructions further cause the one or more processors to calculate an abnormal value from the plurality of past measurements stored in the shadow entity.

Another implementation of the present disclosure is a method for managing data relating to a plurality of sensors connected to one or more electronic communications networks. The method includes generating a database of interconnected smart entities. The smart entities include sensor object entities representing each of the plurality of sensors and data entities representing measurements received from the sensors, the smart entities being interconnected by relational objects indicating relationships between the sensor object entities and the data entities. The method includes receiving a new measurement from a first sensor of the plurality of sensors, identifying a first data entity from a relational object for the first sensor, the first data entity comprising a plurality of past measurements received from the first sensor, and modifying the first data entity within the

database of smart entities to include the new measurement received from the first sensor.

In some embodiments, the method includes periodically receiving new measurements from the first sensor and updating the first data entity each time a new measurement from the first sensor is received.

In some embodiments, the method includes receiving the new measurement from the first sensor in response to the first sensor detecting an event and updating the first data entity to include a data value representative of the event.

In some embodiments, the new measurement from the first sensor is received in a first protocol or format. The method may further include receiving another new measurement from a second sensor of the plurality of sensors. The new measurement from the second sensor may be received in a second protocol or format. The method may include converting the new measurement from the first sensor from the first protocol or format into a third protocol or format and converting the new measurement from the second sensor from the second protocol or format into the third protocol or format.

In some embodiments, each of the sensor object entities includes a static attribute identifying a physical sensor represented by the sensor object entity and a dynamic attribute storing a most recent measurement received from the physical sensor.

In some embodiments, the first data entity includes a static attribute identifying the first sensor and a dynamic attribute storing a most recent measurement received from the first sensor.

In some embodiments, each of the relational objects includes a first attribute identifying one of the sensor object entities and a second attribute identifying one of the data entities.

In some embodiments, modifying the first data entity includes using an attribute of the new measurement received from the first sensor to identify a first sensor object entity associated with the first sensor, identifying a first relational object connecting the first sensor object entity to the first data entity, and storing a value of the new measurement received from the first sensor in the first data entity identified by the first relational object.

In some embodiments, the method includes creating a shadow entity to store the plurality of past measurements received from the first sensor. In some embodiments, the method includes calculating an average value from the plurality of past measurements stored in the shadow entity. In some embodiments, the method includes calculating an abnormal value from the plurality of past measurements stored in the shadow entity.

Another implementation of the present disclosure is one or more non-transitory computer readable media containing program instructions. When executed by one or more processors, the instructions cause the one or more processors to perform operations including generating a database of interconnected smart entities. The smart entities include sensor object entities representing each of the plurality of sensors and data entities representing measurements received from the sensors, the smart entities being interconnected by relational objects indicating relationships between the sensor object entities and the data entities. The operations further include receiving a new measurement from a first sensor of the plurality of sensors, identifying a first data entity from a relational object for the first sensor, the first data entity comprising a plurality of past measurements received from the first sensor, and modifying the first data entity within the database of smart entities to include the new measurement received from the first sensor.

In some embodiments, the instructions further cause the one or more processors to periodically receive new measurements from the first sensor and update the first data entity each time a new measurement from the first sensor is received.

In some embodiments, the instructions further cause the one or more processors to receive the new measurement from the first sensor in response to the first sensor detecting an event and update the first data entity to include a data value representative of the event.

In some embodiments, the new measurement from the first sensor is received in a first protocol or format. The instructions may cause the one or more processors to receive another new measurement from a second sensor of the plurality of sensors. The new measurement from the second sensor may be received in a second protocol or format. The instructions may cause the one or more processors to convert the new measurement from the first sensor from the first protocol or format into a third protocol or format and convert the new measurement from the second sensor from the second protocol or format into the third protocol or format.

In some embodiments, each of the sensor object entities includes a static attribute identifying a physical sensor represented by the sensor object entity and a dynamic attribute storing a most recent measurement received from the physical sensor.

In some embodiments, the first data entity includes a static attribute identifying the first sensor and a dynamic attribute storing a most recent measurement received from the first sensor.

In some embodiments, each of the relational objects includes a first attribute identifying one of the sensor object entities and a second attribute identifying one of the data entities.

In some embodiments, modifying the first data entity includes using an attribute of the measurement received from the first sensor to identify a first sensor object entity associated with the first sensor, identifying a first relational object connecting the first sensor object entity to the first data entity, and storing a value of the measurement received from the first sensor in the first data entity identified by the first relational object.

In some embodiments, the instructions further cause the one or more processors to create a shadow entity to store the plurality of past measurements received from the first sensor. In some embodiments, the instructions further cause the one or more processors to calculate an average value from the plurality of past measurements stored in the shadow entity. In some embodiments, the instructions further cause the one or more processors to calculate an abnormal value from the plurality of past measurements stored in the shadow entity.

Another implementation of the present disclosure is an entity management cloud computing system for managing data relating to a plurality of sensors connected to one or more electronic communications networks. The system includes one or more processors and one or more computer-readable storage media communicably coupled to the one or more processors having instructions stored thereon. When executed by the one or more processors, the instructions cause the one or more processors to generate a database of interconnected smart entities. The smart entities include sensor object entities representing each of the plurality of sensors and data entities representing measurements received from the sensors, the smart entities being intercon-

nected by relational objects indicating relationships between the sensor object entities and the data entities. The instructions cause the one or more processors to receive a new measurement from a first sensor of the plurality of sensors; determine whether the database includes a first sensor object entity representing the first sensor; in response to a determination that the database includes the first sensor object entity, determine whether the database includes a first data entity representing data received from the first sensor; and in response to a determination that the database includes the first data entity, update an attribute of the first data entity to include the new measurement received from the first sensor.

In some embodiments, the instructions cause the one or more processors to periodically receive new measurements from the first sensor and update the first data entity each time a new measurement from the first sensor is received.

In some embodiments, the first sensor is configured to send the new measurement to the cloud computing system in response to detecting an event. The instructions may cause the one or more processors to update the first data entity to include a data value representative of the event.

In some embodiments, the new measurement from the first sensor is received in a first protocol or format. The instructions may cause the one or more processors to receive another new measurement from a second sensor of the plurality of sensors. The new measurement from the second sensor may be received in a second protocol or format. The instructions may cause the one or more processors to convert the new measurement from the first sensor from the first protocol or format into a third protocol or format and convert the new measurement from the second sensor from the second protocol or format into the third protocol or format.

In some embodiments, in response to a determination that the database does not include the first data entity, the instructions further cause the one or more processors to create the first data entity, create a first relational object defining a relationship between the first sensor object entity and the first data entity, and create an attribute of the first data entity and generate a value for the attribute of the first data entity using the new measurement received from the first sensor.

In some embodiments, in response to a determination that the database does not include the first sensor object entity, the instructions further cause the one or more processors to create the first sensor object entity, create the first data entity, create a first relational object defining a relationship between the first sensor object entity and the first data entity, and create an attribute of the first data entity and generate a value for the attribute of the first data entity using the new measurement received from the first sensor.

In some embodiments, determining whether the database includes the first sensor object entity includes reading one or more static attributes of the sensor object entities and determining whether any of the static attributes identify the first sensor.

In some embodiments, determining whether the database includes the first data entity includes reading a relational attribute of the first sensor object entity and determining whether the relational attribute identifies the first data entity.

In some embodiments, determining whether the database includes the first data entity includes identifying a first relational object defining a relationship between the first sensor object entity and one or more of the data entities and determining whether the first relational object identifies the first data entity.

In some embodiments, the first data entity includes a static attribute identifying the first data entity and a dynamic attribute comprising one or more measurements received from the first sensor. Updating the attribute of the first data entity may include updating the dynamic attribute using the new measurement received from the first sensor.

In some embodiments, each of the sensor object entities includes a static attribute identifying a physical sensor represented by the sensor object entity and a dynamic attribute storing a most recent measurement received from the physical sensor.

In some embodiments, the instructions further cause the one or more processors to create a shadow entity to store the plurality of past measurements received from the first sensor. In some embodiments, the instructions further cause the one or more processors to calculate an average value from the plurality of past measurements stored in the shadow entity. In some embodiments, the instructions further cause the one or more processors to calculate an abnormal value from the plurality of past measurements stored in the shadow entity.

Another implementation of the present disclosure is a method for managing data relating to a plurality of sensors connected to one or more electronic communications networks. The method includes generating a database of interconnected smart entities. The smart entities include sensor object entities representing each of the plurality of sensors and data entities representing measurements received from the sensor, the smart entities being interconnected by relational objects indicating relationships between the sensor object entities and the data entities. The method includes receiving a new measurement from a first sensor of the plurality of sensors; determining whether the database includes a first sensor object entity representing the first sensor; in response to a determination that the database includes the first sensor object entity, determining whether the database includes a first data entity representing data received from the first sensor; and in response to a determination that the database includes the first data entity, updating an attribute of the first data entity to include the new measurement received from the first sensor.

In some embodiments, the method includes periodically receiving new measurements from the first sensor and updating the first data entity each time a new measurement from the first sensor is received.

In some embodiments, the method includes receiving the new measurement from the first sensor in response to the first sensor detecting an event and updating the first data entity to include a data value representative of the event.

In some embodiments, the new measurement from the first sensor is received in a first protocol or format. The method may further include receiving another new measurement from a second sensor of the plurality of sensors. The new measurement from the second sensor may be received in a second protocol or format. The method may include converting the new measurement from the first sensor from the first protocol or format into a third protocol or format and converting the new measurement from the second sensor from the second protocol or format into the third protocol or format.

In some embodiments, in response to a determination that the database does not include the first data entity, the method includes creating the first data entity, creating a first relational object defining a relationship between the first sensor object entity and the first data entity, and creating an attribute of the first data entity and generating a value for the attribute of the first data entity using the new measurement received from the first sensor.

In some embodiments, in response to a determination that the database does not include the first sensor object entity, the method includes creating the first sensor object entity, creating the first data entity, creating a first relational object defining a relationship between the first sensor object entity and the first data entity, and creating an attribute of the first data entity and generating a value for the attribute of the first data entity using the new measurement received from the first sensor.

In some embodiments, determining whether the database includes the first sensor object entity includes reading one or more static attributes of the sensor object entities and determining whether any of the static attributes identify the first sensor.

In some embodiments, determining whether the database includes the first data entity includes reading a relational attribute of the first sensor object entity and determining whether the relational attribute identifies the first data entity.

In some embodiments, determining whether the database includes the first data entity includes identifying a first relational object defining a relationship between the first sensor object entity and one or more of the data entities and determining whether the first relational object identifies the first data entity.

In some embodiments, the first data entity includes a static attribute identifying the first data entity and a dynamic attribute comprising one or more measurements received from the first sensor. In some embodiments, updating the attribute of the first data entity includes updating the dynamic attribute using the new measurement received from the first sensor.

In some embodiments, each of the sensor object entities includes a static attribute identifying a physical sensor represented by the sensor object entity and a dynamic attribute storing a most recent measurement received from the physical sensor.

In some embodiments, the method includes creating a shadow entity to store the plurality of past measurements received from the first sensor. In some embodiments, the method includes calculating an average value from the plurality of past measurements stored in the shadow entity. In some embodiments, the method includes calculating an abnormal value from the plurality of past measurements stored in the shadow entity.

Another implementation of the present disclosure is one or more non-transitory computer readable media containing program instructions. When executed by one or more processors, the instructions cause the one or more processors to perform operations including generating a database of interconnected smart entities. The smart entities include sensor object entities representing each of the plurality of sensors and data entities representing measurements received from the sensors, the smart entities being interconnected by relational objects indicating relationships between the sensor object entities and the data entities. The operations include receiving a new measurement from a first sensor of the plurality of sensors; determining whether the database includes a first sensor object entity representing the first sensor; in response to a determination that the database includes the first sensor object entity, determining whether the database includes a first data entity representing measurements received from the first sensor; and in response to a determination that the database includes the first data entity, updating an attribute of the first data entity using the new measurement received from the first sensor.

In some embodiments, the instructions further cause the one or more processors to periodically receive new measurements from the first sensor and update the first data entity each time a new measurement from the first sensor is received.

In some embodiments, the instructions further cause the one or more processors to receive the new measurement from the first sensor in response to the first sensor detecting an event and update the first data entity to include a data value representative of the event.

In some embodiments, the new measurement from the first sensor is received in a first protocol or format. The instructions may cause the one or more processors to receive another new measurement from a second sensor of the plurality of sensors. The new measurement from the second sensor may be received in a second protocol or format. The instructions may cause the one or more processors to convert the new measurement from the first sensor from the first protocol or format into a third protocol or format and convert the new measurement from the second sensor from the second protocol or format into the third protocol or format.

In some embodiments, in response to a determination that the database does not include the first data entity, the instructions further cause the one or more processors to create the first data entity, create a first relational object defining a relationship between the first sensor object entity and the first data entity, and create an attribute of the first data entity and generate a value for the attribute of the first data entity using the new measurement received from the first sensor.

In some embodiments, in response to a determination that the database does not include the first sensor object entity, the instructions further cause the one or more processors to create the first sensor object entity, create the first data entity, create a first relational object defining a relationship between the first sensor object entity and the first data entity, and create an attribute of the first data entity and generate a value for the attribute of the first data entity using the new measurement received from the first sensor.

In some embodiments, determining whether the database includes the first sensor object entity includes reading one or more static attributes of the sensor object entities and determining whether any of the static attributes identify the first sensor.

In some embodiments, determining whether the database includes the first data entity includes reading a relational attribute of the first sensor object entity and determining whether the relational attribute identifies the first data entity.

In some embodiments, determining whether the database includes the first data entity includes identifying a first relational object defining a relationship between the first sensor object entity and one or more of the data entities and determining whether the first relational object identifies the first data entity.

In some embodiments, the first data entity includes a static attribute identifying the first data entity and a dynamic attribute comprising one or more measurements received from the first sensor. Updating the attribute of the first data entity may include updating the dynamic attribute using the new measurement received from the first sensor.

In some embodiments, each of the sensor object entities includes a static attribute identifying a physical sensor represented by the sensor object entity and a dynamic attribute storing a most recent measurement received from the physical sensor.

In some embodiments, the instructions further cause the one or more processors to create a shadow entity to store the plurality of past measurements received from the first sensor. In some embodiments, the instructions further cause the

one or more processors to calculate an average value from the plurality of past measurements stored in the shadow entity. In some embodiments, the instructions further cause the one or more processors to calculate an abnormal value from the plurality of past measurements stored in the shadow entity.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other aspects and features of the present disclosure will become more apparent to those skilled in the art from the following detailed description of the example embodiments with reference to the accompanying drawings, in which:

FIG. **1** is a block diagram of an IoT environment according to some embodiments;

FIG. **2** is a block diagram of an IoT management system, according to some embodiments;

FIG. **3** is a block diagram of another IoT management system, according to some embodiments;

FIG. **4** is a block diagram illustrating a Cloud entity service of FIG. **3** in greater detail, according to some embodiments;

FIG. **5** in an example entity graph of entity data, according to some embodiments;

FIG. **6** is a flow diagram of a process or method for updating/creating an attribute of a related entity based on data received from a device, according to some embodiments;

FIG. **7** is an example entity graph of entity data, according to some embodiments; and

FIG. **8** is a flow diagram of a process or method for analyzing data from a second related device based on data from a first device, according to some embodiments.

DETAILED DESCRIPTION

Hereinafter, example embodiments will be described in more detail with reference to the accompanying drawings.

FIG. **1** is a block diagram of an IoT environment according to some embodiments. The environment **100** is, in general, a network of connected devices configured to control, monitor, and/or manage equipment, sensors, and other devices in the IoT environment **100**. The environment **100** may include, for example, a plurality of IoT devices **102***a*-**102***n*, a Cloud IoT platform **104**, at least one IoT application **106**, a client device **108**, and any other equipment, applications, and devices that are capable of managing and/or performing various functions, or any combination thereof. Some examples of an IoT environment may include smart homes, smart buildings, smart cities, smart cars, smart medical implants, smart wearables, and the like.

The Cloud IoT platform **104** can be configured to collect data from a variety of different data sources. For example, the Cloud IoT platform **104** can collect data from the IoT devices **102***a*-**102***n*, the IoT application(s) **106**, and the client device(s) **108**. For example, IoT devices **102***a*-**102***n* may include physical devices, sensors, actuators, electronics, vehicles, home appliances, wearables, smart speaker, mobile phones, mobile devices, medical devices and implants, and/or other Things that have network connectivity to enable the IoT devices **102** to communicate with the Cloud IoT platform **104** and/or be controlled over a network (e.g., a WAN, the Internet, a cellular network, and/or the like) **110**. Further, the Cloud IoT platform **104** can be configured to collect data from a variety of external systems or services (e.g., 3rd party services) **112**. For example, some of the data collected from external systems or services **112** may include weather data from a weather service, news data from a news service, documents and other document-related data from a document service, media (e.g., video, images, audio, social media, etc.) from a media service, and/or the like. While the devices described herein are generally referred to as IoT devices, it should be understood that, in various embodiments, the devices references in the present disclosure could be any type of devices capable of communicating data over an electronic network.

In some embodiments, IoT devices **102***a*-**102***n* include sensors or sensor systems. For example, IoT devices **102***a*-**102***n* may include acoustic sensors, sound sensors, vibration sensors, automotive or transportation sensors, chemical sensors, electric current sensors, electric voltage sensors, magnetic sensors, radio sensors, environment sensors, weather sensors, moisture sensors, humidity sensors, flow sensors, fluid velocity sensors, ionizing radiation sensors, subatomic particle sensors, navigation instruments, position sensors, angle sensors, displacement sensors, distance sensors, speed sensors, acceleration sensors, optical sensors, light sensors, imaging devices, photon sensors, pressure sensors, force sensors, density sensors, level sensors, thermal sensors, heat sensors, temperature sensors, proximity sensors, presence sensors, and/or any other type of sensors or sensing systems.

Examples of acoustic, sound, or vibration sensors include geophones, hydrophones, lace sensors, guitar pickups, microphones, and seismometers. Examples of automotive or transportation sensors include air flow meters, air-fuel ratio meters, AFR sensors, blind spot monitors, crankshaft position sensors, defect detectors, engine coolant temperature sensors, Hall effect sensors, knock sensors, map sensors, mass flow sensors, oxygen sensors, parking sensors, radar guns, speedometers, speed sensors, throttle position sensors, tire-pressure monitoring sensors, torque sensors, transmission fluid temperature sensors, turbine speed sensors, variable reluctance sensors, vehicle speed sensors, water sensors, and wheel speed sensors.

Examples of chemical sensors include breathalyzers, carbon dioxide sensors, carbon monoxide detectors, catalytic bead sensors, chemical field-effect transistors, chemiresistors, electrochemical gas sensors, electronic noses, electrolyte-insulator-semiconductor sensors, fluorescent chloride sensors, holographic sensors, hydrocarbon dew point analyzers, hydrogen sensors, hydrogen sulfide sensors, infrared point sensors, ion-selective electrodes, nondispersive infrared sensors, microwave chemistry sensors, nitrogen oxide sensors, olfactometers, optodes, oxygen sensors, ozone monitors, pellistors, pH glass electrodes, potentiometric sensors, redox electrodes, smoke detectors, and zinc oxide nanorod sensors.

Examples of electromagnetic sensors include current sensors, Daly detectors, electroscopes, electron multipliers, Faraday cups, galvanometers, Hall effect sensors, Hall probes, magnetic anomaly detectors, magnetometers, magnetoresistances, mems magnetic field sensors, metal detectors, planar hall sensors, radio direction finders, and voltage detectors.

Examples of environmental sensors include actinometers, air pollution sensors, bedwetting alarms, ceilometers, dew warnings, electrochemical gas sensors, fish counters, frequency domain sensors, gas detectors, hook gauge evaporimeters, humistors, hygrometers, leaf sensors, lysimeters, pyranometers, pyrgeometers, psychrometers, rain gauges, rain sensors, seismometers, SNOTEL sensors, snow gauges, soil moisture sensors, stream gauges, and tide gauges.

Examples of flow and fluid velocity sensors include air flow meters, anemometers, flow sensors, gas meter, mass flow sensors, and water meters.

Examples of radiation and particle sensors include cloud chambers, Geiger counters, Geiger-Muller tubes, ionisation chambers, neutron detections, proportional counters, scintillation counters, semiconductor detectors, and thermoluminescent dosimeters. Wexamples of navigation instruments include air speed indicators, altimeters, attitude indicators, depth gauges, fluxgate compasses, gyroscopes, inertial navigation systems, inertial reference nits, magnetic compasses, MHD sensors, ring laser gyroscopes, turn coordinators, tialinx sensors, variometers, vibrating structure gyroscopes, and yaw rate sensors.

Examples of position, angle, displacement, distance, speed, and acceleration sensors include auxanometers, capacitive displacement sensors, capacitive sensing devices, flex sensors, free fall sensors, gravimeters, gyroscopic sensors, impact sensors, inclinometers, integrated circuit piezoelectric sensors, laser rangefinders, laser surface velocimeters, LIDAR sensors, linear encoders, linear variable differential transformers (LVDT), liquid capacitive inclinometers odometers, photoelectric sensors, piezoelectric accelerometers, position sensors, position sensitive devices, angular rate sensors, rotary encoders, rotary variable differential transformers, selsyns, shock detectors, shock data loggers, tilt sensors, tachometers, ultrasonic thickness gauges, variable reluctance sensors, and velocity receivers.

Examples of optical, light, imaging, and photon sensors include charge-coupled devices, CMOS sensors, colorimeters, contact image sensors, electro-optical sensors, flame detectors, infra-red sensors, kinetic inductance detectors, led as light sensors, light-addressable potentiometric sensors, Nichols radiometers, fiber optic sensors, optical position sensors, thermopile laser sensors, photodetectors, photodiodes, photomultiplier tubes, phototransistors, photoelectric sensors, photoionization detectors, photomultipliers, photoresistors, photoswitches, phototubes, scintillometers, Shack-Hartmann sensors, single-photon avalanche diodes, superconducting nanowire single-photon detectors, transition edge sensors, visible light photon counters, and wavefront sensors.

Examples of pressure sensors include barographs, barometers, boost gauges, bourdon gauges, hot filament ionization gauges, ionization gauges, McLeod gauges, oscillating u-tubes, permanent downhole gauges, piezometers, pirani gauges, pressure sensors, pressure gauges, tactile sensors, and time pressure gauges. Examples of force, density, and level sensors include bhangmeters, hydrometers, force gauge and force sensors, level sensors, load cells, magnetic level gauges, nuclear density gauges, piezocapacitive pressure sensors, piezoelectric sensors, strain gauges, torque sensors, and viscometers.

Examples of thermal, heat, and temperature sensors include bolometers, bimetallic strips, calorimeters, exhaust gas temperature gauges, flame detections, Gardon gauges, Golay cells, heat flux sensors, infrared thermometers, microbolometers, microwave radiometers, net radiometers, quartz thermometers, resistance thermometers, silicon bandgap temperature sensors, special sensor microwave/imagers, temperature gauges, thermistors, thermocouples, thermometers, and pyrometers. Examples of proximity and presence sensors include alarm sensors, Doppler radars, motion detectors, occupancy sensors, proximity sensors, passive infrared sensors, reed switches, stud finders, triangulation sensors, touch switches, and wired gloves.

In some embodiments, different sensors send measurements or other data to Cloud IoT platform **104** using a variety of different communications protocols or data formats. Cloud IoT platform **104** can be configured to ingest sensor data received in any protocol or data format and translate the inbound sensor data into a common data format. Cloud IoT platform **104** can create a sensor object smart entity for each sensor that communicates with Cloud IoT platform **104**. Each sensor object smart entity may include one or more static attributes that describe the corresponding sensor, one or more dynamic attributes that indicate the most recent values collected by the sensor, and/or one or more relational attributes that relate sensors object smart entities to each other and/or to other types of smart entities (e.g., space entities, system entities, data entities, etc.).

In some embodiments, Cloud IoT platform **104** stores sensor data using data entities. Each data entity may correspond to a particular sensor and may include a timeseries of data values received from the corresponding sensor. In some embodiments, Cloud IoT platform **104** stores relational objects that define relationships between sensor object entities and the corresponding data entity. For example, each relational object may identify a particular sensor object entity, a particular data entity, and may define a link between such entities.

In some embodiments, Cloud IoT platform **104** generates data internally. For example, Cloud IoT platform **104** may include a web advertising system, a website traffic monitoring system, a web sales system, and/or other types of platform services that generate data. The data generated by Cloud IoT platform **104** can be collected, stored, and processed along with the data received from other data sources. Cloud IoT platform **104** can collect data directly from external systems or devices or via the network **110**. Cloud IoT platform **104** can process and transform collected data to generate timeseries data and entity data.

Client device(s) **108** can include one or more human-machine interfaces or client interfaces (e.g., graphical user interfaces, reporting interfaces, text-based computer interfaces, client-facing web services, web servers that provide pages to web clients, and/or the like) for controlling, viewing, or otherwise interacting with the IoT environment, IoT devices **102**, IoT applications **106**, and/or the Cloud IoT platform **104**. Client device(s) **108** can be a computer workstation, a client terminal, a remote or local interface, or any other type of user interface device. Client device **108** can be a stationary terminal or a mobile device. For example, client device **108** can be a desktop computer, a computer server with a user interface, a laptop computer, a tablet, a smartphone, a PDA, or any other type of mobile or non-mobile device.

IoT applications **106** may be applications running on the client device **108** or any other suitable device that provides an interface for presenting data from the IoT devices **102** and/or the Cloud IoT platform **104** to the client device **108**. In some embodiments, the IoT applications **106** may provide an interface for providing commands or controls from the client device **108** to the IoT devices **102** and/or the Cloud IoT platform **104**.

IoT Management System

Referring now to FIG. **2**, a block diagram of an IoT management system (IoTMS) **200** is shown, according to some embodiments. IoTMS **200** can be implemented in an IoT environment to automatically monitor and control various device functions. IoTMS **200** is shown to include Cloud IoT controller **266** and IoT devices **228**. IoT devices **228** are shown to include a plurality of IoT devices. However, the

number of IoT devices are not limited to those shown in FIG. **2**. Each of the IoT devices **228** may include any suitable device having network connectivity, such as, for example, a mobile phone, laptop, tablet, smart speaker, vehicle, appliance, light fixture, thermostat, wearable, medical implant, equipment, sensor, and/or the like. Further, each of the IoT devices **228** can include any number of devices, controllers, and connections for completing its individual functions and control activities. For example, any of the IoT devices **228** can be a system of devices in itself including controllers, equipment, sensors, and/or the like.

Cloud IoT controller **266** can include one or more computer systems (e.g., servers, supervisory controllers, subsystem controllers, etc.) that serve as system level controllers, application or data servers, head nodes, or master controllers the IoT devices **228** and/or other controllable systems or devices in an IoT environment. Cloud IoT controller **266** may communicate with multiple downstream IoT devices **228** and/or systems via a communications link (e.g., IoT device interface **209**) according to like or disparate protocols (e.g., HTTP(s), TCP-IP, HTML, SOAP, REST, LON, BACnet, OPC-UA, ADX, and/or the like).

In some embodiments, the IoT devices **228** receive information from Cloud IoT controller **266** (e.g., commands, setpoints, operating boundaries, etc.) and provides information to Cloud IoT controller **266** (e.g., measurements, valve or actuator positions, operating statuses, diagnostics, etc.). For example, the IoT devices **228** may provide Cloud IoT controller **266** with measurements from various sensors, equipment on/off states, equipment operating capacities, and/or any other information that can be used by Cloud IoT controller **266** to monitor or control a variable state or condition within the IoT environment.

Still referring to FIG. **2**, Cloud IoT controller **266** is shown to include a communications interface **207** and an IoT device interface **209**. Interface **207** may facilitate communications between Cloud IoT controller **266** and external applications (e.g., monitoring and reporting applications **222**, enterprise control applications **226**, remote systems and applications **244**, applications residing on client devices **248**, and the like) for allowing user control, monitoring, and adjustment to Cloud IoT controller **266** and/or IoT devices **228**. Interface **207** may also facilitate communications between Cloud IoT controller **266** and client devices **248**. IoT device interface **209** may facilitate communications between Cloud IoT controller **266** and IoT devices **228**.

Interfaces **207**, **209** can be or include wired or wireless communications interfaces (e.g., jacks, antennas, transmitters, receivers, transceivers, wire terminals, etc.) for conducting data communications with IoT devices **228** or other external systems or devices. In various embodiments, communications via interfaces **207**, **209** can be direct (e.g., local wired or wireless communications) or via a communications network **246** (e.g., a WAN, the Internet, a cellular network, etc.). For example, interfaces **207**, **209** can include an Ethernet card and port for sending and receiving data via an Ethernet-based communications link or network. In another example, interfaces **207**, **209** can include a Wi-Fi transceiver for communicating via a wireless communications network. In another example, one or both of interfaces **207**, **209** can include cellular or mobile phone communications transceivers. In some embodiments, communications interface **207** is a power line communications interface and IoT device interface **209** is an Ethernet interface. In other embodiments, both communications interface **207** and IoT device interface **209** are Ethernet interfaces or are the same Ethernet interface.

Still referring to FIG. **2**, in various embodiments, Cloud IoT controller **266** is implemented using a distributed or cloud computing environment with a plurality of processors and memory. That is, Cloud IoT controller **266** can be distributed across multiple servers or computers (e.g., that can exist in distributed locations). For convenience of description, Cloud IoT controller **266** is shown as including at least one processing circuit **204** including a processor **206** and memory **208**. Processing circuit **204** can be communicably connected to IoT device interface **209** and/or communications interface **207** such that processing circuit **204** and the various components thereof can send and receive data via interfaces **207**, **209**. Processor **206** can be implemented as a general purpose processor, an application specific integrated circuit (ASIC), one or more field programmable gate arrays (FPGAs), a group of processing components, or other suitable electronic processing components.

Memory **208** (e.g., memory, memory unit, storage device, etc.) can include one or more devices (e.g., RAM, ROM, Flash memory, hard disk storage, etc.) for storing data and/or computer code for completing or facilitating the various processes, layers and modules described in the present application. Memory **208** can be or include volatile memory or non-volatile memory. Memory **208** can include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures described in the present application. According to some embodiments, memory **208** is communicably connected to processor **206** via processing circuit **204** and includes computer code for executing (e.g., by processing circuit **204** and/or processor **206**) one or more processes described herein.

However, the present disclosure is not limited thereto, and in some embodiments, Cloud IoT controller **266** can be implemented within a single computer (e.g., one server, one housing, etc.). Further, while FIG. **2** shows applications **222** and **226** as existing outside of Cloud IoT controller **266**, in some embodiments, applications **222** and **226** can be hosted within Cloud IoT controller **266** (e.g., within memory **208**).

Still referring to FIG. **2**, memory **208** is shown to include an enterprise integration layer **210**, an automated measurement and validation (AM&V) layer **212**, a fault detection and diagnostics (FDD) layer **216**, an integrated control layer **218**, and an IoT device integration later **220**. Layers **210-220** can be configured to receive inputs from IoT deices **228** and other data sources, determine optimal control actions for the IoT devices **228** based on the inputs, generate control signals based on the optimal control actions, and provide the generated control signals to IoT devices **228**.

Enterprise integration layer **210** can be configured to serve clients or local applications with information and services to support a variety of enterprise-level applications. For example, enterprise control applications **226** can be configured to provide subsystem-spanning control to a graphical user interface (GUI) or to any number of enterprise-level business applications (e.g., accounting systems, user identification systems, etc.). Enterprise control applications **226** may also or alternatively be configured to provide configuration GUIs for configuring Cloud IoT controller **266**. In yet other embodiments, enterprise control applications **226** can work with layers **210-220** to optimize the IoT environment based on inputs received at interface **207** and/or IoT device interface **209**.

IoT device integration layer **220** can be configured to manage communications between Cloud IoT controller **266** and the IoT devices **228**. For example, IoT device integration layer **220** may receive sensor data and input signals

from the IoT devices **228**, and provide output data and control signals to the IoT devices **228**. IoT device integration layer **220** may also be configured to manage communications between the IoT devices **228**. IoT device integration layer **220** translate communications (e.g., sensor data, input signals, output signals, etc.) across a plurality of multi-vendor/multi-protocol systems.

Integrated control layer **218** can be configured to use the data input or output of IoT device integration layer **220** to make control decisions. Due to the IoT device integration provided by the IoT device integration layer **220**, integrated control layer **218** can integrate control activities of the IoT devices **228** such that the IoT devices **228** behave as a single integrated supersystem. In some embodiments, integrated control layer **218** includes control logic that uses inputs and outputs from a plurality of IoT device subsystems to provide insights that separate IoT device subsystems could not provide alone. For example, integrated control layer **218** can be configured to use an input from a first IoT device subsystem to make a control decision for a second IoT device subsystem. Results of these decisions can be communicated back to IoT device integration layer **220**.

Automated measurement and validation (AM&V) layer **212** can be configured to verify that control strategies commanded by integrated control layer **218** are working properly (e.g., using data aggregated by AM&V layer **212**, integrated control layer **218**, IoT device integration layer **220**, FDD layer **216**, and/or the like). The calculations made by AM&V layer **212** can be based on IoT device data models and/or equipment models for individual IoT devices or subsystems. For example, AM&V layer **212** may compare a model-predicted output with an actual output from IoT devices **228** to determine an accuracy of the model.

Fault detection and diagnostics (FDD) layer **216** can be configured to provide on-going fault detection for the IoT devices **228** and subsystem devices (equipment, sensors, and the like), and control algorithms used by integrated control layer **218**. FDD layer **216** may receive data inputs from integrated control layer **218**, directly from one or more IoT devices or subsystems, or from another data source. FDD layer **216** may automatically diagnose and respond to detected faults. The responses to detected or diagnosed faults can include providing an alert message to a user, a maintenance scheduling system, or a control algorithm configured to attempt to repair the fault or to work-around the fault.

FDD layer **216** can be configured to output a specific identification of the faulty component or cause of the fault (e.g., faulty IoT device or sensor) using detailed subsystem inputs available at IoT device integration layer **220**. In other exemplary embodiments, FDD layer **216** is configured to provide "fault" events to integrated control layer **218** which executes control strategies and policies in response to the received fault events. According to some embodiments, FDD layer **216** (or a policy executed by an integrated control engine or business rules engine) may shut-down IoT systems, devices, and/or or components or direct control activities around faulty IoT systems, devices, and/or components to reduce waste, extend IoT device life, or to assure proper control response.

FDD layer **216** can be configured to store or access a variety of different system data stores (or data points for live data). FDD layer **216** may use some content of the data stores to identify faults at the IoT device or equipment level and other content to identify faults at component or subsystem levels. For example, the IoT devices **228** may generate temporal (i.e., time-series) data indicating the performance of IoTMS **200** and the various components thereof. The data generated by the IoT devices **228** can include measured or calculated values that exhibit statistical characteristics and provide information about how the corresponding system or IoT application process is performing in terms of error from its setpoint. These processes can be examined by FDD layer **216** to expose when the system begins to degrade in performance and alert a user to repair the fault before it becomes more severe.

IoT Management System with Cloud IoT Platform Services

Referring now to FIG. **3**, a block diagram of another IoT management system (IoTMS) **300** is shown, according to some embodiments. IoTMS **300** can be configured to collect data samples (e.g., raw data) from IoT devices **228** and provide the data samples to Cloud IoT platform services **320** to generate raw timeseries data, derived timeseries data, and/or entity data from the data samples. Cloud IoT platform services **320** can process and transform the raw timeseries data to generate derived timeseries data. Throughout this disclosure, the term "derived timeseries data" is used to describe the result or output of a transformation or other timeseries processing operation performed by Cloud IoT platform services **320** (e.g., data aggregation, data cleansing, virtual point calculation, etc.). The term "entity data" is used to describe the attributes of various smart entities (e.g., IoT systems, devices, components, sensors, and the like) and the relationships between the smart entities. The derived timeseries data can be provided to various applications **330** of IoTMS **300** and/or stored in storage **314** (e.g., as materialized views of the raw timeseries data). In some embodiments, Cloud IoT platform services **320** separates data collection; data storage, retrieval, and analysis; and data visualization into three different layers. This allows Cloud IoT platform services **320** to support a variety of applications **330** that use the derived timeseries data and/or entity data, and allows new applications **330** to reuse the existing infrastructure provided by Cloud IoT platform services **320**.

It should be noted that the components of IoTMS **300** and/or Cloud IoT platform services **320** can be integrated within a single device (e.g., a supervisory controller, a IoT device controller, etc.) or distributed across multiple separate systems or devices. In other embodiments, some or all of the components of IoTMS **300** and or Cloud IoT platform services **320** can be implemented as part of a cloud-based computing system configured to receive and process data from one or more IoT systems, devices, and/or components. In other embodiments, some or all of the components of IoTMS **300** and/or Cloud IoT platform services **320** can be components of a subsystem level controller, a subplant controller, a device controller, a field controller, a computer workstation, a client device, or any other system or device that receives and processes data from IoT devices.

IoTMS **300** can include many of the same components as IoTMS **200**, as described with reference to FIG. **2**. For example, IoTMS **300** is shown to include an IoT device interface **302** and a communications interface **304**. Interfaces **302-304** can include wired or wireless communications interfaces (e.g., jacks, antennas, transmitters, receivers, transceivers, wire terminals, etc.) for conducting data communications with IoT devices **228** or other external systems or devices. Communications conducted via interfaces **302-304** can be direct (e.g., local wired or wireless communications) or via a communications network **246** (e.g., a WAN, the Internet, a cellular network, etc.).

Communications interface **304** can facilitate communications between IoTMS **300** and external applications (e.g., remote systems and applications **244**) for allowing user

control, monitoring, and adjustment to IoTMS **300**. Communications interface **304** can also facilitate communications between IoTMS **300** and client devices **248**. IoT device interface **302** can facilitate communications between IoTMS **300**, Cloud IoT platform services **320**, and IoT devices **228**. IoTMS **300** can be configured to communicate with IoT devices **228** and/or Cloud IoT platform services **320** using any suitable protocols (e.g., HTTP(s), TCP-IP, HTML, SOAP, REST, LON, BACnet, OPC-UA, ADX, and/or the like). In some embodiments, IoTMS **300** receives data samples from IoT devices **228** and provides control signals to IoT devices **228** via IoT device interface **302**.

IoT devices **228** may include any suitable device having network connectivity, such as, for example, a mobile phone, laptop, tablet, smart speaker, vehicle, appliance, light fixture, thermostat, wearable, medical implant, equipment, sensor, and/or the like. Further, each of the IoT devices **228** can include any number of devices, controllers, and connections for completing its individual functions and control activities. For example, any of the IoT devices **228** can be a system of devices in itself including controllers, equipment, sensors, and/or the like.

Still referring to FIG. **3**, each of IoTMS **300** and Cloud IoT platform services **320** includes a processing circuit including a processor and memory. Each of the processors can be a general purpose or specific purpose processor, an application specific integrated circuit (ASIC), one or more field programmable gate arrays (FPGAs), a group of processing components, or other suitable processing components. Each of the processors is configured to execute computer code or instructions stored in memory or received from other computer readable media (e.g., CDROM, network storage, a remote server, etc.).

The memory can include one or more devices (e.g., memory units, memory devices, storage devices, etc.) for storing data and/or computer code for completing and/or facilitating the various processes described in the present disclosure. Memory can include random access memory (RAM), read-only memory (ROM), hard drive storage, temporary storage, non-volatile memory, flash memory, optical memory, or any other suitable memory for storing software objects and/or computer instructions. Memory can include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures described in the present disclosure. Memory can be communicably connected to the processor via the processing circuit and can include computer code for executing (e.g., by the processor) one or more processes described herein.

Still referring to FIG. **3**, Cloud IoT platform services **320** is shown to include a data collector **312**. Data collector **312** is shown receiving data samples from the IoT devices **228** via the IoT device interface **302**. However, the present disclosure is not limited thereto, and the data collector **312** may receive the data samples directly from the IoT devices **228** (e.g., via network **246** or via any suitable method). In some embodiments, the data samples include data values for various data points. The data values can be measured or calculated values, depending on the type of data point. For example, a data point received from a sensor can include a measured data value indicating a measurement by the sensor. A data point received from a controller can include a calculated data value indicating a calculated efficiency of the controller. Data collector **312** can receive data samples from multiple different devices (e.g., IoT systems, devices, components, sensors, and the like) of the IoT devices **228**.

The data samples can include one or more attributes that describe or characterize the corresponding data points. For example, the data samples can include a name attribute defining a point name or ID (e.g., "B1F4R2.T-Z"), a device attribute indicating a type of device from which the data samples are received, a unit attribute defining a unit of measure associated with the data value (e.g., ° F., ° C., kPA, etc.), and/or any other attribute that describes the corresponding data point or provides contextual information regarding the data point. The types of attributes included in each data point can depend on the communications protocol used to send the data samples to Cloud IoT platform services **320**. For example, data samples received via the ADX protocol or BACnet protocol can include a variety of descriptive attributes along with the data value, whereas data samples received via the Modbus protocol may include a lesser number of attributes (e.g., only the data value without any corresponding attributes).

In some embodiments, each data sample is received with a timestamp indicating a time at which the corresponding data value was measured or calculated. In other embodiments, data collector **312** adds timestamps to the data samples based on the times at which the data samples are received. Data collector **312** can generate raw timeseries data for each of the data points for which data samples are received. Each timeseries can include a series of data values for the same data point and a timestamp for each of the data values. For example, a timeseries for a data point provided by a temperature sensor can include a series of temperature values measured by the temperature sensor and the corresponding times at which the temperature values were measured. An example of a timeseries which can be generated by data collector **312** is as follows:
[<key,$timestamp_1$, $value_1$>, <key,$timestamp_2$,$value_2$>, <key, $timestamp_3$,$value_3$>] where key is an identifier of the source of the raw data samples (e.g., timeseries ID, sensor ID, etc.), timestamp identifies the time at which the ith sample was collected, and $value_i$ indicates the value of the ith sample. Data collector **312** can add timestamps to the data samples or modify existing timestamps such that each data sample includes a local timestamp. Each local timestamp indicates the local time at which the corresponding data sample was measured or collected and can include an offset relative to universal time. The local timestamp indicates the local time at the location the data point was measured at the time of measurement. The offset indicates the difference between the local time and a universal time (e.g., the time at the international date line). For example, a data sample collected in a time zone that is six hours behind universal time can include a local timestamp (e.g., Timestamp=2016-03-18T14:10:02) and an offset indicating that the local timestamp is six hours behind universal time (e.g., Offset=−6:00). The offset can be adjusted (e.g., +1:00 or −1:00) depending on whether the time zone is in daylight savings time when the data sample is measured or collected.

The combination of the local timestamp and the offset provides a unique timestamp across daylight saving time boundaries. This allows an application using the timeseries data to display the timeseries data in local time without first converting from universal time. The combination of the local timestamp and the offset also provides enough information to convert the local timestamp to universal time without needing to look up a schedule of when daylight savings time occurs. For example, the offset can be subtracted from the local timestamp to generate a universal time

value that corresponds to the local timestamp without referencing an external database and without requiring any other information.

In some embodiments, data collector **312** organizes the raw timeseries data. Data collector **312** can identify a system or device associated with each of the data points. For example, data collector **312** can associate a data point with an IoT device, system, component, sensor, or any other type of system or device. In some embodiments, a data point entity may be created for the data point, in which case, the data collector **312** can associate the data point with the data point entity. In various embodiments, data collector uses the name of the data point, a range of values of the data point, statistical characteristics of the data point, or other attributes of the data point to identify a particular system, device, or data point entity associated with the data point. Data collector **312** can then determine how that system or device relates to the other systems or devices in the IoT environment from entity data. For example, data collector **312** can determine that the identified system or device is part of a larger system or serves a particular function within the larger system from the entity data. In some embodiments, data collector **312** uses or retrieves an entity graph (e.g., via the entity service **326**) based on the entity data when organizing the timeseries data.

Data collector **312** can provide the raw timeseries data to the other Cloud IoT platform services **320** and/or store the raw timeseries data in storage **314**. Storage **314** may be internal storage or external storage. For example, storage **314** can be internal storage with relation to Cloud IoT platform service **320** and/or IoTMS **300**, and/or may include a remote database, cloud-based data hosting, or other remote data storage. Storage **314** can be configured to store the raw timeseries data obtained by data collector **312**, the derived timeseries data generated by Cloud IoT platform services **320**, and/or directed acyclic graphs (DAGs) used by Cloud IoT platform services **320** to process the timeseries data.

Still referring to FIG. **3**, Cloud IoT platform services **320** can receive the raw timeseries data from data collector **312** and/or retrieve the raw timeseries data from storage **314**. Cloud IoT platform services **320** can include a variety of services configured to analyze, process, and transform the raw timeseries data. For example, Cloud IoT platform services **320** is shown to include a security service **322**, an analytics service **324**, an entity service **326**, and a timeseries service **328**. Security service **322** can assign security attributes to the raw timeseries data to ensure that the timeseries data are only accessible to authorized individuals, systems, or applications. Security service **322** may include a messaging layer to exchange secure messages with the entity service **326**. In some embodiment, security service **322** may provide permission data to entity service **326** so that entity service **326** can determine the types of entity data that can be accessed by a particular entity or device. Entity service **324** can assign entity information (or entity data) to the timeseries data to associate data points with a particular system, device, or component. Timeseries service **328** and analytics service **324** can apply various transformations, operations, or other functions to the raw timeseries data to generate derived timeseries data.

In some embodiments, timeseries service **328** aggregates predefined intervals of the raw timeseries data (e.g., quarter-hourly intervals, hourly intervals, daily intervals, monthly intervals, etc.) to generate new derived timeseries of the aggregated values. These derived timeseries can be referred to as "data rollups" since they are condensed versions of the raw timeseries data. The data rollups generated by timeseries service **328** provide an efficient mechanism for IoT applications **330** to query the timeseries data. For example, IoT applications **330** can construct visualizations of the timeseries data (e.g., charts, graphs, etc.) using the pre-aggregated data rollups instead of the raw timeseries data. This allows IoT applications **330** to simply retrieve and present the pre-aggregated data rollups without requiring IoT applications **330** to perform an aggregation in response to the query. Since the data rollups are pre-aggregated, IoT applications **330** can present the data rollups quickly and efficiently without requiring additional processing at query time to generate aggregated timeseries values.

In some embodiments, timeseries service **328** calculates virtual points based on the raw timeseries data and/or the derived timeseries data. Virtual points can be calculated by applying any of a variety of mathematical operations (e.g., addition, subtraction, multiplication, division, etc.) or functions (e.g., average value, maximum value, minimum value, thermodynamic functions, linear functions, nonlinear functions, etc.) to the actual data points represented by the timeseries data. For example, timeseries service **328** can calculate a virtual data point ($pointID_3$) by adding two or more actual data points ($pointID_1$ and $pointID_2$) (e.g., $pointID_3=point_1+pointID_2$). As another example, timeseries service **328** can calculate an enthalpy data point ($pointID_4$) based on a measured temperature data point ($pointID_5$) and a measured pressure data point ($pointID_6$) (e.g., $pointID_4=enthalpy(pointID_5, pointID_6)$). The virtual data points can be stored as derived timeseries data.

IoT applications **330** can access and use the virtual data points in the same manner as the actual data points. IoT applications **330** do not need to know whether a data point is an actual data point or a virtual data point since both types of data points can be stored as derived timeseries data and can be handled in the same manner by IoT applications **330**. In some embodiments, the derived timeseries are stored with attributes designating each data point as either a virtual data point or an actual data point. Such attributes allow IoT applications **330** to identify whether a given timeseries represents a virtual data point or an actual data point, even though both types of data points can be handled in the same manner by IoT applications **330**.

In some embodiments, analytics service **324** analyzes the raw timeseries data and/or the derived timeseries data with the entity data to detect faults. Analytics service **324** can apply a set of fault detection rules based on the entity data to the timeseries data to determine whether a fault is detected at each interval of the timeseries. Fault detections can be stored as derived timeseries data. For example, analytics service **324** can generate a new fault detection timeseries with data values that indicate whether a fault was detected at each interval of the timeseries. The fault detection timeseries can be stored as derived timeseries data along with the raw timeseries data in storage **314**.

Still referring to FIG. **3**, IoTMS **300** is shown to include several IoT applications **330** including a resource management application **332**, monitoring and reporting applications **334**, and enterprise control applications **336**. Although only a few IoT applications **330** are shown, it is contemplated that IoT applications **330** can include any of a variety of applications configured to use the derived timeseries generated by Cloud IoT platform services **320**. In some embodiments, IoT applications **330** exist as a separate layer of IoTMS **300** (e.g., a part of Cloud IoT platform services **320** and/or data collector **312**). In other embodiments, IoT applications **330**

can exist as remote applications that run on remote systems or devices (e.g., remote systems and applications **244**, client devices **248**, and/or the like).

IoT applications **330** can use the derived timeseries data and entity data to perform a variety data visualization, monitoring, and/or control activities. For example, resource management application **332** and monitoring and reporting application **334** can use the derived timeseries data and entity data to generate user interfaces (e.g., charts, graphs, etc.) that present the derived timeseries data and/or entity data to a user. In some embodiments, the user interfaces present the raw timeseries data and the derived data rollups in a single chart or graph. For example, a dropdown selector can be provided to allow a user to select the raw timeseries data or any of the data rollups for a given data point.

Enterprise control application **336** can use the derived timeseries data and/or entity data to perform various control activities. For example, enterprise control application **336** can use the derived timeseries data and/or entity data as input to a control algorithm (e.g., a state-based algorithm, an extremum seeking control (ESC) algorithm, a proportional-integral (PI) control algorithm, a proportional-integral-derivative (PID) control algorithm, a model predictive control (MPC) algorithm, a feedback control algorithm, etc.) to generate control signals for IoT devices **228**. In some embodiments, IoT devices **228** use the control signals to operate other systems, devices, components, and/or sensors, which can affect the measured or calculated values of the data samples provided to IoTMS **300** and/or Cloud IoT platform services **320**. Accordingly, enterprise control application **336** can use the derived timeseries data and/or entity data as feedback to control the systems and devices of the IoT devices **228**.

Cloud Entity IoT Platform Service

Referring now to FIG. **4**, a block diagram illustrating entity service **326** in greater detail is shown, according to some embodiments. Entity service **326** registers and manages various devices and entities in the Cloud IoT platform services **320**. According to various embodiments, an entity may be any person, place, or physical object, hereafter referred to as an object entity. Further, an entity may be any event, data point, or record structure, hereinafter referred to as data entity. In addition, relationships between entities may be defined by relational objects.

In some embodiments, an object entity may be defined as having at least three types of attributes. For example, an object entity may have a static attribute, a dynamic attribute, and a behavioral attribute. The static attribute may include any unique identifier of the object entity or characteristic of the object entity that either does not change over time or changes infrequently (e.g., a device ID, a person's name or social security number, a place's address or room number, and the like). The dynamic attribute may include a property of the object entity that changes over time (e.g., location, age, measurement, data point, and the like). In some embodiments, the dynamic attribute of an object entity may be linked to a data entity. In this case, the dynamic attribute of the object entity may simply refer to a location (e.g., data/network address) or static attribute (e.g., identifier) of the linked data entity, which may store the data (e.g., the value or information) of the dynamic attribute. Accordingly, in some such embodiments, when a new data point is received for the object entity, only the linked data entity may be updated, while the object entity remains unchanged. Therefore, resources that would have been expended to update the object entity may be reduced.

However, the present disclosure is not limited thereto. For example, in some embodiments, there may also be some data that is updated (e.g., during predetermined intervals) in the dynamic attribute of the object entity itself. For example, the linked data entity may be configured to be updated each time a new data point is received, whereas the corresponding dynamic attribute of the object entity may be configured to be updated less often (e.g., at predetermined intervals less than the intervals during which the new data points are received). In some implementations, the dynamic attribute of the object entity may include both a link to the data entity and either a portion of the data from the data entity or data derived from the data of the data entity. For example, in an embodiment in which periodic odometer readings are received from a connected car, an object entity corresponding to the car could include the last odometer reading and a link to a data entity that stores a series of the last ten odometer readings received from the car.

The behavioral attribute may define a function of the object entity, for example, based on inputs, capabilities, and/or permissions. For example, behavioral attributes may define the types of inputs that the object entity is configured to accept, how the object entity is expected to respond under certain conditions, the types of functions that the object entity is capable of performing, and the like. As a non-limiting example, if the object entity represents a person, the behavioral attribute of the person may be his/her job title or job duties, user permissions to access certain systems, expected location or behavior given a time of day, tendencies or preferences based on connected activity data received by entity service **326** (e.g., social media activity), and the like. As another non-limiting example, if the object entity represents a device, the behavioral attributes may include the types of inputs that the device can receive, the types of outputs that the device can generate, the types of controls that the device is capable of, the types of software or versions that the device currently has, known responses of the device to certain types of input (e.g., behavior of the device defined by its programming), and the like.

In some embodiments, the data entity may be defined as having at least a static attribute and a dynamic attribute. The static attribute of the data entity may include a unique identifier or description of the data entity. For example, if the data entity is linked to a dynamic attribute of an object entity, the static attribute of the data entity may include an identifier that is used to link to the dynamic attribute of the object entity. In some embodiments, the dynamic attribute of the data entity represents the data for the dynamic attribute of the linked object entity. In some embodiments, the dynamic attribute of the data entity may represent some other data that is analyzed, inferred, calculated, or determined based on data from a plurality of data sources.

In some embodiments, the relational object may be defined as having at least a static attribute. The static attribute of the relational object may semantically define the type of relationship between two or more entities. For example, in a non-limiting embodiment, a relational object for a relationship that semantically defines that Entity A has a part of Entity B, or that Entity B is a part of Entity A may include:

hasPart{Entity A, Entity B}

where the static attribute hasPart defines what the relationship is of the listed entities, and the order of the listed entities or data field of the relational object specifies which entity is the part of the other (e.g., Entity A→hasPart→Entity B).

In various embodiments, the relational object is an object-oriented construct with predefined fields that define the

relationship between two or more entities, regardless of the type of entities. For example, Cloud IoT platform service **320** can provide a rich set of pre-built entity models with standardized relational objects that can be used to describe how any two or more entities are semantically related, as well as how data is exchanged and/or processed between the entities. Accordingly, a global change to a definition or relationship of a relational object at the system level can be effected at the object level, without having to manually change the entity relationships for each object or entity individually. Further, in some embodiments, a global change at the system level can be propagated through to third-party applications integrated with Cloud IoT platform services **320** such that the global change can be implemented across all of the third-party applications without requiring manual implementation of the change in each disparate application.

For example, referring to FIG. **5**, an example entity graph of entity data is shown, according to some embodiments. The term "entity data" is used to describe the attributes of various entities and the relationships between the entities. For example, entity data may be represented in the form of an entity graph. In some embodiments, entity data includes any suitable predefined data models (e.g., as a table, JSON data, and/or the like), such as entity type or object, and further includes one or more relational objects that semantically define the relationships between the entities. The relational objects may help to semantically define, for example, hierarchical or directed relationships between the entities (e.g., entity X controls entity Y, entity A feeds entity B, entity **1** is located in entity **2**, and the like). For example, an object entity (e.g., IoT device) may be represented by entity type or object, which generally describes how data corresponding to the entity will be structured and stored.

For example, an entity type (or object) "Activity Tracker" may be represented via the below schema:

```
Activity Tracker {
  Type,
  Model No,
  Device Name,
  Manufactured date,
  Serial number,
  MAC address,
  Location,
  Current Time,
  Current Date,
  Current Heart Rate,
  Daily Number of Steps,
  Target Daily Number of Steps,
  Point schedule
}
```

where various attributes are static attributes (e.g., "Type," "Model Number," "Device Name," etc.,), dynamic attributes (e.g., "Location," "Current Time," etc.), or behavioral attributes (e.g., "Current Heart Rate," "Daily Number of Steps," etc.) for the object entity "Activity Tracker." In a relational database, the object "Activity Tracker" is a table name, and the attributes represents column names.

An example of an object entity data model for a person named John Smith in a relational database may be represented by the below table:

First Name	Last Name	Tel. No.	Age	Location	Job Title
John	Smith	(213)220-XXXX	36	Home	Engineer

where various attributes are static attributes (e.g., "First Name," "Last Name," etc.,), dynamic attributes (e.g., "Age," "Location," etc.), or behavioral attributes (e.g., "Engineer") for the object entity "John Smith."

An example data entity for the data point "Daily Number of Steps" for the "Activity Tracker" owned by John Smith in a relational database may be represented by the below table:

Present-Value	Description	Device_Type	Unit of measure
2365	"John's current daily number of steps"	Activity Tracker	2 feet/step

where various attributes are static attributes (e.g., "Description" and "Device_Type") and dynamic attributes (e.g., "Present-Value").

While structuring the entities via entity type or object may help to define the data representation of the entities, these data models do not provide information on how the entities relate to each other. For example, an IoT application, controller, or platform may need data from a plurality of sources as well as information on how the sources relate to each other in order to provide a proper decision, action, or recommendation. Accordingly, in various embodiments, the entity data further includes the relational objects to semantically define the relationships between the entities, which may help to increase speeds in analyzing data, as well as provide ease of navigation and browsing.

For example, still referring to FIG. **5**, an entity graph **500** for the Activity Tracker object entity **502** includes various class entities (e.g., User, Address, SetPoint Command, and Activity Object), object entities (e.g., John and Activity Tracker), relational objects (e.g., isAKindOf, Owns, isLinked, hasStorage, and hasOperation), and data entities (AI 201-01, TS ID 1, Daily Average 1, AO 101-1, and Geo 301-01). The relational objects describe the relationships between the various class, object, and data entities in a semantic and syntactic manner, so that an application or user viewing the entity graph **500** can quickly determine the relationships and data process flow of the Activity Tracker object entity **502**, without having to resort to a data base analyst or engineer to create, index, and/or manage the entities (e.g., using SQL or NoSQL). In some embodiments, each of the entities (e.g., class entity, object entity, and data entity) represents a node on the entity graph **500**, and the relational objects define the relationships or connections between the entities (or nodes).

For example, the entity graph **500** shows that a person named John (object entity) **504** isAKindOf (relational object) **506** User (class entity) **508**. John **504** Owns (relational object) **510** the Activity Tracker (object entity) **502**. The Activity Tracker **502** has a location attribute (dynamic attribute) **512** that isLinked (relational object) **514** to Geo 301-01 (data entity) **316**, which isAKindOf (relational object) **518** an Address (class entity) **520**. Accordingly, Geo 301-01 **316** should have a data point corresponding to an address.

The Activity Tracker **502** further includes a "Daily Number of Steps" attribute (dynamic attribute) **522** that isLinked

(relational object) **524** to AI 201-01 (data entity) **526**. AI 201-01 **526** isAKindOf (relational object) **528** Activity Object (class entity) **530**. Thus, AI 201-01 **526** should contain some sort of activity related data. AI 201-01 **526** hasStorage (relational object) **532** at TS ID 1 (data entity) **534**. AI 201-01 **526** hasOperation (relational object) **536** of Daily Average 1 (data entity) **538**, which isAKindOf (relational object) **540** Analytic Operator (class entity) **542**. Accordingly, Daily Average 1 should hold some data that is the result of an analytic operation.

In this example, the data entity AI 201-01 **526** may be represented by the following data model:

```
point {
   name: "AI 201-01";
   type: "analog input";
   value: 2365;
   unit: "2 feet/step";
   source: "Pedometer Sensor 1"
}
```

where "point" is an example of a data entity that may be created by Cloud IoT platform Services **320** to hold the value for the linked "Daily Number of Steps" **522** dynamic attribute of the Activity Tracker entity **502**, and source is the sensor or device in the Activity Tracker device **502** that provides the data to the linked "Daily Number of Steps" **522** dynamic attribute.

The data entity TS Id 1 **534** may be represented, for example, by the following data model:

```
timeseries {
   name: "TS Id 1";
   type: "Daily Average";
   values: "[2365, 10683, 9166, 8254, 12982];
   unit: "2 feet/step";
   point: "AI 201-01";
   source: "Daily Average 1"
}
```

where the data entity Daily Average 1 **538** represents a specific analytic operator used to create the data entity for the average daily timeseries TS Id 1 **534** based on the values of the corresponding data entity for point AI 201-01 **526**. The relational object hasOperation shows that the AI 201-01 data entity **526** is used as an input to the specific logic/math operation represented by Daily Average 1 **538**. TS Id 1 **534** might also include an attribute that identifies the analytic operator Daily Average 1 **538** as the source of the data samples in the timeseries.

Still referring to FIG. **5**, the entity graph **500** for Activity Tracker **502** shows that the "Target Daily Number of Steps" attribute (dynamic attribute) **544** isLinked (relational attribute) **546** to the data entity AO 101-01 (data entity) **548**. AO 101-01 data entity isAKindOf (relational attribute) **550** a SetPoint Command (class entity) **552**. Thus, the data in data entity AO 101-01 **548** may be set via a command by the user or other entity. Accordingly, in various embodiments, entity graph **500** provides a user friendly view of the various relationships between the entities (or nodes) and data processing flow, which provides for ease of navigation, browsing, and analysis of data.

In some embodiments, any two entities (or nodes) can be connected to each other via one or more relational objects that define different relationships between the two entities (or nodes). For example, still referring to FIG. **5**, the object entity John **504** is shown to be connected to the object entity Activity Tracker **502** via one relational object Owns **510**. However, in another embodiment, the object entity John **504** can be connected to the object entity Activity Tracker **502** via more than one relational object, such that, in addition to the relational object Owns **510**, another relational object can define another relationship between the object entity John **504** and the object entity Activity Tracker **502**. For example, another relational object such as isWearing or isNotWearing can define whether or not John (or the entity object for John **504**) is currently wearing (e.g., via the relational object isWearing) or currently not wearing (e.g., via the relational object isNotWearing) the activity tracker (or the entity object for the activity tracker **502**).

In this case, when the data entities associated with the activity tracker object entity **502** indicates that John is wearing the activity tracker (e.g., which may be determined from the daily number of steps attribute **522** or the location attribute **512**), the relational object isWearing may be created between the object entity for John **510** and the object entity for activity tracker **502**. On the other hand, when the data entities associated with the activity tracker object entity **502** indicates that John is not wearing the activity tracker (e.g., which may be determined when the daily number of steps attribute **522** for a current day is zero or the location attribute **512** shows a different location from a known location of John), the relational object isNotWearing can be created between the object entity for John **510** and the object entity for activity tracker **502**. For example, the relational object isNotWearing can be created by modifying the relational object isWearing or deleting the relational object isWearing and creating the relational object isNotWearing. Thus, in some embodiments, the relational objects can be dynamically created, modified, or deleted as needed or desired.

Referring again to FIG. **4**, entity service **326** may transforms raw data samples and/or raw timeseries data into data corresponding to entity data. For example, as discussed above with reference to FIG. **5**, entity service **326** can create data entities that use and/or represent data points in the timeseries data. Entity service **326** includes a web service **402**, a registration service **404**, a management service **406**, a transformation service **408**, a search service **410**, and storage **412**. In some embodiments, storage **412** may be internal storage or external storage. For example, storage **412** may be storage **314** (see FIG. **3**), internal storage with relation to entity service **326**, and/or may include a remote database, cloud-based data hosting, or other remote data storage.

Web service **402** can be configured to interact with web-based applications to send entity data and/or receive raw data (e.g., data samples, timeseries data, and the like). For example, web service **402** can provide an interface (e.g., API, UI/UX, and the like) to manage (e.g., register, create, edit, delete, and/or update) an entity (e.g., class entity, object entity, data entity, and/or the like) and the relational objects that define the relationships between the entities. In some embodiments, web service **402** provides entity data to web-based applications. For example, if one or more of applications **330** are web-based applications, web service **402** can provide entity data to the web-based applications. In some embodiments, web service **402** receives raw data samples and/or raw timeseries data including device information from a web-based data collector, or a web-based security service to identify authorized entities and to exchange secured messages. For example, if data collector **312** is a web-based application, web service **402** can receive the raw data samples and/or timeseries data including a device

attribute indicating a type of device (e.g., IoT device) from which the data samples and/or timeseries data are received from data collector **312**. In some embodiments, web service **402** may message security service **322** to request authorization information and/or permission information of a particular entity or device. In some embodiments, the entity service **326** processes and transforms the collected data to generate the entity data.

The registration service **404** can perform registration of devices and entities. For example, registration service **404** can communicate with IoT devices **228** and client devices **248** (e.g., via web service **402**) to register each IoT device with Cloud IoT platform services **320**. In some embodiments, registration service **404** registers a particular IoT device **228** with a specific user and/or a specific set of permissions and/or entitlements. For example, a user may register a device key and/or a device ID associated with the IoT device **228** via a web portal (e.g., web service **402**). In some embodiments, the device ID and the device key may be unique to the IoT device **228**. The device ID may be a unique number associated with the device such as a unique alphanumeric string, a serial number of IoT device **228**, and/or any other static identifier. In various embodiments, IoT device **228** is provisioned by a manufacturer and/or any other entity. In various embodiments, the device key and/or device ID are saved to IoT device **228** based on whether IoT device **228** includes a trusted platform module (TPM). If the IoT device **228** includes a TPM, the IoT device **228** may store the device key and/or device ID according to the protocols of the TPM. If the IoT device **228** does not include a TPM, the IoT device **228** may store the device key and/or device ID in a file and/or file field which may be stored in a secure storage location. Further, in some embodiments, the device ID may be stored with BIOS software of the IoT device **228**. For example, a serial number of BIOS software may become and/or may be updated with the device ID.

In various embodiments, the device key and/or the device ID are uploaded to registration service **404** (e.g., an IoT hub such as AZURE® IoT Hub). In some embodiments, registration service **404** is configured to store the device key and the device ID in secure permanent storage and/or may be stored by security service **322** (e.g., by a security API). In some embodiments, a manufacturer and/or any other individual may register the device key and the device ID with registration service **404** (e.g., via web service **402**). In various embodiments, the device key and the device ID are linked to a particular profile associated with the IoT device **228** and/or a particular user profile (e.g., a particular user). In this regard, a device (e.g., IoT device **228**) can be associated with a particular user. In various embodiments, the device key and the device ID make up the profile for IoT device **228**. The profile may be registered as a device that has been manufactured and/or provisioned but has not yet been purchased by an end user.

In various embodiments, registration service **404** adds and/or updates a device in an IoT hub device registry. In various embodiments, registration service **404** may determine if the device is already registered, can set various authentication values (e.g., device ID, device key), and can update the IoT hub device registry. In a similar manner, registration service **404** can update a document database with the various device registration information.

In some embodiments, registration service **404** can be configured to create a virtual representation (e.g., "digital twins" or "shadow records") of each IoT device in an IoT environment within Cloud IoT platform services **320**. In some embodiments, the virtual device representations are smart entities that include attributes defining or characterizing the corresponding physical IoT devices and are associated to the corresponding physical IoT devices via relational objects defining the relationship of the IoT device and the smart entity representation thereof. In some embodiments, the virtual device representations maintain shadow copies of the IoT devices with versioning information so that Cloud entity service **326** can store not only the most recent update of an attribute (e.g., a dynamic attribute) associated with the IoT device, but records of previous states of the attributes (e.g., dynamic attributes) and/or entities. For example, the shadow record may be created as a type of data entity that is related to a linked data entity corresponding to the dynamic attribute of the object entity (e.g., IoT device). For example, the shadow entity may be associated with the linked data entity via a relational object (e.g., isLinked, hasStorage, hasOperation, and the like). In this case, the shadow entity may be used to determine additional analytics for the data point of the dynamic attribute. For example, the shadow entity may be used to determine an average value, and expected value, or an abnormal value of the data point from the dynamic attribute.

Management service **406** may create, modify, or update various attributes, data entities, and/or relational objects of the devices managed by Cloud IoT platform services **326** for each entity rather than per class or type of entity. This allows for separate processing/analytics for each individual entity rather than only to a class or type of entity. Some attributes (or data entities) may correspond to, for example, the most recent value of a data point provided to Cloud IoT platform services **326** via the raw data samples and/or timeseries data. For example, the "Daily Number of Steps" dynamic attribute of the "Activity Tracker" object entity **502** in the example discussed above may be the most recent value of a number of steps data point provided by the Activity Tracker device. Management service **406** can use the relational objects of the entity data for Activity Tracker to determine where to update the data of the attribute.

For example, Management service **406** may determine that a data entity (e.g., AI 201-01) is linked to the "Daily Number of Steps" dynamic attribute of Activity Tracker via an isLinked relational object. In this case, Management service **406** may automatically update the attribute data in the linked data entity. Further, if a linked data entity does not exist, Management service **406** can create a data entity (e.g., AI 201-01) and an instance of the isLinked relational object **524** to store and link the "Daily Number of Steps" dynamic attribute of Activity Tracker therein. Accordingly, processing/analytics for activity tracker **502** may be automated. As another example, a "most recent view" attribute (or linked data entity) of a webpage object entity may indicate the most recent time at which the webpage was viewed. Management service **406** can use the entity data from a related click tracking system object entity or web server object entity to determine when the most recent view occurred and can automatically update the "most recent view" attribute (or linked data entity) of the webpage entity accordingly.

Other data entities and/or attributes may be created and/or updated as a result of an analytic, transformation, calculation, or other processing operation based on the raw data and/or entity data. For example, Management service **406** can use the relational objects in entity data to identify a related access control device (e.g., a card reader, a keypad, etc.) at the entrance/exit of a building object entity. Management service **406** can use raw data received from the identified access control device to track the number of occupants entering and exiting the building object entity

(e.g., via related card entities used by the occupants to enter and exit the building). Management service **406** can update a "number of occupants" attribute (or corresponding data entity) of the building object entity each time a person enters or exits the building using a related card object entity, such that the "number of occupants" attribute (or data entity) reflects the current number of occupants within the building (or related building object entity). As another example, a "total revenue" attribute associated with a product line object entity may be the summation of all the revenue generated from related point of sales entities. Management service **406** can use the raw data received from the related point of sales entities to determine when a sale of the product occurs, and can identify the amount of revenue generated by the sales. Management service **406** can then update the "total revenue" attribute (or related data entity) of the product line object entity by adding the most recent sales revenue from each of the related point of sales entities to the previous value of the attribute.

In some embodiments, management service **406** uses entity data and/or raw data from multiple different data sources to update the attributes (or corresponding data entities) of various object entities. For example, an object entity representing a person (e.g., a person's cellular device or other related object entity) may include a "risk" attribute that quantifies the person's level of risk attributable to various physical, environmental, or other conditions. Management service **406** can use relational objects of the person object entity to identify a related card device and/or a related card reader from a related building object entity (e.g., the building in which the person works) to determine the physical location of the person at any given time. Management service **406** can use weather data from a weather service in the region in which the building object entity is located to determine whether any severe weather is approaching the person's location. Similarly, management service **406** can use building data from related building entities of the building object entity to determine whether the building in which the person is located is experiencing any emergency conditions (e.g., fire, building lockdown, etc.) or environmental hazards (e.g., detected air contaminants, pollutants, extreme temperatures, etc.) that could increase the person's level of risk. Management service **406** can use these and other types of data as inputs to a risk function that calculates the value of the person object entity's "risk" attribute and can update the person object entity (or related device entity of the person) accordingly.

In some embodiments, management service **406** can be configured to synchronize configuration settings, parameters, and other device-specific information between the entities and Cloud IoT platform services **320**. In some embodiments, the synchronization occurs asynchronously. Management service **406** can be configured to manage device properties dynamically. The device properties, configuration settings, parameters, and other device-specific information can be synchronized between the smart entities created by and stored within Cloud IoT platform services **320**.

In some embodiments, management service **406** is configured to manage a manifest for each of the IoT devices. The manifest may include a set of relationships between the IoT devices and various entities. Further, the manifest may indicate a set of entitlements for the IoT devices and/or entitlements of the various entities and/or other entities. The set of entitlements may allow an IoT device and/or a user of the device to perform certain actions within the IoT environment (e.g., control, configure, monitor, and/or the like).

Still referring to FIG. **4**, transformation service **408** can provide data virtualization, and can transform various predefined standard data models for entities in a same class or type to have the same entity data structure, regardless of the device or Thing that the entity represents. For example, each device entity under a device class may include a location attribute, regardless of whether or not the location attribute is used. Thus, if an application is later developed requiring that each device entity includes a location attribute, manual mapping of heterogenous data of different entities in the same class may be avoided. Accordingly, interoperability between IoT devices and scalability of IoT applications may be improved.

In some embodiments, transformation service **408** can provide entity matching, cleansing, and correlation so that a unified cleansed view of the entity data including the entity related information (e.g., relational objects) can be provided. Transformation service **408** can support semantic and syntactic relationship description in the form of standardized relational objects between the various entities. This may simplify machine learning because the relational objects themselves provide all the relationship description between the other entities. Accordingly, the rich set of pre-built entity models and standardized relational objects may provide for rapid application development and data analytics.

For example, FIG. **6** shows a flow diagram of a process or method for updating/creating a data entity based on data received from a device, according to some embodiments. Referring to FIG. **6**, the process starts, and when raw data and/or timeseries data is received from an IoT device, the transformation service **407** may determine an identifier of the IoT device from the received data at block **605**. At block **610**, the transformation service **407** may compare an identity static attribute from the data with identity static attributes of registered object entities to locate a data container for the IoT device. If a match does not exist from the comparison at block **615**, the transformation service **407** may invoke the registration service to register the IoT device at block **620**. If a match exists from the comparison at block **615**, the transformation service **407** may generate an entity graph or retrieve entity data for the device at block **625**. From the entity graph or entity data, transformation service **407** may determine if a corresponding data entity exists based on the relational objects (e.g., isLinked) for the IoT device to update a dynamic attribute from the data at block **625**. If not, management service **406** may create a data entity for the dynamic attribute and an instance of a corresponding relational object (e.g., isLinked) to define the relationship between the dynamic attribute and created data entity at block **640**. If the corresponding data entity exists, management service **406** may update the data entity corresponding to the dynamic attribute from the data at block **645**. Then, transformation service **470** may update or regenerate the entity graph or entity data at block **650**, and the process may end.

Referring again to FIG. **4**, the search service **410** provides a unified view of product related information in the form of the entity graph, which correlates entity relationships (via relational objects) among multiple data sources (e.g., CRM, ERP, MRP and the like). In some embodiments, the search service **410** is based on a schema-less and graph based indexing architecture. For example, in some embodiments, the search service **410** provides the entity graph in which the entities are represented as nodes with relational objects defining the relationship between the entities (or nodes). The search service **410** facilitates simple queries without having to search multiple levels of the hierarchical tree of the entity

graph. For example, search service **410** can return results based on searching of entity type, individual entities, attributes, or even relational objects without requiring other levels or entities of the hierarchy to be searched.

FIG. **7** is an example entity graph of entity data according to an embodiment of the present disclosure. The example of FIG. **7** assumes that a fault based application has detected a faulty measurement with respect to IoT device 2. However, IoT device 2 relies on various other systems and devices in order to operate properly. Thus, while the faulty measurement was detected with respect to IoT device 2, IoT device 2 itself may be operating properly. Accordingly, in order to pin point the cause of the faulty measurement, the fault based application may require additional information from various related IOT systems and devices (e.g., entity objects), as well as the zones and locations (e.g., entity objects) that the systems and devices are configured to serve, in order to properly determine or infer the cause of the faulty measurement.

Referring to FIG. **7**, entity graph **700** represents each of the entities (e.g., IoT device 2 and other related entities) as nodes on the entity graph **700**, and shows the relationship between IoT device 2 and related entities via relational objects (e.g., Feeds, hasPoint, hasPart, Controls, etc.). For example, entity graph **700** shows that the entities related to IoT device 2 include a plurality of IoT systems 1-4, IoT device 1, zones 1 and 2, and locations 1 and 2, each represented as a node on the entity graph **700**. Further, the relational objects indicate that IoT device 2 provides a data point (e.g., hasPoint) to zone 1. Zone 1 is shown to service location 1 (e.g., hasPart), which is also serviced by zone 2 (e.g., hasPart). Zone 2 also services location 2 (e.g., hasPart), and is controlled by IoT system 4 (e.g., controls). IoT device 2 is shown to also provide a data point (e.g., hasPoint) to IoT system 2. IoT system 2 is shown to include IoT system 3 (e.g., hasPart), and feeds (e.g., Feeds) zone 1. Further, IoT system 2 is fed (e.g., Feeds) by IoT system 1, which receives a data point (e.g., hasPoint) from IoT device 1.

Accordingly, in the example of FIG. **7**, in response to receiving the faulty measurement from IoT device 2, the fault based application and/or analytics service **324** can determine from the entity graph that the fault could be caused by some malfunction in one or more of the other related entities, and not necessarily a malfunction of the IoT device 2. Thus, the fault based application and/or the analytics service **324** can investigate into the other related entities to determine or infer the most likely cause of the fault.

For example, FIG. **8** is a flow diagram of a process or method for analyzing data from a second related device based on data from a first device, according to some embodiments. Referring to FIG. **8**, the process starts and data including an abnormal measurement is received from a first device at block **805**. Transformation service **407** determines an identifier of the first device from the received data at block **810**. Transformation service **407** identifies a second device related to the first device through relational objects associated with the first device at block **815**. Transformation service **407** invokes web service **402** to retrieve measurement data from the second device at block **820**. Analytics service **324** analyzes the data from the first device and the second device at block **825**. Analytics service **324** provides a recommendation from the analysis of the data from each of the first device and the second device at block **830**, and the process ends.

Configuration of Exemplary Embodiments

The construction and arrangement of the systems and methods as shown in the various exemplary embodiments are illustrative only. Although only a few embodiments have been described in detail in this disclosure, many modifications are possible (e.g., variations in sizes, dimensions, structures, shapes and proportions of the various elements, values of parameters, mounting arrangements, use of materials, colors, orientations, etc.). For example, the position of elements can be reversed or otherwise varied and the nature or number of discrete elements or positions can be altered or varied. Accordingly, all such modifications are intended to be included within the scope of the present disclosure. The order or sequence of any process or method steps can be varied or re-sequenced according to alternative embodiments. Other substitutions, modifications, changes, and omissions can be made in the design, operating conditions and arrangement of the exemplary embodiments without departing from the scope of the present disclosure.

The present disclosure contemplates methods, systems and program products on any machine-readable media for accomplishing various operations. The embodiments of the present disclosure can be implemented using existing computer processors, or by a special purpose computer processor for an appropriate system, incorporated for this or another purpose, or by a hardwired system. Embodiments within the scope of the present disclosure include program products comprising machine-readable media for carrying or having machine-executable instructions or data structures stored thereon. Such machine-readable media can be any available media that can be accessed by a general purpose or special purpose computer or other machine with a processor. By way of example, such machine-readable media can comprise RAM, ROM, EPROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to carry or store desired program code in the form of machine-executable instructions or data structures and which can be accessed by a general purpose or special purpose computer or other machine with a processor. Combinations of the above are also included within the scope of machine-readable media. Machine-executable instructions include, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing machines to perform a certain function or group of functions.

Although the figures show a specific order of method steps, the order of the steps may differ from what is depicted. Also two or more steps can be performed concurrently or with partial concurrence. Such variation will depend on the software and hardware systems chosen and on designer choice. All such variations are within the scope of the disclosure. Likewise, software implementations could be accomplished with standard programming techniques with rule based logic and other logic to accomplish the various connection steps, processing steps, comparison steps and decision steps.

The term "client or "server" include all kinds of apparatus, devices, and machines for processing data, including by way of example a programmable processor, a computer, a system on a chip, or multiple ones, or combinations, of the foregoing. The apparatus may include special purpose logic circuitry, e.g., a field programmable gate array (FPGA) or an application specific integrated circuit (ASIC). The apparatus may also include, in addition to hardware, code that creates an execution environment for the computer program in question (e.g., code that constitutes processor firmware, a protocol stack, a database management system, an operating

system, a cross-platform runtime environment, a virtual machine, or a combination of one or more of them). The apparatus and execution environment may realize various different computing model infrastructures, such as web services, distributed computing and grid computing infrastructures.

The systems and methods of the present disclosure may be completed by any computer program. A computer program (also known as a program, software, software application, script, or code) may be written in any form of programming language, including compiled or interpreted languages, declarative or procedural languages, and it may be deployed in any form, including as a stand-alone program or as a module, component, subroutine, object, or other unit suitable for use in a computing environment. A computer program may, but need not, correspond to a file in a file system. A program may be stored in a portion of a file that holds other programs or data (e.g., one or more scripts stored in a markup language document), in a single file dedicated to the program in question, or in multiple coordinated files (e.g., files that store one or more modules, sub programs, or portions of code). A computer program may be deployed to be executed on one computer or on multiple computers that are located at one site or distributed across multiple sites and interconnected by a communication network.

The processes and logic flows described in this specification may be performed by one or more programmable processors executing one or more computer programs to perform actions by operating on input data and generating output. The processes and logic flows may also be performed by, and apparatus may also be implemented as, special purpose logic circuitry (e.g., an FPGA or an ASIC).

Processors suitable for the execution of a computer program include, by way of example, both general and special purpose microprocessors, and any one or more processors of any kind of digital computer. Generally, a processor will receive instructions and data from a read only memory or a random access memory or both. The essential elements of a computer are a processor for performing actions in accordance with instructions and one or more memory devices for storing instructions and data. Generally, a computer will also include, or be operatively coupled to receive data from or transfer data to, or both, one or more mass storage devices for storing data (e.g., magnetic, magneto-optical disks, or optical disks). However, a computer need not have such devices. Moreover, a computer may be embedded in another device (e.g., a mobile telephone, a personal digital assistant (PDA), a mobile audio or video player, a game console, a Global Positioning System (GPS) receiver, or a portable storage device (e.g., a universal serial bus (USB) flash drive), etc.). Devices suitable for storing computer program instructions and data include all forms of non-volatile memory, media and memory devices, including by way of example semiconductor memory devices (e.g., EPROM, EEPROM, and flash memory devices; magnetic disks, e.g., internal hard disks or removable disks; magneto-optical disks; and CD ROM and DVD-ROM disks). The processor and the memory may be supplemented by, or incorporated in, special purpose logic circuitry.

In various implementations, the steps and operations described herein may be performed on one processor or in a combination of two or more processors. For example, in some implementations, the various operations could be performed in a central server or set of central servers configured to receive data from one or more devices (e.g., edge computing devices/controllers) and perform the operations. In some implementations, the operations may be performed by one or more local controllers or computing devices (e.g., edge devices), such as controllers dedicated to and/or located within a particular building or portion of a building. In some implementations, the operations may be performed by a combination of one or more central or offsite computing devices/servers and one or more local controllers/computing devices. All such implementations are contemplated within the scope of the present disclosure. Further, unless otherwise indicated, when the present disclosure refers to one or more computer-readable storage media and/or one or more controllers, such computer-readable storage media and/or one or more controllers may be implemented as one or more central servers, one or more local controllers or computing devices (e.g., edge devices), any combination thereof, or any other combination of storage media and/or controllers regardless of the location of such devices.

To provide for interaction with a user, implementations of the subject matter described in this specification may be implemented on a computer having a display device (e.g., a CRT (cathode ray tube), LCD (liquid crystal display), OLED (organic light emitting diode), TFT (thin-film transistor), or other flexible configuration, or any other monitor for displaying information to the user and a keyboard, a pointing device, e.g., a mouse, trackball, etc., or a touch screen, touch pad, etc.) by which the user may provide input to the computer. Other kinds of devices may be used to provide for interaction with a user as well; for example, feedback provided to the user may be any form of sensory feedback (e.g., visual feedback, auditory feedback, or tactile feedback), and input from the user may be received in any form, including acoustic, speech, or tactile input. In addition, a computer may interact with a user by sending documents to and receiving documents from a device that is used by the user; for example, by sending web pages to a web browser on a user's client device in response to requests received from the web browser.

Implementations of the subject matter described in this disclosure may be implemented in a computing system that includes a back-end component (e.g., as a data server), or that includes a middleware component (e.g., an application server), or that includes a front end component (e.g., a client computer) having a graphical user interface or a web browser through which a user may interact with an implementation of the subject matter described in this disclosure, or any combination of one or more such back end, middleware, or front end components. The components of the system may be interconnected by any form or medium of digital data communication (e.g., a communication network). Examples of communication networks include a LAN and a WAN, an inter-network (e.g., the Internet), and peer-to-peer networks (e.g., ad hoc peer-to-peer networks).

The present disclosure may be embodied in various different forms, and should not be construed as being limited to only the illustrated embodiments herein. Rather, these embodiments are provided as examples so that this disclosure will be thorough and complete, and will fully convey the aspects and features of the present disclosure to those skilled in the art. Accordingly, processes, elements, and techniques that are not necessary to those having ordinary skill in the art for a complete understanding of the aspects and features of the present disclosure may not be described. Unless otherwise noted, like reference numerals denote like elements throughout the attached drawings and the written description, and thus, descriptions thereof may not be repeated. Further, features or aspects within each example

embodiment should typically be considered as available for other similar features or aspects in other example embodiments.

It will be understood that, although the terms "first," "second," "third," etc., may be used herein to describe various elements, components, regions, layers and/or sections, these elements, components, regions, layers and/or sections should not be limited by these terms. These terms are used to distinguish one element, component, region, layer or section from another element, component, region, layer or section. Thus, a first element, component, region, layer or section described below could be termed a second element, component, region, layer or section, without departing from the spirit and scope of the present disclosure.

The terminology used herein is for the purpose of describing particular embodiments and is not intended to be limiting of the present disclosure. As used herein, the singular forms "a" and "an" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises," "comprising," "includes," and "including," "has," "have," and "having," when used in this specification, specify the presence of the stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items. Expressions such as "at least one of," when preceding a list of elements, modify the entire list of elements and do not modify the individual elements of the list.

As used herein, the term "substantially," "about," and similar terms are used as terms of approximation and not as terms of degree, and are intended to account for the inherent variations in measured or calculated values that would be recognized by those of ordinary skill in the art. Further, the use of "may" when describing embodiments of the present disclosure refers to "one or more embodiments of the present disclosure." As used herein, the terms "use," "using," and "used" may be considered synonymous with the terms "utilize," "utilizing," and "utilized," respectively. Also, the term "exemplary" is intended to refer to an example or illustration.

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What is claimed is:

1. A web platform comprising:

one or more computer readable storage media storing instructions thereon that, when executed by one or more processors, cause the one or more processors to:

generate a database of digital twins, the database of digital twins comprising sensor digital twins representing sensors of an environment, data entities representing measurements received from the sensors, and relational objects indicating relationships between the digital twins and the data entities, the relational objects including a plurality of semantic relationship types;

receive a new measurement from a sensor of the sensors;

identify a data entity of the data entities by identifying a relational object of the relational objects including a particular semantic relationship type of the plurality of semantic relationship types between a sensor digital twin of the sensor digital twins representing the sensor and the data entity; and

in response to identifying that the data entity is related to the sensor digital twin representing the sensor by the relational object including the particular semantic relationship type, modify the data entity to include or be associated with the new measurement received from the sensor.

2. The web platform of claim **1**, wherein the instructions cause the one or more processors to:

periodically receive new measurements from the sensor; and

update the data entity each time a particular new measurement from the sensor is received.

3. The web platform of claim **1**, further comprising:

the sensor configured to send the new measurement to a cloud computing system of the web platform in response to detecting an event;

wherein the instructions cause the one or more processors to update the data entity to include a data value representative of the event.

4. The web platform of claim **1**, wherein the new measurement from the sensor is received in a first protocol or format;

wherein the instructions cause the one or more processors to:

receive a second new measurement from a second sensor of the sensors, wherein the new measurement from the second sensor is received in a second protocol or format;

convert the new measurement from the sensor from the first protocol or format into a third protocol or format; and

convert the second new measurement from the second sensor from the second protocol or format into the third protocol or format.

5. The web platform of claim **1**, wherein the sensor digital twins include static attributes identifying the sensors represented by the sensor digital twins and dynamic attributes storing a most recent measurement received from the sensors.

6. The web platform of claim **1**, wherein the data entity includes a static attribute identifying the sensor and a dynamic attribute storing a most recent measurement received from the sensor.

7. The web platform of claim **1**, wherein the relational objects include attributes identifying the sensor digital twins and second attributes identifying the data entities.

8. The web platform of claim **1**, wherein the instructions cause the one or more processors to modify the data entity by:

using an attribute of the new measurement received from the sensor to identify the sensor digital twin associated with the sensor;

identifying the relational object connecting the sensor digital twin to the data entity; and

storing a value of the new measurement received from the sensor in the data entity identified by the relational object.

9. The web platform of claim **1**, wherein the data entity includes or is associated with a plurality of past measurements received from the sensor.

10. A method comprising:

generating, by one or more processing circuits, a database of digital twins, the database of digital twins compris-

ing sensor digital twins representing sensors of an environment, data entities representing measurements received from the sensors, and relational objects indicating relationships between the digital twins and the data entities, the relational objects including a plurality of semantic relationship types;

receiving, by the one or more processing circuits, a new measurement from a sensor of the sensors;

identifying, by the one or more processing circuits, a data entity of the data entities by identifying a relational object of the relational objects including a particular semantic relationship type of the plurality of semantic relationship types between a sensor digital twin of the sensor digital twins representing the sensor and the data entity; and

in response to identifying that the data entity is related to the sensor digital twin representing the sensor by the relational object including the particular semantic relationship type, modifying, by the one or more processing circuits, the data entity to include or be associated with the new measurement received from the sensor.

11. The method of claim **10**, further comprising:

periodically receiving, by the one or more processing circuits, new measurements from the sensor; and

updating, by the one or more processing circuits, the data entity each time a particular new measurement from the sensor is received.

12. The method of claim **10**, further comprising:

receiving, by the one or more processing circuits, the new measurement from the sensor in response to the sensor detecting an event; and

updating, by the one or more processing circuits, the data entity to include a data value representative of the event.

13. The method of claim **10**, wherein the new measurement from the sensor is received in a first protocol or format; the method comprising:

receiving, by the one or more processing circuits, a second new measurement from a second sensor of the sensors, wherein the new measurement from the second sensor is received in a second protocol or format;

converting, by the one or more processing circuits, the new measurement from the sensor from the first protocol or format into a third protocol or format; and

converting, by the one or more processing circuits, the second new measurement from the second sensor from the second protocol or format into the third protocol or format.

14. The method of claim **10**, wherein the sensor digital twins include static attributes identifying the sensors represented by the sensor digital twins and dynamic attributes storing a most recent measurement received from the sensors.

15. The method of claim **10**, wherein the data entity includes a static attribute identifying the sensor and a dynamic attribute storing a most recent measurement received from the sensor.

16. The method of claim **10**, wherein the relational objects include attributes identifying the sensor digital twins and second attributes identifying the data entities.

17. The method of claim **10**, wherein modifying, by the one or more processing circuits, the data entity comprises:

using an attribute of the new measurement received from the sensor to identify the sensor digital twin associated with the sensor;

identifying the relational object connecting the sensor digital twin to the data entity; and

storing a value of the new measurement received from the sensor in the data entity identified by the relational object.

18. One or more computer-readable storage media having instructions stored thereon that, when executed by one or more processors, cause the one or more processors to:

generate a database of digital twins, the database of digital twins comprising sensor digital twins representing sensors of an environment, data entities representing measurements received from the sensors, and relational objects indicating relationships between the sensor digital twins and the data entities, the relational objects including a plurality of semantic relationship types;

receive a new measurement from a sensor;

identify a data entity of the data entities by identifying a relational object of the relational objects including a particular semantic relationship type of the plurality of semantic relationship types between a sensor digital twin of the sensor digital twins representing the sensor and the data entity; and

in response to identifying that the data entity is related to the sensor digital twin representing the sensor by the relational object including the particular semantic relationship type, modify the data entity to include or be associated with the new measurement received from the sensor.

19. The one or more computer-readable storage media of claim **18**, wherein the data entity includes a static attribute identifying the sensor and a dynamic attribute storing a most recent measurement received from the sensor.

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