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(71) Applicant: **QEATECH INC.** [CA/CA]; 48 Riviera Drive, Markham, Ontario L3R 5M1 (CA).

(72) Inventors: **ASRANI, Mansour**; c/o QEATECH INC., 48 Riviera Drive, Markham, Ontario L3R 5M1 (CA). **RAD, Peyvand Melati**; c/o QEATECH INC., 48 Riviera Drive, Markham, Ontario L3R 5M1 (CA). **ALAEI, Omid**; c/o QEATECH INC., 48 Riviera Drive, Markham, Ontario L3R 5M1 (CA).

(74) Agent: **HINTON, James W.**; Own Innovation, 210-137 Glasgow St, Office 214, Kitchener, Ontario N2G 4X8 (CA).

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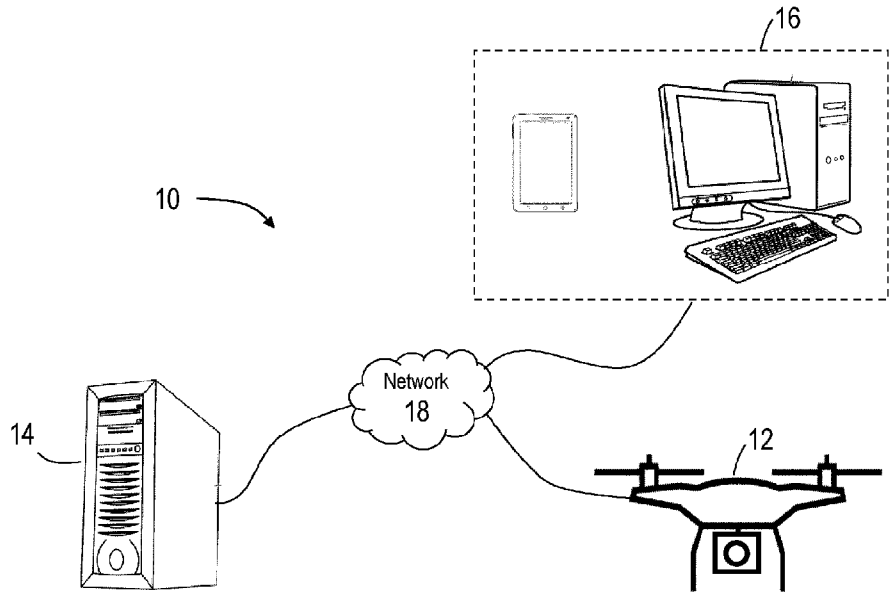


FIG. 1

(57) Abstract: A system and associated method for thermal inspection of structures is provided. The method includes providing one or more unmanned aerial vehicles ("UAV"), each UAV comprising at least one of a thermal camera and/or a visible light camera, and a positioning system, flying the UAV along a predetermined flight path around an inspection structure, capturing thermal image data and light image data of the inspection structure, and positioning data at regular intervals, while the UAV flies along the flight path, transmitting captured data to a processing device inputting the thermal image data, visible light image data and the positioning data into a building envelope element detection module, generating building element data and inputting building element data, thermal image data and visible light image data into a thermal anomaly module of the processing device, generating thermal anomaly data as an output, the thermal anomaly data comprising thermal anomaly locations and classifications.

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METHOD AND SYSTEM FOR BUILDING ENVELOPE ANOMALY DETECTION

Technical Field

[0001] The following relates generally to thermal anomaly detection systems and methods, and more particularly to systems and methods for detecting thermal anomalies of buildings by comparing visible light and thermal images captured using unmanned aerial vehicles.

Introduction

[0002] Structures, such as buildings may be configured to maintain internal temperatures differing from external temperatures, by the application of HVAC systems which maintain the internal climate of the structure according to certain specifications.

[0003] Buildings may be insulated to reduce the rate of heat transfer from the interior of the building or structure to the exterior, or vice versa. This reduction of heat transfer may advantageously result in reduced energy requirements (and therefore cost) to maintain internal building climate, and may maintain a more consistent temperature across the interior of the building or structure.

[0004] Insulation, such as wall panels, roof panels, insulating windows and other insulating components may be subject to wear and tear and degradation, which may reduce insulating performance. It may be difficult to detect such degradation, as it may not be visible to the naked eye.

[0005] Similarly, while certain equipment such as thermal cameras may detect thermal leakages which indicate insulation degradation, the use of such equipment may require large amounts of skilled labor to conduct the inspection and analyze the acquired thermal images to detect thermal anomalies.

[0006] Accordingly, there is a need for improved systems and methods for structural thermal anomaly detection that overcome at least some of the disadvantages of the current systems and methods.

Summary

[0007] Described herein is a thermal inspection method. The method includes providing one or more unmanned aerial vehicles (“UAV”), each UAV comprising one or more camera

systems (e.g., a thermal infrared camera for capturing thermal image data, a visible light camera for capturing visible light image data), and a positioning system for capturing positioning data; operating the UAV by flying the UAV along a predetermined flight path around an inspection structure; capturing thermal image data of the inspection structure, visible light image data of the inspection structure, and positioning data at regular intervals, while the UAV flies along the flight path; transmitting thermal image data, visible light image data and positioning data to a processing device; receiving the thermal image data, visible light image data, and positioning data at the processing device; inputting the thermal image data, visible light image data and the positioning data into a building envelope element detection module of the processing device; generating building element data; and inputting building element data, thermal image data and visible light image data into a thermal anomaly module of the processing device; generating thermal anomaly data as an output, the thermal anomaly data comprising thermal anomaly locations and classifications.

[0008] According to some embodiments, the method further comprising providing thermal anomaly data into a report generation module of the processing device, receiving a thermal inspection report as an output.

[0009] According to some embodiments, the thermal anomaly module inputs building element data, infrared image data and visible light image data into the input layer of a trained neural network, and receives thermal anomaly data as an output.

[0010] According to some embodiments, regions within thermal image data and visible light image data are assessed for thermal anomalies using the thermal anomaly module according to the associated building element of each region.

[0011] According to some embodiments, the processing device further comprising a position correlation module, the method further comprising: providing positioning data, visible light image data, and thermal image data to the position correlation module as input, and generating scale data, inputting the scale data into the thermal anomaly module when generating thermal anomaly data, and inputting the scale data into the building element detection module when generating building element data.

[0012] According to some embodiments, the thermal camera comprises a resolution of at least 1024 x 1024 pixels.

[0013] According to some embodiments, the building element data comprises wall, door, window or roof class building elements.

[0014] According to some embodiments, the thermal report comprises heat loss data.

[0015] According to some embodiments, thermal anomaly data is characterized according to building element data.

[0016] Described herein is a thermal inspection system. The system includes: one or more UAVs, each UAV comprising one or more camera systems (e.g., a thermal camera for capturing thermal image data and/or a visible light camera for capturing visible light image data) and a positioning system for capturing position data, an inspection structure, and a processing device, wherein each UAV is configured to: fly along a predetermined flight path around an inspection structure, capturing thermal image data of the inspection structure, visible light image data of the inspection structure, and positioning data at regular intervals, while the UAV flies along the flight path, and transmit thermal image data, visible light image data and positioning data to a processing device, through a network, wherein the processing device is configured to: receive the thermal image data, visible light image data, and positioning data; input the thermal image data, visible light image data and the positioning data into a building envelope element detection module of the processing device, generating building element data, and input building element data, thermal image data and visible light image data to a thermal anomaly module of the processing device, generating thermal anomaly data as an output, the thermal anomaly data comprising thermal anomaly locations and classifications.

[0017] According to some embodiments, the processing device is further configured to provide thermal anomaly data into a report generation module of the processing device, and receive a thermal inspection report as an output.

According to some embodiments, the thermal anomaly module inputs building element data, infrared image data and visible light image data into the input layer of a trained neural network, and receives thermal anomaly data as an output.

[0018] According to some embodiments, regions within thermal image data and visible light image data are assessed for thermal anomalies using the thermal anomaly module according to the associated building element of each region.

[0019] According to some embodiments, the processing device further comprises a position correlation module, the processing device further configured to: provide positioning data, visible light image data, and thermal image data to the position correlation module as input, and generating scale data, input the scale data into the thermal anomaly module when generating thermal anomaly data, and input the scale data into the building element detection module when generating building element data.

[0020] According to some embodiments, the thermal camera comprises a resolution of at least 1024 x 1024 pixels. According to some embodiments, the building element data comprises wall, door, window or roof class building elements.

[0021] According to some embodiments, the thermal report comprises heat loss data. According to some embodiments, thermal anomaly data is characterized according to building element data.

[0022] Other aspects and features will become apparent to those ordinarily skilled in the art, upon review of the following description of some exemplary embodiments.

Brief Description of the Drawings

[0023] The drawings included herewith are for illustrating various examples of articles, methods, and apparatuses of the present specification. In the drawings:

[0024] Figure 1 is a system diagram of a thermal inspection system, according to an embodiment;

[0025] Figure 2 is a system diagram of a computing device, for use with a thermal inspection system, according to an embodiment;

[0026] Figure 3 is a system diagram of a thermal inspection system, according to another embodiment;

[0027] Figure 4 is a system block diagram of the UAV of the thermal inspection system of Figure 3, according to an embodiment;

[0028] Figure 5 is a system block diagram of the cloud processing device of the thermal inspection system of Figures 3 and 4, according to an embodiment;

[0029] Figure 6 is a system block diagram of the memory of the cloud processing device of Figures 3 to 5, according to an embodiment;

[0030] Figure 7 is a depiction of an image stitching operation before stitching, as may be applied by the thermal inspection system of Figures 3 to 6, according to an embodiment;

[0031] Figure 8 is a depiction of an image stitching operation after stitching, as may be applied by the thermal inspection system of Figures 3 to 6, according to an embodiment;

[0032] Figure 9 is a depiction of the output of a building envelope element detection process, as may be applied by the thermal inspection system of Figures 3 to 6, according to an embodiment;

[0033] Figure 10 is a depiction of the output of a thermal anomaly detection process, as may be applied by the thermal inspection system of Figures 3 to 6, according to an embodiment;

[0034] Figure 11 is a side by side depiction a thermal image and visible light image of an inspection structure, as may be captured by the thermal inspection system of Figures 3 to 6, according to an embodiment;

[0035] Figure 12 is a side by side depiction a thermal image and visible light image of an inspection structure, as may be captured by the thermal inspection system of Figures 3 to 6, according to another embodiment;

[0036] Figure 13 is a depiction of a sample thermal inspection report, as may be generated by the thermal inspection system of Figures 3 to 6, according to an embodiment; and

[0037] Figure 14 is a flow chart of a thermal inspection method, according to an embodiment.

Detailed Description

[0038] Various apparatuses or processes will be described below to provide an example of each claimed embodiment. No embodiment described below limits any claimed embodiment and any claimed embodiment may cover processes or apparatuses that differ from those described below. The claimed embodiments are not limited to apparatuses or processes having all of the features of any one apparatus or process described below or to features common to multiple or all of the apparatuses described below.

[0039] One or more systems described herein may be implemented in computer programs executing on programmable computers, each comprising at least one processor, a data storage system (including volatile and non-volatile memory and/or storage elements), at least one input device, and at least one output device. For example, and without limitation, the programmable computer may be a programmable logic unit, a mainframe computer, server, and personal computer, cloud-based program or system, laptop, personal data assistance, cellular telephone, smartphone, or tablet device.

[0040] Each program is preferably implemented in a high-level procedural or object-oriented programming and/or scripting language to communicate with a computer system. However, the programs can be implemented in assembly or machine language, if desired. In any case, the language may be a compiled or interpreted language. Each such computer program is preferably stored on a storage media or a device readable by a general or special purpose programmable computer for configuring and operating the computer when the storage media or device is read by the computer to perform the procedures described herein.

[0041] A description of an embodiment with several components in communication with each other does not imply that all such components are required. On the contrary, a variety of optional components are described to illustrate the wide variety of possible embodiments of the present invention.

[0042] Further, although process steps, method steps, algorithms or the like may be described (in the disclosure and / or in the claims) in a sequential order, such processes, methods and algorithms may be configured to work in alternate orders. In other words, any sequence or order of steps that may be described does not necessarily indicate a requirement that the steps be performed in that order. The steps of processes described herein may be performed in any order that is practical. Further, some steps may be performed simultaneously.

[0043] When a single device or article is described herein, it will be readily apparent that more than one device / article (whether or not they cooperate) may be used in place of a single device / article. Similarly, where more than one device or article is described herein (whether or not they cooperate), it will be readily apparent that a single device / article may be used in place of the more than one device or article.

[0044] The following relates generally to methods and systems for detecting structure defects, and more particularly to systems and methods for detecting thermal anomalies, such as cracks, moisture leaks of buildings using visible light images and thermal images captured using one or more unmanned aerial vehicles.

[0045] A large expense associated with operating a building or structure is climate control, wherein the interior portions of the building are heated, cooled, humidified and/or dehumidified. In order to reduce energy usage and therefore costs associated with climate control, buildings may be insulated to reduce heat transfer into and out of the building.

[0046] Over time, insulating materials and structures may degrade. For example, multi-pane glass windows may degrade such that internal gas tight seals no longer function, decreasing the insulating performance of the glass windows. This may increase the rate of heat transfer across the window.

[0047] Similarly, insulation or panels on the exterior of the building or structure may develop cracks or moisture leaks. Such cracks or leaks may reduce insulating performance of the insulation or panel, increasing the rate of heat transfer across the panel or window.

[0048] It may be difficult to detect such defects leading to reduced insulating performance. Insulation defects are often impossible to detect with the naked eye. Inspectors may employ technology such as infrared / thermal cameras to detect insulation defects, however, such methods are time consuming to carry out and analyze, and require highly skilled human operators.

[0049] Described herein are systems and methods for detecting structure thermal anomalies. One or more unmanned aerial vehicles may be provided. The unmanned aerial vehicle may conduct a preplanned flight around a structure, and capture a comprehensive set of overlapping images, along with position and orientation data. Images may be captured both the visible light and thermal infrared domains. Thermal images and visible light images may be taken at approximately the same angles, such that corresponding thermal and visible light images of each scene exist.

[0050] After images have been captured, images may be provided to a computing device for processing. The computing device may be configured to stitch together separate images into a continuous image, determine image scale and orientation using UAV position and orientation data,

apply automated methods to detect building elements, and analyze thermal images to detect thermal anomalies, such as cracks.

[0051] Once thermal anomalies have been detected, thermal inspection reports may be generated and outputted, for further action. For example, such a thermal report may be provided to a building manager or property owner, such that they may arrange for appropriate repairs or maintenance, or a prospective investor or purchaser, to assess the value of the structure.

[0052] Referring first to Figure 1, shown therein is a block diagram illustrating a thermal inspection system 10, in accordance with an embodiment. The system 10 includes one or more inspection unmanned aerial vehicles (UAV) 12 which communicates with a cloud processing device 14, and an operator terminal 16 via a network 18. The cloud processing device 14 may be a purpose-built machine designed specifically for processing thermal images, visible light images and other associated inspection data captured by UAV 12 to generate thermal inspection reports. The UAV 12 may be an unmanned aerial vehicle equipped with at least one camera (e.g., a thermal camera and/or a visible light camera) and positioning system, and may be operated to collect inspection data. The UAV 12 and/or the inspection operation as a whole may be configured or controlled by operator terminal 16 (e.g. the desired inspection target or flight path may be input into the terminal 16 by an operator).

[0053] In some examples of system 10, cloud processing device 14, and operator terminal 16 may comprise a single device.

[0054] The cloud processing device 14, and operator terminal 16 may be a server computer, desktop computer, notebook computer, tablet, PDA, smartphone, or another computing device. The devices 14, 16 may include a connection with the network 18 such as a wired or wireless connection to the Internet. In some cases, the network 18 may include other types of computer or telecommunication networks. The devices 14, 16 may include one or more of a memory, a secondary storage device, a processor, an input device, a display device, and an output device. Memory may include random access memory (RAM) or similar types of memory. Also, memory may store one or more applications for execution by processor. Applications may correspond with software modules comprising computer executable instructions to perform processing for the functions described below. Secondary storage device may include a hard disk drive, Blu-ray drive, or other types of non-volatile data storage. Processor may execute

applications, computer readable instructions or programs. The applications, computer readable instructions or programs may be stored in memory or in secondary storage, or may be received from the Internet or other network 18. Input device may include any device for entering information into device 14, 16. For example, input device may be a keyboard, keypad, cursor-control device, touch-screen, camera, or microphone. Display device may include any type of device for presenting visual information. For example, display device may be a computer monitor, a flat-screen display, a projector or a display panel. Output device may include any type of device for presenting a hard copy of information, such as a printer for example. Output device may also include other types of output devices such as speakers, for example. In some cases, device 14, 16 may include multiple of any one or more of processors, applications, software modules, second storage devices, network connections, input devices, output devices, and display devices.

[0055] Although devices 14, 16 are described with various components, one skilled in the art will appreciate that the devices 14, 16 may in some cases contain fewer, additional or different components. In addition, although aspects of an implementation of the devices 14, 16 may be described as being stored in memory, one skilled in the art will appreciate that these aspects can also be stored on or read from other types of computer program products or computer-readable media, such as secondary storage devices, including hard disks, floppy disks, CDs, or DVDs; a carrier wave from the Internet or other network; or other forms of RAM or ROM. The computer-readable media may include instructions for controlling the devices 14, 16 and/or processor to perform a particular method.

[0056] In the description that follows, devices such as UAV 12, cloud processing device 14, and operator terminal 16 are described performing certain acts. It will be appreciated that any one or more of these devices may perform an act automatically or in response to an interaction by a user of that device. That is, the user of the device may manipulate one or more input devices (e.g. a touchscreen, a mouse, or a button) causing the device to perform the described act. In many cases, this aspect may not be described below, but it will be understood.

[0057] As an example, it is described below that the devices 12, 16 may send information to the cloud processing device 14. For example, an operator user using the operator terminal 16 may manipulate one or more input devices (e.g. a mouse and a keyboard) to interact with a user interface displayed on a display of the operator terminal 16. Generally, the device may receive a

user interface from the network 18 (e.g. in the form of a webpage). Alternatively, or in addition, a user interface may be stored locally at a device (e.g. a cache of a webpage or a mobile application).

[0058] Cloud processing device 14 may be configured to receive a plurality of information, from the UAV 12, and operator device 16. Generally, the information may comprise at least a thermal image and a visible light image.

[0059] In response to receiving information, the cloud processing device 14 may store the information in a storage database. The storage may correspond with secondary storage of the device 12, 14, 16. Generally, the storage database may be any suitable storage device such as a hard disk drive, a solid state drive, a memory card, or a disk (e.g. CD, DVD, or Blu-ray etc.). Also, the storage database may be locally connected with cloud processing device 14. In some cases, storage database may be located remotely from cloud processing device 14 and accessible to cloud processing device 14 across a network for example. In some cases, storage database may comprise one or more storage devices located at a networked cloud storage provider.

[0060] Referring now to Figure 2, Figure 2 shows a simplified block diagram of components of a computing device 1000, such as a mobile device or portable electronic device, according to an embodiment. Software modules described in the disclosure herein may be configured to run on a computing device, such as device 1000 of Figure 2. The device 1000 includes multiple components such as a processor 1020 that controls the operations of the device 1000. Communication functions, including data communications, voice communications, or both may be performed through a communication subsystem 1040. Data received by the device 1000 may be decompressed and decrypted by a decoder 1060. The communication subsystem 1040 may receive messages from and send messages to a wireless network 1500.

[0061] The wireless network 1500 may be any type of wireless network, including, but not limited to, data-centric wireless networks, voice-centric wireless networks, and dual-mode networks that support both voice and data communications.

[0062] The device 1000 may be a battery-powered device and as shown includes a battery interface 1420 for receiving one or more rechargeable batteries 1440.

[0063] The processor 1020 also interacts with additional subsystems such as a Random Access Memory (RAM) 1080, a flash memory 1100, a display 1120 (e.g. with a touch-sensitive overlay 1140 connected to an electronic controller 1160 that together comprise a touch-sensitive display 1180), an actuator assembly 1200, one or more optional force sensors 1220, an auxiliary input/output (I/O) subsystem 1240, a data port 1260, a speaker 1280, a microphone 1300, short-range communications systems 1320 and other device subsystems 1340.

[0064] In some embodiments, user-interaction with the graphical user interface may be performed through the touch-sensitive overlay 1140. The processor 1020 may interact with the touch-sensitive overlay 1140 via the electronic controller 1160. Information, such as text, characters, symbols, images, icons, and other items that may be displayed or rendered on a portable electronic device generated by the processor 102 may be displayed on the touch-sensitive display 118.

[0065] The processor 1020 may also interact with an accelerometer 1360 as shown in Figure 2. The accelerometer 1360 may be utilized for detecting direction of gravitational forces or gravity-induced reaction forces.

[0066] To identify a subscriber for network access according to the present embodiment, the device 1000 may use a Subscriber Identity Module or a Removable User Identity Module (SIM/RUIM) card 1380 inserted into a SIM/RUIM interface 1400 for communication with a network (such as the wireless network 1500). Alternatively, user identification information may be programmed into the flash memory 1100 or performed using other techniques.

[0067] The device 1000 also includes an operating system 1460 and software components 1480 that are executed by the processor 1020 and which may be stored in a persistent data storage device such as the flash memory 1100. Additional applications may be loaded onto the device 1000 through the wireless network 1500, the auxiliary I/O subsystem 1240, the data port 1260, the short-range communications subsystem 1320, or any other suitable device subsystem 1340.

[0068] For example, in use, a received signal such as a text message, an e-mail message, web page download, or other data may be processed by the communication subsystem 1040 and input to the processor 1020. The processor 1020 then processes the received signal for output to the display 1120 or alternatively to the auxiliary I/O subsystem 1240. A subscriber may also

compose data items, such as e-mail messages, for example, which may be transmitted over the wireless network 1500 through the communication subsystem 1040.

[0069] For voice communications, the overall operation of the portable electronic device 1000 may be similar. The speaker 1280 may output audible information converted from electrical signals, and the microphone 1300 may convert audible information into electrical signals for processing.

[0070] Referring now to Figure 3, pictured therein is a system block diagram of thermal inspection system 100. System 100 may correspond to systems 10 and 1000 of Figures 1 and 2. System 100 includes one or more UAV 102, inspection structure 104, network 106, and cloud processing device 108.

[0071] UAV 102 is an unmanned aerial vehicle. UAV 102 may comprise a multi-rotor unmanned aircraft, such as a quadcopter. UAV 102 may be configured to conduct autonomous flights with predetermined flight paths 110. For example, UAV 102 may be programmed to take off from a launch location, fly upwards 2m, forwards 4m, backwards 4m, and downwards 4m to land, such that UAV 102 is back at its original position. Similarly, UAV 102 may be preprogrammed to fly a certain pre-determined path around a building.

[0072] UAV 102 may comprise a UAV compatible with dual synchronized camera system payload (e.g., synchronized thermal and visible light cameras), and a UAV comprising advanced flight controller systems, 6 directional sensing and positioning, a first-person view camera, collision mitigation system, radar, return-to-home, obstacle sensing, artificial intelligence based spot-check, awareness of nearby aircraft, auxiliary lights for night operation, and hot swappable batteries. Inspection structure 104 is any building or structure known in the art wherein thermal insulation performance may be of interest. For example, inspection structure 104 may be a permanent concrete building, a modular building, a mobile home, or other structure having an interior volume, wherein the interior volume is to be maintained at a temperature other than the external environmental temperature.

[0073] UAV 102 may be configured to fly a predetermined flight path 110 around inspection structure 104, and capture images (thermal and/or visible light images) of all external surfaces or a subset of the external surfaces of inspection structure 104 (e.g. see imaging field of view 112 of Figure 3). Where the UAV 102 comprises both visible light and thermal camera

systems, visible light images and thermal images may be captured simultaneously. In some embodiments, images may be captured from inside the inspection structure 104. "Captured images", as used herein, collectively refers to both thermal images and visible light images.

[0074] Flight path 110 may include position and time data for the entire flight, as well as UAV 102 orientation throughout the entire flight. Flight path 110 may be preprogrammed by a skilled operator, assisted by flight planning software. Flight path 110 data may be stored in electronic form and provided to UAV 102. In some examples, an external operator terminal, or controller (e.g. device 16 of system 10) may be used to transmit flight path 110 data to UAV, over a network (e.g. network 18 of system 10). In embodiments where multiple UAVs are used to capture images of the inspection structure, the flight paths of each UAV adhere to a singular preprogrammed flight path to ensure the images captured by each UAV are superimposable using the position data for the captured images.

[0075] In other embodiments, instead of a pre-configured flight path, the UAV may be flown manually by a skilled operator. In some embodiments, instead of capturing data with a UAV, a stationary imaging system may be utilized for the herein systems and methods.

[0076] Referring now to Figure 4, shown therein is a block diagram detailing components of UAV 102. The UAV 102 includes at least one camera system – a thermal camera system 114 and/or a visible light camera system 116. The UAV 102 further a storage medium 118, a network interface 120, and a positioning system 122. According to various embodiments, the UAV 102 may be configured for daytime or nighttime operation. For example, for nighttime operations, a first UAV 102 is equipped with both a thermal camera system 114 and a visible light camera system 116, the latter being used when lighting conditions permit; for daytime operations, a second UAV 102 is equipped with a high-resolution, high framerate visible light camera system 116, specifically tailored for generating 3D models.

[0077] Thermal camera system 114 includes at least one thermal camera. The thermal camera may capture thermal images in the infrared electromagnetic radiation band, including wavelengths between 1000 nm and 14000 nm. Each pixel of each captured thermal image may correspond to an intensity of received infrared radiation.

[0078] Thermal camera system 114 may be calibrated, such that each captured pixel may correspond to a temperature value. For example, a thermal image may include 1024x1024 pixels,

capturing a specific scene. The top left pixel of the image may correspond to a 25 degree Celsius reading, while each neighboring pixel may correspond to a 24 degree Celsius reading. Such thermal correlation of captured data may be conducted at the firmware level of thermal camera system 114 or otherwise at a low hardware level of thermal camera system 114.

[0079] All captured thermal images may be stored on storage medium 118. Captured thermal images may be additionally associated with metadata when stored on storage medium. Such metadata may include, for example, time of capture, UAV position and orientation at time of capture, ambient temperature at the time of capture and associated visible light images. Additional metadata may be captured which may not be associated with any specific or particular images, for example, without limitation, times and dates, flying time per session, latitude, longitude, height, height max, speed, rotational speed of each motor, speed components in the x, y, and z directions, pitch, yaw, roll, list of comments from flight controller, GPS data, number of GPS satellites, battery history, flight path, takeoff history and landing history.

[0080] Visible light camera 116 may capture images in the visible light electromagnetic radiation band, including wavelengths between 400 nm and 700 nm. Visible light camera 116 may capture images of a minimum resolution of 640 pixels by 512 pixels. In other examples, visible light camera 116 may capture images with different resolutions, such as 4K resolution. Visible light cameras with greater resolutions may provide for greater precision and/or performance.

[0081] Visible light camera 116 may be mounted to UAV 102 on a gimbal, allowing for the relative position of visible light camera 116 and UAV 102 to be varied. Such a gimbal may allow for rotation at a rate of 100° per second, and a rotational range of +330° to -330°, +135° to -45°, and +25° to -90° in the pan, tilt and roll directions respectively. In some examples, the gimbal may be configured to operate in environments between -20°C and +50°C.

[0082] All captured visible light images may be stored on storage medium 118. Captured visible light mages may be additionally associated with metadata when stored on storage medium 118. Such metadata may include, for example, time of capture, UAV position and orientation at time of capture, ambient temperature at the time of capture. And associated thermal images.

[0083] The storage medium 118 comprises any non-transient computer readable memory known in the art. Storage medium 118 may be, without limitation, a hard drive, solid state drive, NAND flash, or tape drive.

[0084] The network interface 120 may include any device, hardware, module or system that may enable UAV 102 to communicate with another electronic device, such as a computer system, and transmit data to such devices. Network interface 120 may comprise a RF transmission subsystem. Network interface 120 may be configured to enable UAV 102 to transmit data over GSM, LTE, HSPA, 5G or other cellular networks, Wi-Fi networks, satellite data networks, or any other communication network known in the art.

[0085] Positioning system 122 may include a plurality of sensors (e.g. GPS, GLONASS, accelerometers, gyroscopes, barometers and other sensors) as well as processing devices, which may generate a position and orientation data output. The position and orientation data may include a latitude, longitude, elevation and orientation data. In other examples, the position and orientation data may comprise a relative orientation and position output. For example, position may be specified relative to inspection structure 104, such as X, Y, Z coordinates relative to a central point of inspection structure 104. Similarly, orientation may be specified in relation to camera fields of view and external surfaces of inspection structure 104.

[0086] In some examples, positioning system 122 may be further configured to capture and record environmental data, such as ambient temperature, and ambient barometric pressure.

[0087] Positioning system 122 may be configured to output and store timestamped position and orientation data at regular intervals. For example, through interaction with an internal clock, position and orientation data may be output at an interval of 1000 samples per second. In other examples, position and orientation data may be outputted and stored at different intervals, or at the same intervals as image captures, such that a corresponding position and orientation data sample exists for every captured image.

[0088] Referring to Figure 3, UAV 102 is configured to conduct an autonomous flight around inspection structure 104, with a pre-determined flight path 110. Flight path 110 may be configured based on the field of view 112 of visible light camera 116 and thermal camera 114. For example, flight path 110 may include a spiral path around a generally cube shaped structure. Flight path 110 may include orientation directions of the UAV 102, such that imaging equipment of UAV 102 (thermal camera system 114, visible light camera 116) is directed towards external surfaces of inspection structure 104 (or internal surfaces, in examples wherein inspection is conducted internally).

[0089] During UAV 102 flight according to flight path 110, UAV 102 may simultaneously (in a synchronized configuration) capture visible light images and thermal images of structure 104 using visible light camera 116 and thermal camera 114 respectively. According to embodiments where more than one UAV 102 is used to capture images of the inspection structure 104, each UAV 102 is configured to conduct an autonomous flight around the inspection structure 104 following the same pre-determined flight path 110.

[0090] Images may be captured at a rate such that images captured are just partially overlapping. For example, if flight path 110 includes a perfectly horizontal flight portion, images may be captured such that the right-most 10% of a first image, and the left-most 10% of a second image overlap. Similarly, when images of structure 104 above the portions of structure 104 above first image and second image are captured, upper portions of first image and second image may overlap with lower portions of subsequent images. These overlapping images may be stitched together into continuous images by any number of image stitching algorithms and methods known in the art.

[0091] Image capture rate may be proportional to UAV 102 flight speed. For example, image capture rate be determined by calculating, through knowledge of image capture fields of view and UAV 102 flight speed, image capture frequency that results in a specific amount of image overlap.

[0092] Images from both camera systems 114, 116 may be captured along flight path 110 until images of every exterior surface and portion of structure 104 has been captured. In some examples, only certain portions of structure 104 may be of interest, or some portions of structure 104 may not be easily surveyed by the method described herein (e.g. line of site access is difficult or unavailable to a typical UAV 102).

[0093] Once all of these images have been captured, they may be transmitted to cloud processing device 108 through network 106. Additionally, all associated metadata (e.g. position and orientation data, environmental data, other metadata, etc.) may be transmitted to cloud processing device 108 through network 106.

[0094] In some examples, all captured images and metadata may be transmitted after the completion of the UAV 102 flight. Such an arrangement may reduce energy consumption of the UAV 102 (by reducing network usage), increasing UAV 102 flight range.

[0095] In other examples, captured images and metadata may be transmitted as soon as they have been captured. Such an arrangement may reduce waiting time needed between the end of the flight and data processing, and may reduce storage medium 118 capacity requirements, as only a storage buffer is required, as images may be deleted from storage medium 118 as soon as they have been transmitted to cloud processing device 108.

[0096] Referring now to Figure 5, shown therein is a detailed system block diagram of cloud processing device 108. Cloud processing device 108 includes memory 124, processor 126, storage medium 128 and network interface 130. Cloud processing device 108 may be an x86 or ARM architecture server, computer, or microcontroller.

[0097] Cloud processing device 108 in some examples may be an instance of a commercially provided cloud computing service, such as Amazon Web Services, Google Cloud Platform, Microsoft Azure or other commercial or privately provided cloud computing platforms. In such examples, subcomponents of cloud processing device 108 such as memory 124, processor 126, storage medium 128 and network interface 130 may be virtualized instances of such components.

[0098] Memory 124 comprises any memory known in the art that may temporarily store data (e.g. machine instructions, input data, and output data) for use, input and output of a computer processor (e.g. processor 126).

[0099] Processor 126 may be any processor known in the art that may receive processor architecture specific machine instructions and execute these received instructions. Processor 126 may be a x86, ARM or other architecture general purpose processor or any other computer processor known in the art.

[0100] Storage medium 128 comprises any non-transient computer readable memory known in the art. Storage medium 128 may be, without limitation, a hard drive, solid state drive, NAND flash, or tape drive.

[0101] Network interface 130 may include any device, hardware, module or system that may enable cloud processing device 108 to communicate with another electronic device, such as a computer system, and transmit data to such devices. Network interface 130 may be configured to enable cloud processing device to transmit data over the Internet or other networks through

GSM, LTE, HSPA, 5G or other cellular networks, Wi-Fi networks, satellite data networks, wired ethernet networks, or any other communication network known in the art. Network interface 130 may enable cloud processing device 108 to communicate with other cloud computing devices or instances, within the same network or platform, or other networks or platforms.

[0102] Referring now to Figure 6, pictured therein is a detailed system block diagram of memory 124. Memory 124 may include building envelope element detection module 132, thermal analysis module 134, report generation module 136, position correlation module 138, thermal anomaly data 140, building element data 142, position and orientation data 144, image data 146, thermal inspection report 148, and scale data 150. In some examples, software modules and data shown included within memory 124 may be stored in other portions of system 100. For example, software modules and data of memory 124 may be stored in storage medium 128 for long term storage, and may be copied onto memory 124 as needed, and vice versa. In some examples, data types pictured within memory 124 may only be present after certain portions of the inspection process described herein have been completed. For example, thermal inspection report 148 may not be present on memory 124 until the cloud processing device has processed data collected by UAV 102, and generated the thermal inspection report 148, as described herein.

[0103] Position correlation module 138 comprises a software module configured to receive thermal image data, visible light image data, and position and orientation data 144 from UAV 102, and determine the scale and orientation of each thermal image, and visible light image. By assessing the distance between the inspection structure 104, and considering the known field of view of the thermal camera and visible light camera, and the relative orientation of the inspection structure 104, and UAV 102, scale data 150 may be determined for each image. Scale data 150 may include data describing the distance that each pixel corresponds to within each image (thermal or visible light).

[0104] In some examples, scale data 150 may be uniform across a single captured image, or may vary across each image. In examples wherein scale data 150 varies across each image, scale data 150 may comprise a scale map, wherein the differing scales values may be described, each corresponding to different regions of the image.

[0105] In some examples, instead of storing scale data 150 separately from images, images may be modified to incorporate scale data, such as writing scale data 150 to image metadata.

[0106] In some examples, each image may be warped, or stretched, such that the scale is uniform across the entire image. Due to a non-direct image capture angle, the lower portions of a captured image may include comprise a different scale than upper portions of the image. The contents of each image may be stretched such that each pixel within the image represents the same linear distance (e.g. each pixel corresponds to a distance of 0.01 m).

[0107] In some examples, position correlation module 138 may be further configured to determine the relative position of the subject matter of each thermal image and visible light image, such that the images may be oriented in three-dimensional space. For example, such positional data may be combined with the images in order to generate a 3D model or representation of the inspection structure 104. 3D models may be generated using photogrammetric analysis. Two-pixel ground sampling distance (GSD) may be applied in the X, Y directions and three pixels GSD in the Z direction to generate a 3D model, digital surface models and an orthomosaic map. Such models and maps may be used to map, measure, and document the progress of thermal inspection operations conducted using the systems and methods described herein.

[0108] In some examples, relative positions may be determined to sub centimeter accuracy, wherein at least 250 images are captured. In other examples, other numbers of images may be captured to provide for sub centimeter accuracy.

[0109] Building envelope element detection (BEED) module 132 comprises a software module configured to receive thermal images, visible light images, and scale data, and detect building elements within these images.

[0110] The BEED module 132 is first configured to stitch both visible light images and thermal images together into larger continuous images, providing for a wholesome view of the inspection structure 104. Any image stitching method or algorithm known in the art may be applied to stitch the image together.

[0111] Referring now to Figure 7, shown therein is an exemplary image stitching operation, such as may be applied by BEED module 132. Four images 202, 204, 206, 208 are captured such that the subject matter of each bordering image is overlapping.

[0112] Referring now to Figure 8, shown therein is the result of the image stitching operation of Figure 7, wherein the images 202, 204, 206 and 208 were stitched together into a single, larger image 210, including the contents of all four constituent images 202, 204, 206, 208.

[0113] After image stitching, stitched images may be stored in memory 124 or storage medium 128 (e.g. as image data 146).

[0114] Once images have been stitched into larger, continuous images, building elements within the stitched images may be identified. Building elements may include structural or functional features, such as, without limitation, windows, doors, vents, window frames, solid walls, roof panels, roof elements or other building elements.

[0115] BEED module 132 may apply machine learning or artificial intelligence methods, such as supervised, unsupervised, or semi-supervised learning to detect building elements. In one example, BEED module 132 may receive visible light images, thermal images, and scale data 150 as an input, provide these inputs to a trained neural network, and receive building element data 142 as an output from the trained neural network.

[0116] BEED module 132 includes a neural network configured to receive input data (thermal images, visible light images, and scale data 150) and generate at least one output (building element data 142). The neural network may be a feed-forward neural network. The neural network comprises a plurality of processing nodes. The processing nodes may include a multi-variable input layer having a plurality of input nodes, at least one hidden layer of nodes, and an output layer having at least one output node. During operation of the neural network, each of the nodes in the hidden layer applies an activation/transfer function and a weight to any input arriving at that node (from the input layer or from another layer of the hidden layer). The node may provide an output to other nodes (of a subsequent hidden layer or to the output layer). The neural network may be configured to perform a regression analysis providing a continuous output, or a classification analysis to classify data. The neural networks may be trained using supervised or unsupervised learning techniques, as described below.

[0117] According to a supervised learning technique, a training dataset is provided at the input layer in conjunction with a set of known output values at the output layer. During a training stage, the neural network may process the training dataset. It is intended that the neural network learn how to provide an output for new input data by generalizing the information it learns in the

training stage from the training data. Training may be effected by back propagating an error to determine weights of the nodes of the hidden layers to minimize the error. Once trained, or optionally during training, test or verification data can be provided to the neural network to provide an output. A neural network may thus cross-correlate inputs provided to the input layer to provide at least one output at the output layer. The output provided by a neural network in each embodiment is preferably close to a desired output for a given input, such that the neural network satisfactorily processes the input data.

[0118] Once building elements have been detected, as described above, a bounding box may be defined around each detected building element. Bounding boxes may include coordinates of the bounding box. Additionally, for each identified building element, a class label may be associated with the detected building element. Class labels may include, for example, windows, doors, vents, window frames, solid walls, roof panels, roof elements or other building elements. Bounding box data, and class label data may be stored as building element data 142.

[0119] Referring now to Figure 9, shown therein is an exemplary depiction of a visible light image 210, including a competed BEED process applied to the image 210. Within image 210, therein is a window 212 and a door 214. BEED module 132 has processed image 210, such that building elements 212, 214 within image 210 have been detected, located and classified. Surrounding the window 212 is a bounding box 216, denoting the boundary of the window 212 within the image 210. Similarly, surrounding the door 214 is a bounding box 218, denoting the boundary of the door 214 within the image 210. Additionally, text format class labels are visible within each bounding box, labelling each element with a class ("window" and "door" for box 216 and 218 respectively). Additionally pictured in Figure 9 is scale 220, which corresponds to the linear distance across the image 210, which may be derived from scale data 150.

[0120] The example of Figure 9 shows a graphical representation of a BEED module 132 processed image, however, the associated building element data 142 may be stored in other formats. For example, building element data 142 may be stored as plain text data, or other structured data (e.g. XML format data) including the associated image for the building element data, and bounding box location, bounding box size, and element class label for each located building element. Such data may be easily machine read for further analysis and processing.

[0121] Element classes may comprise elements including "wall", "roof", "window" and "door". In some examples, element classes may further comprise sub-classes. For example, a "window" class element may further comprise a sub-class of "single pane", "double pane", "triple pane", "argon filled", "nitrogen filled", and other sub-classes.

[0122] Referring again to Figure 6, thermal anomaly module 134 comprises a software module configured to receive building element data 142 from BEED module 132, as well as both thermal images and visible light images (e.g. image data 146), and scale data 150 as an input, and generate thermal anomaly data 140 as an output.

[0123] Thermal anomaly module 134 may consider previously generated building element data 142 to apply different detection methods to differing building elements. For example, building element data 142 may denote certain regions of the captured images as "windows" or "doors", as described previously. Such detected regions may be assessed differently for thermal anomalies. In some examples, image areas not associated with a detected building element may be assessed in a default manner.

[0124] Certain thermal defects may be present within a typical window, and each thermal defect may be associated with a specific thermal signature. For example, multi-pane windows may possess a thermal defect wherein the inert gas between panes leaks out, introducing air and or moisture between the windowpanes. This may affect the thermal performance of the window. Thermal anomaly module 134 may be particularly configured to detect the thermal signature of such a thermal defect within regions labelled by BEED module 132 as window regions. Similarly, specific, known defects may exist for other building elements. For such elements, image regions associated with known building elements, may be assessed according to their building element class.

[0125] In some examples, thermal anomaly module 134 may apply direct algorithmic methods such as edge detection and various image processing filters on thermal image data to detect thermal anomalies. In some examples, thermal anomaly module 134 may assess the size, shape, and temperature of elevated or lowered temperature regions within the thermal images to locate thermal anomalies. Such assessment may occur at the pixel level of the thermal images.

[0126] In some examples, thermal anomaly module 134 may apply machine learning and or neural network type techniques to detect thermal anomalies.

[0127] For example, thermal anomaly module 134 includes a neural network configured to receive input data (thermal images, visible light images, building element data 142 and scale data 150) and generate at least one output (thermal anomaly data 140). The neural network may be a feed-forward neural network. The neural network may have a plurality of processing nodes. The processing nodes may include a multi-variable input layer having a plurality of input nodes, at least one hidden layer of nodes, and an output layer having at least one output node. During operation of the neural network, each of the nodes in the hidden layer applies an activation/transfer function and a weight to any input arriving at that node (from the input layer or from another layer of the hidden layer). The node may provide an output to other nodes (of a subsequent hidden layer or to the output layer). The neural network may be configured to perform a regression analysis providing a continuous output, or a classification analysis to classify data. The neural networks may be trained using supervised or unsupervised learning techniques, as described below.

[0128] According to a supervised learning technique, a training dataset is provided at the input layer in conjunction with a set of known output values at the output layer. During a training stage, the neural network may process the training dataset. It is intended that the neural network learn how to provide an output for new input data by generalizing the information it learns in the training stage from the training data. Training may be effected by back propagating an error to determine weights of the nodes of the hidden layers to minimize the error. Once trained, or optionally during training, test or verification data can be provided to the neural network to provide an output. A neural network may thus cross-correlate inputs provided to the input layer to provide at least one output at the output layer. The output provided by a neural network in each embodiment is preferably close to a desired output for a given input, such that the neural network satisfactorily processes the input data.

[0129] The untrained neural network may be provided with manually tagged thermal image data as a training dataset. Such manually tagged data may include a thermal image with an associated scale (e.g. including scale data 150), building element data, a bounding box surrounding the thermal anomaly and a class label associated with the thermal anomaly, placed by a skilled operator.

[0130] The neural network may apply supervised, semi-supervised, or unsupervised learning techniques.

[0131] Thermal anomaly data 140 may include the location of each detected thermal anomaly, as well as a class label for each thermal anomaly. Thermal anomaly classes may include, without limitation, wall cracks, window seal failures, ceiling cracks, insulation failures, masonry failures, and more. Location of a thermal anomaly may be denoted by an associated image indicator, bounding box location (e.g. center location), and bounding box dimensions. Thermal anomaly data 140 may be of a machine-readable format, such as plain text, or XML, such that thermal anomaly data 140 may be further processed and/or analyzed.

[0132] Referring now to Figure 10, shown therein is an exemplary depiction of a thermal image 310, including a competed thermal anomaly detection process applied to the image 310. Within image 310, therein is a window and a door. BEED module 132 has processed image 310, such that building elements within image 310 have been detected, located and classified.

[0133] The thermal anomaly detection process has located a thermal anomaly 302 within the image 310. Surrounding the thermal anomaly 302 is a bounding box, denoting the boundary of the thermal anomaly 302 within the image 310. The thermal anomaly 302 is associated with a thermal anomaly class label (not pictured).

[0134] The example of Figure 10 shows a graphical representation of a thermal anomaly module 134 processed image, however, the associated thermal anomaly data 140 may be stored in other formats. For example, thermal anomaly data 140 may be stored as plain text data, or other structured data (e.g. XML format data) including the associated image for the thermal anomaly data 140, and bounding box location, bounding box size, and element class label for each located thermal anomaly. Such data may be easily machine read for further analysis and processing.

[0135] Referring now to Figure 11, shown therein is a side-by-side comparison of an exemplary visible light image 322, and a corresponding exemplary thermal image 324. While not visible within visible light image 322, a thermal crack 323 is depicted within thermal image 324. This thermal crack 323 may be detected, located and classified by thermal anomaly module 134. Image 322, and 324 have been captured by one or more UAVs.

[0136] Referring now to Figure 12 shown therein is a side-by-side comparison of an example visible light image 326, and corresponding example thermal image 328. While not visible within visible light image 322, a thermal defect 327 is depicted within thermal image 324. This

thermal defect 327 may be detected, located and classified by thermal anomaly module 134. Image 326, and 328 have been captured by a UAV.

[0137] In other examples, other thermal defects may be present and may be detected. For example, defects may include, for a roof element: moisture accumulation within gravel, moisture accumulation within roofing membrane, inconsistent thermal layer, decay of insulation, decayed connection between roof and exterior wall, heat loss at overhang, heat loss at concrete pavers, heat loss to vegetation, no perimeter insulation, and heat loss at parapet. Defects may include, for a door element: heat loss through door frame. heat loss through door, heat loss through garage door, and heat loss at main floor enclosure. Defects may include, for a window element: moisture accumulation behind cladding and window frame, moisture accumulation within window frame, heat loss through uninsulated framing, heat loss through IGUs, heat loss through frame and IGUs, heat loss through caulking, heat loss through connection between wall and window, and skylight IGUs. Defects may include, for a curtain wall element: heat loss through uninsulated framing, and heat loss through IGUs. Defects may include, for a wall element: connection between foundation wall and exterior wall, connection between exterior walls at corners, connection at fasteners of cladding, thermal bridging through connections of building envelope, thermal bridging through framing, connection between exterior wall and roof assembly, inconsistent insulation, decay of insulation, connection between wall and window, thermal bridge between structural load bearing elements and other elements, connection between wall and floor slabs, connection between wall and garage door, connection between walls and doors, connection between siding joints, thermal bridge through overhand, thermal crack in wall assembly due to moisture, moisture accumulation due to lack of ventilation, moisture accumulation between wall and window connection, and moisture accumulation due to lack of ventilation in metal siding. In other examples, other defect types may be present and/or detectable.

[0138] Referring back to Figure 6, report generation module 136 comprises a software module configured to receive thermal anomaly data 140 and image data 146 as an input, and output a thermal inspection report 148, associated with the inspection structure 104. The thermal inspection report (for example, thermal inspection report 400 as shown in Figure 13) comprises data detailing the results of the thermal inspection. For example, thermal inspection report 148 may comprise a list of all located or suspected thermal anomalies, including location, classification

(e.g. crack, moisture leakage, window seal failure or more) and other attributes, such as estimated heat loss.

[0139] In some examples, thermal inspection report may additionally include an estimated energy cost associated with the defect. For example, in addition to collected data, report generation module 136 may be provided with a heating type (e.g. forced air gas, electric, etc.), and energy cost, and may estimate the approximate financial cost associated with each located thermal anomaly.

[0140] In some examples, report generation module 136 may be additionally provided with more input data, such as inspection metadata, and environmental data.

[0141] Referring now to Figure 13, pictured therein is a portion of a thermal inspection report 400, according to an embodiment. Thermal inspection report 400 includes data summarizing 30 located thermal anomalies. Figure 13 pictures a summary of a single, located thermal anomaly, wall crack 402.

[0142] In the embodiment of Figure 13, thermal inspection report 400 includes identification metadata of the inspection structure ("Structure 104"), thermal anomaly identifier ("1 of 30"), thermal anomaly class ("Wall Crack"), an image crop of the thermal anomaly, anomaly size data ("0.5m x 0.1m"), anomaly energy loss rate ("202.1W"), and yearly estimated anomaly cost ("$367.32").

[0143] In some examples, thermal inspection reports may include additional features and data, for example, without limitation: metadata such as inspection operator, or date and time of inspection, project identifier, inspection hardware identifiers, area inspected, total time of inspection, quality check data, preview thermal and visible light images, calibration details, image capture positions, manual tie point positions, absolute camera position and orientation uncertainties, image overlap map, bundle block adjustment details, internal camera parameters, 2D keypoints table, 3D points from 2D keypoints matches, 2D keypoints matches, geolocation details, data processing details and configuration, and point cloud densification details.

[0144] In some examples, quality check data may include a number of keypoints per image, image calibration information, camera optimization information, matching data information and georeferencing information.

[0145] In some examples of the system described herein, the thermal inspection report may be configured such that it is machine readable. For example, the thermal inspection report may be structured such that all text is stored as machine readable text data, and image data within the report is stored separately from the rest of the thermal inspection report.

[0146] In some examples, thermal inspection report may be transmitted by cloud processing device 108, over a network, to another computing device, for further use.

[0147] In operation, system 100 may be directed to collect data using UAV 102 as described above. Once data has been collected, collected data (including position and orientation data, visible light image data, and thermal image data) may be transmitted to cloud processing device 108 through network 106.

[0148] Cloud processing device 108 may receive collected data, and provide the position and orientation data, visible light image data, and thermal image data to position correlation module 138. Position correlation module may process collected data, and determine a scale for each captured image, and may skew or warp each image, such that the scale uniformly applied to each captured image. Position correlation module 138 may then output scale data 150. Data outputted by position correlation module 138 may be temporarily stored in memory 124, or storage medium 128 for archival or further processing.

[0149] Visible light image data, thermal image data, and scale data 150 may be provided to building envelope element detection module 132. Building envelope element detection module 132 may detect building elements within images as previously described. Building envelope element detection module 132 may output building element data 142, including a bounding box for each located building element, as well as a building element class label associated with each located building element. Building element data 150 may be temporarily stored in memory 124, or storage medium 128 for archival or further processing.

[0150] Visible light image data, thermal image data, scale data 150 and building element data 142 may be provided to thermal anomaly module 134 for processing to detect thermal anomalies within captured images, generating thermal anomaly data 140.

[0151] Visible light image data, thermal image data, scale data 150, building element data 142, and thermal anomaly data 140 may be provided to report generation module 136 for

processing and generation of a thermal inspection report 148. As previously described, the thermal inspection report 148 may be configured to be machine readable, such that the thermal inspection report 148 may be further processed. Additionally, the thermal inspection report may be configured and formatted, such that it may be read and interpreted by a human analyst.

[0152] The systems described above are configured such that once the flight path 110 has been selected and provided to the system, the system may generate a thermal report with little to no additional human intervention. The one or more UAVs 102 may conduct the flight(s), collect all required data, including position and orientation data, thermal and visible light images, and environmental data, and transmit this data to the cloud processing device 108. Once received by the cloud processing device, the collected data may be processed into a thermal report with no additional human intervention.

[0153] In some examples, small amounts of human intervention may be required or optionally permitted. For example, a human operator may input report generation parameters (e.g. select report format, and analysis conducted), select a subset of the inspection structure that is to be inspected, manually review collected data before manually prompting the system to proceed with report generation, and other parameter adjustment and managerial type inputs.

[0154] Referring now to Figure 14, pictured therein is a flowchart depicting a method 500 of structure thermal inspection, according to an embodiment. Method 500 comprises steps 504, 506, 508, 510 and optionally steps 502 and 512. Description above in reference to systems 10, 100, and 200 above may apply to method 500.

[0155] At step 502, at least one UAV is provided. According to various embodiments, the at least one UAV may comprise a single UAV or multiple UAVs, each UAV having a thermal camera system and/or a visible light camera system and a positioning system. According to a preferred embodiment, two UAVs are provided: a first UAV configured for daytime operation and having a high-resolution, high framerate visible light camera; and a second UAV configured for nighttime operation and having both thermal and visible light camera systems.

[0156] At step 504, the UAV is flown, along a preplanned flight path, capturing visible light images, thermal images, and positioning data. According to embodiments where more than one UAV is used to capture images of the inspection structure, each UAV follows the same preplanned flight path, with each UAV flight session being staggered or occurring at different

times (e.g., daytime, nighttime). According to a preferred embodiment, visible light images are captured during a daytime flight session and thermal images are captured during a nighttime flight session.

[0157] At step 506, captured data is transmitted to and received by a processing device.

[0158] At step 508, captured data is provided to a building element envelope detection module of the processing device to generate building element data.

[0159] At step 510, captured data and building element data is provided to a thermal anomaly module of the processing device to generate thermal anomaly data.

[0160] At step 512, captured data and thermal anomaly data is provided to a report generation module of the processing device to generate a thermal report.

[0161] While the above description provides examples of one or more apparatus, methods, or systems, it will be appreciated that other apparatus, methods, or systems may be within the scope of the claims as interpreted by one of skill in the art.

Claims:

1. A thermal inspection method, the method comprising:

   receiving thermal image data of an inspection structure, visible light image data of the inspection structure, and positioning data from one or more unmanned aerial vehicles (UAVs) at a processing device;

   inputting the thermal image data, the visible light image data and the positioning data into a building envelope element detection module of the processing device to generate building element data; and

   inputting the building element data, the thermal image data and the visible light image data into a thermal anomaly module of the processing device to generate thermal anomaly data, the thermal anomaly data comprising thermal anomaly locations in the inspection structure and classifications of thermal anomalies.

2. The method of claim 1, further comprising providing the thermal anomaly data to a report generation module of the processing device and generating a thermal inspection report.

3. The method of claim 1 further comprising:

   flying the one of more UAVs along a predetermined flight path around the inspection structure, each UAV comprising:

      a thermal camera for capturing the thermal image data and/or a visible light camera for capturing the visible light image data; and

      a positioning system for capturing the positioning data;

   capturing the thermal image data of the inspection structure, the visible light image data of the inspection structure, and the positioning data at regular intervals as the one or more UAVs traverse the flight path; and

   transmitting the thermal image data, the visible light image data and the positioning data to the processing device.

4. The method of claim 3, further comprising providing the one or more UAVs.

5. The method of claim 3, further comprising:

capturing the visible light image data during a daytime flight along the predetermined flight path around the inspection structure; and

capturing the thermal image data during nighttime flight along the predetermined flight path around the inspection structure.

6. The method of any one of claims 1 to 5, further comprising:

inputting the building element data, the thermal image data and the visible light image data into an input layer of a trained neural network of the thermal anomaly module; and

receiving the thermal anomaly data as an output of the neural network.

7. The method of any one of claims 1 to 6, further comprising:

assessing regions within the thermal image data and the visible light image data for thermal anomalies by the thermal anomaly module according to the building element data of each region.

8. The method of any one of claims 1 to 7, further comprising:

providing the positioning data, the visible light image data, and the thermal image data as input to a position correlation module of the processing device to generate scale data;

inputting the scale data to the thermal anomaly module when generating the thermal anomaly data; and

inputting the scale data into the building element detection module when generating the building element data.

9. The method of any one of claims 1 to 8, wherein the thermal camera comprises a resolution of at least 1024 x 1024 pixels.

10. The method of any one of claims 1 to 9, wherein the building element data comprises wall, door, window or roof classifications of building elements.

11. The method of claim 2, wherein the thermal inspection report comprises heat loss data.

12. The method of any one of claims 1 to 11, wherein the thermal anomaly data is characterized according to the building element data.

13. A thermal inspection system comprising:

one or more unmanned aerial vehicles (UAVs), each UAV comprising:

a thermal camera for capturing thermal image data and/or a visible light camera for capturing visible light image data; and

a positioning system for capturing position data;

wherein each UAV is configured to:

fly along a predetermined flight path around an inspection structure;

capture the thermal image data and/or the visible light image data of the inspection structure;

capture the positioning data at regular intervals; and

transmit the thermal image data the visible light image data and the positioning data to a processing device, over a network;

wherein the processing device is configured to:

receive the thermal image data, the visible light image data, and the positioning data;

input the thermal image data, the visible light image data and the positioning data to a building envelope element detection module of the processing device to generate building element data; and

input the building element data, the thermal image data and the visible light image data to a thermal anomaly module of the processing device to generate thermal anomaly data, the thermal anomaly data comprising thermal anomaly locations and classifications.

14. The system of claim 13, wherein the processing device is further configured to provide the thermal anomaly data to a report generation module of the processing device, and generate a thermal inspection report.

15. The system of any one of claims 14 or 15, wherein the thermal anomaly module inputs the building element data, the thermal image data and the visible light image data into an input

layer of a trained neural network, and receives the thermal anomaly data as an output of the neural network.

16. The system of any one of claims 13 to 15, wherein regions within the thermal image data and the visible light image data are assessed for thermal anomalies by the thermal anomaly module according to the building element data of each region.

17. The system of any one of claims 13 to 16, wherein the processing device further comprises a position correlation module, the processing device further configured to:

provide positioning data, visible light image data, and thermal image data to the position correlation module as input to generate scale data;

input the scale data into the thermal anomaly module when generating the thermal anomaly data; and

input the scale data into the building element detection module when generating the building element data.

18. The system of any one of claims 13 to 17, wherein the thermal camera comprises a resolution of at least 1024 x 1024 pixels.

19. The system of any one of claims 13 to 18, wherein the building element data comprises wall, door, window or roof classifications of building elements.

20. The system of claim 14, wherein the thermal inspection report comprises heat loss data.

21. The system of any one of claims 13 to 20, wherein the thermal anomaly data is characterized according to the building element data.

22. The system of any one of claims 13-21, wherein a first UAV is configured for daytime flight operations and a second UAV is configured for nighttime flight operations.

23. The system of claim 22, wherein the first UAV comprises a high definition, high framerate visible light camera.

24. The system of claim 22, wherein the second UAV comprises a thermal camera and a visible light camera.

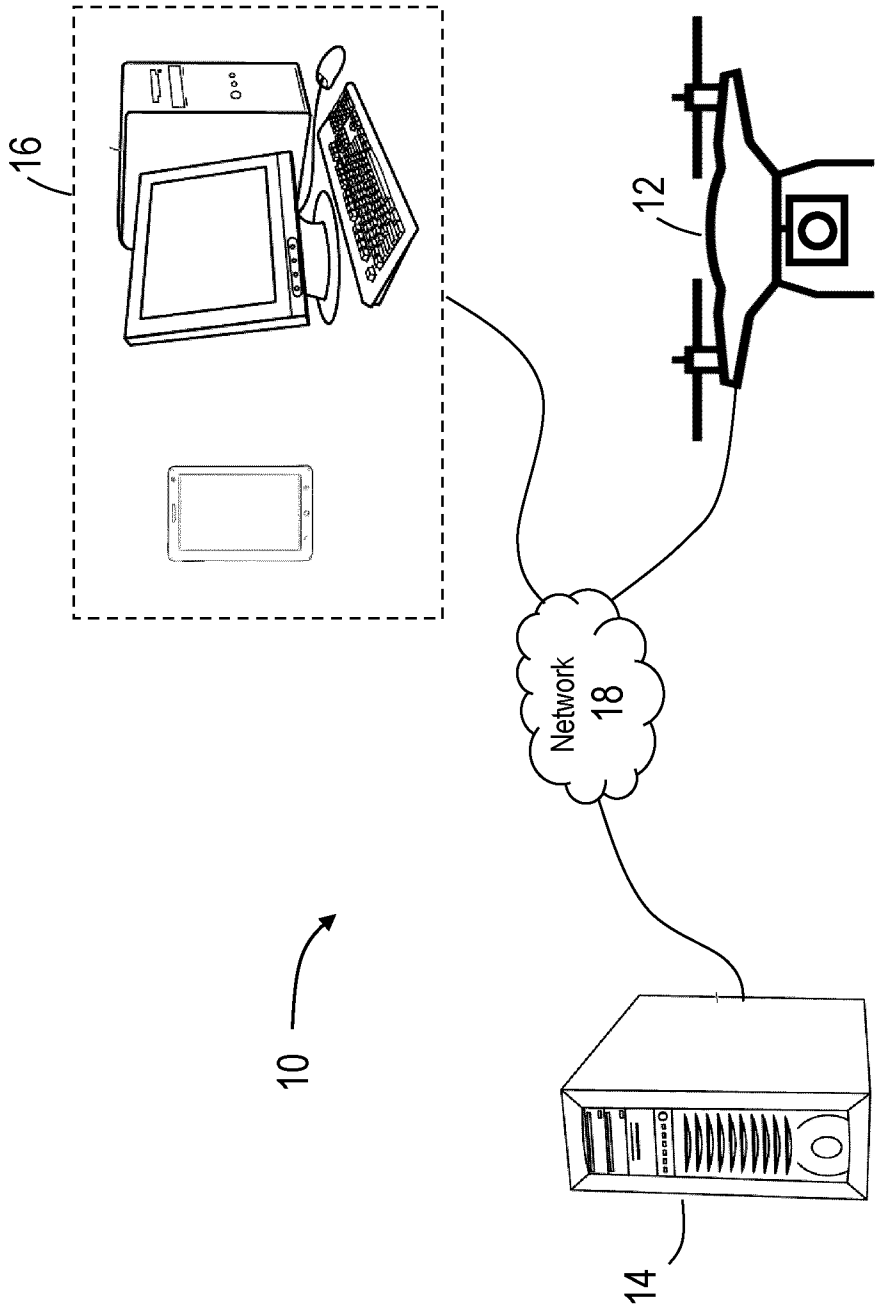


FIG. 1

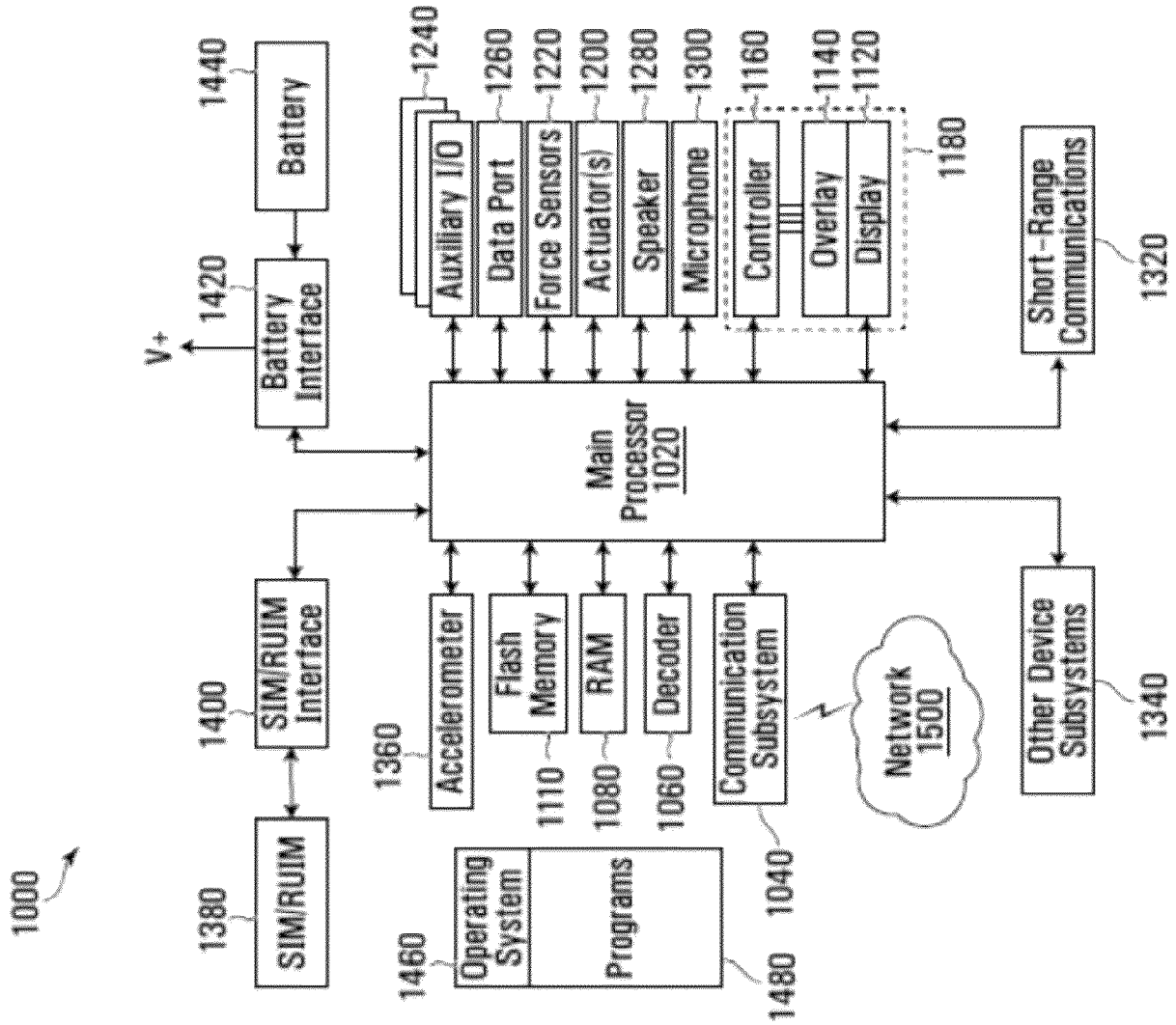

1000
1380
SIM/RUIM
1400
SIM/RUIM Interface
1420
Battery Interface
V+
1440
Battery
Main Processor 1020
1360
Accelerometer
1110
Flash Memory
1080
RAM
1060
Decoder
1040
Communication Subsystem
1460
Operating System
Programs
1480
Network 1500
1240
Auxiliary I/O
1260
Data Port
1220
Force Sensors
1200
Actuator(s)
1280
Speaker
1300
Microphone
1160
Controller
1140
Overlay
1120
Display
1180
1320
Short-Range Communications
1340
Other Device Subsystems

FIG. 2

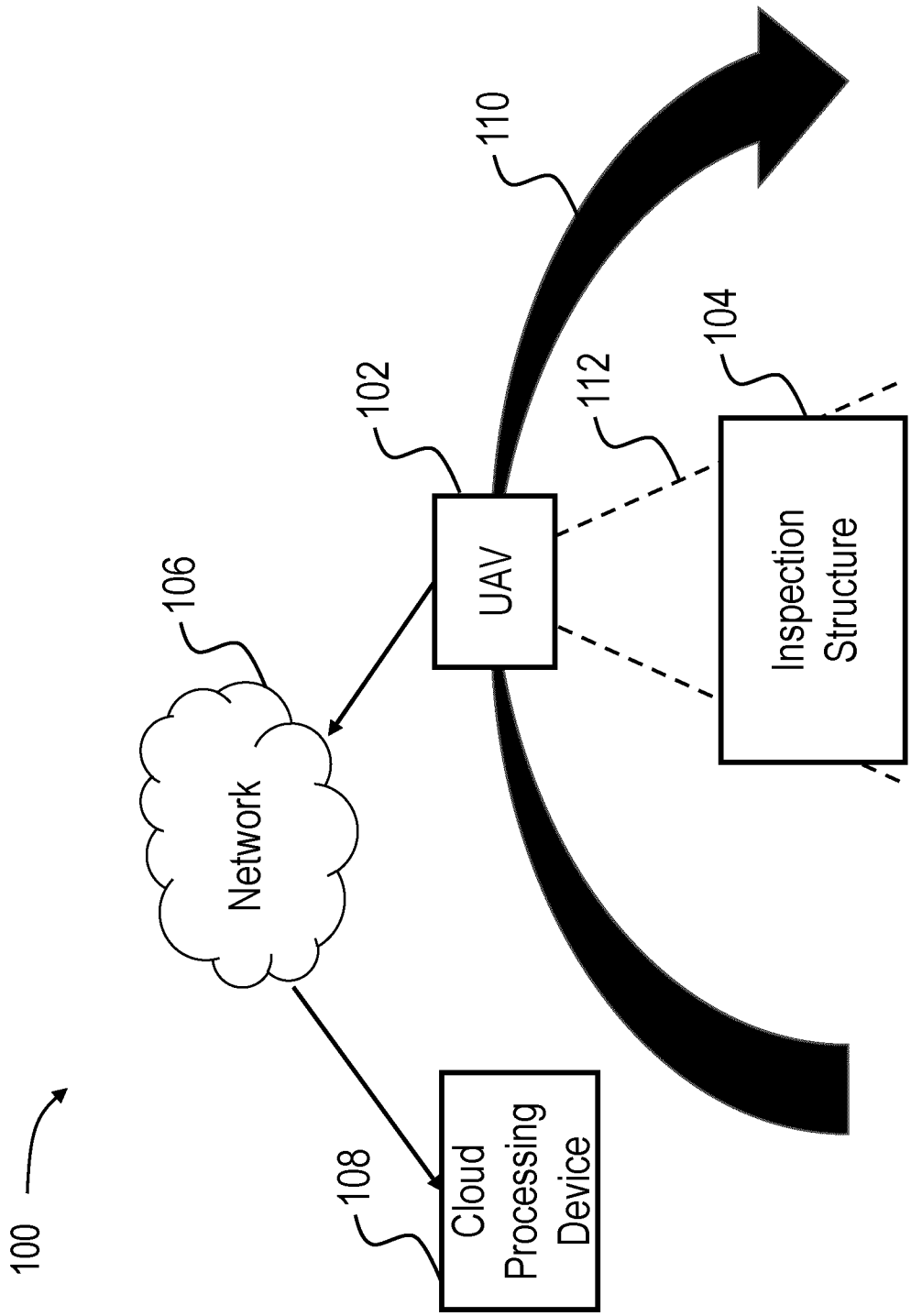

100
Cloud Processing Device
108
Network
106
UAV
102
112
Inspection Structure
104
110

FIG. 3

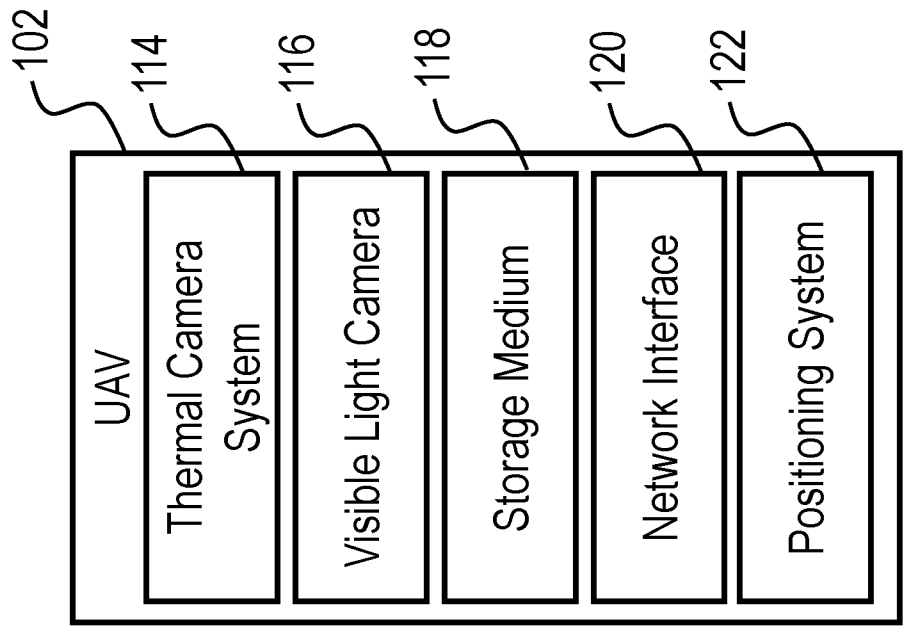

102
114
116
118
120
122
UAV
Thermal Camera System
Visible Light Camera
Storage Medium
Network Interface
Positioning System

FIG. 4

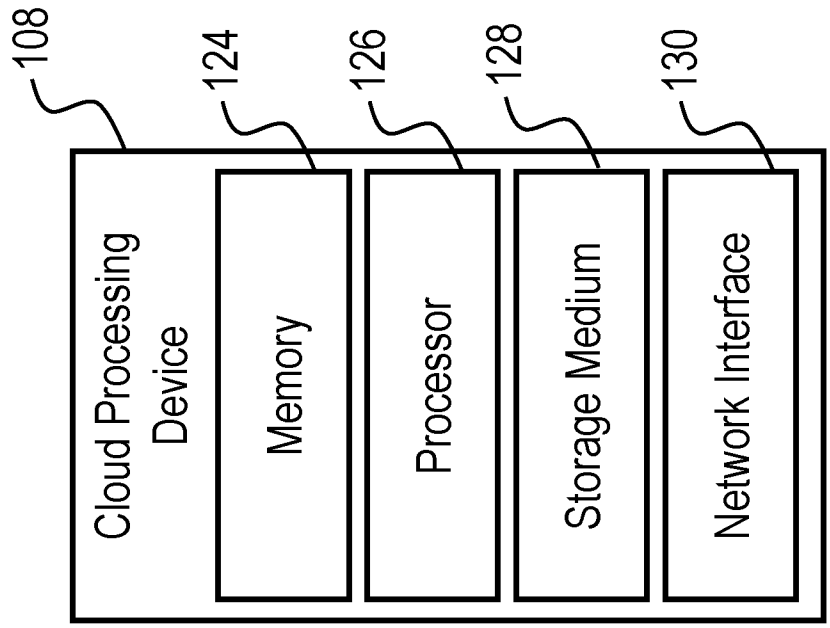

108
124
126
128
130
Cloud Processing Device
Memory
Processor
Storage Medium
Network Interface

FIG. 5

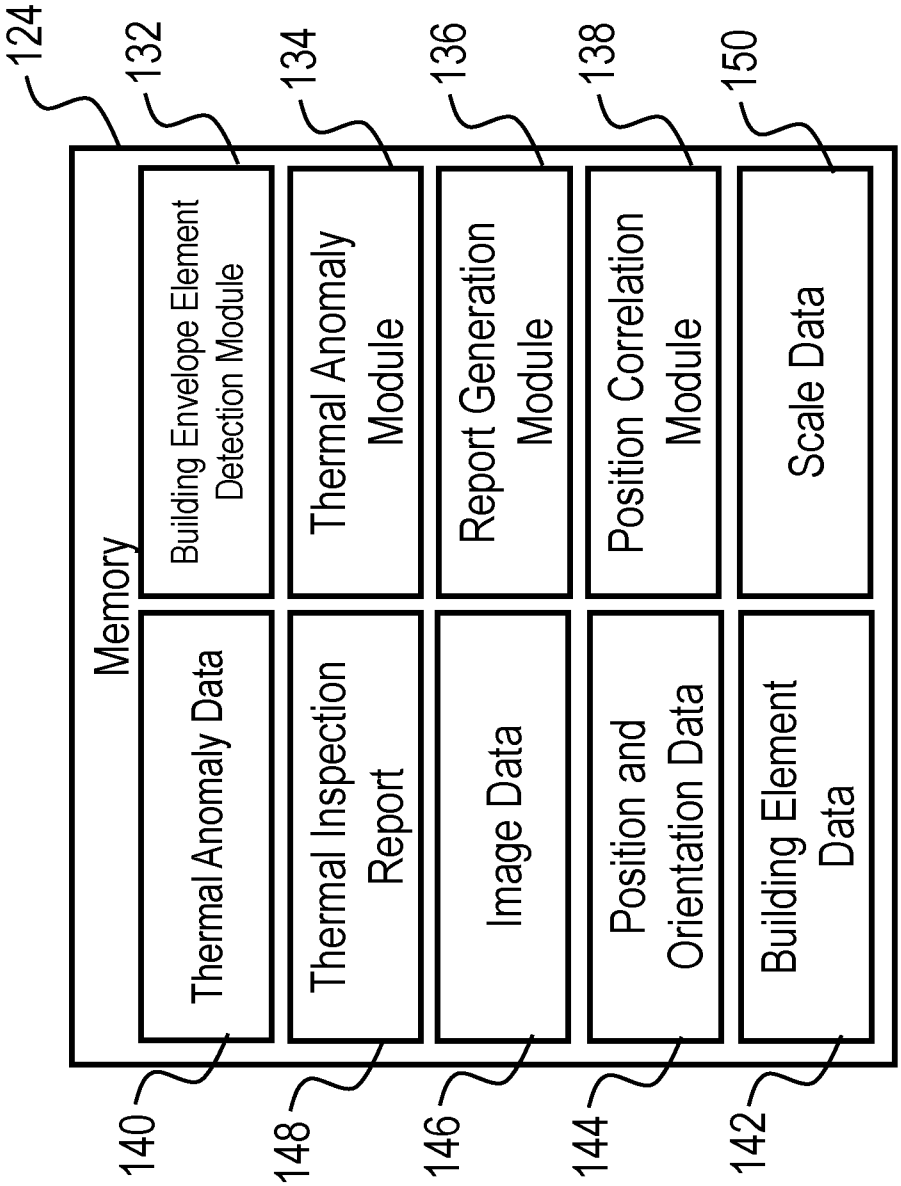

124
132
134
136
138
150
Memory
Building Envelope Element Detection Module
Thermal Anomaly Module
Report Generation Module
Position Correlation Module
Scale Data
Thermal Anomaly Data
Thermal Inspection Report
Image Data
Position and Orientation Data
Building Element Data
140
148
146
144
142

FIG. 6

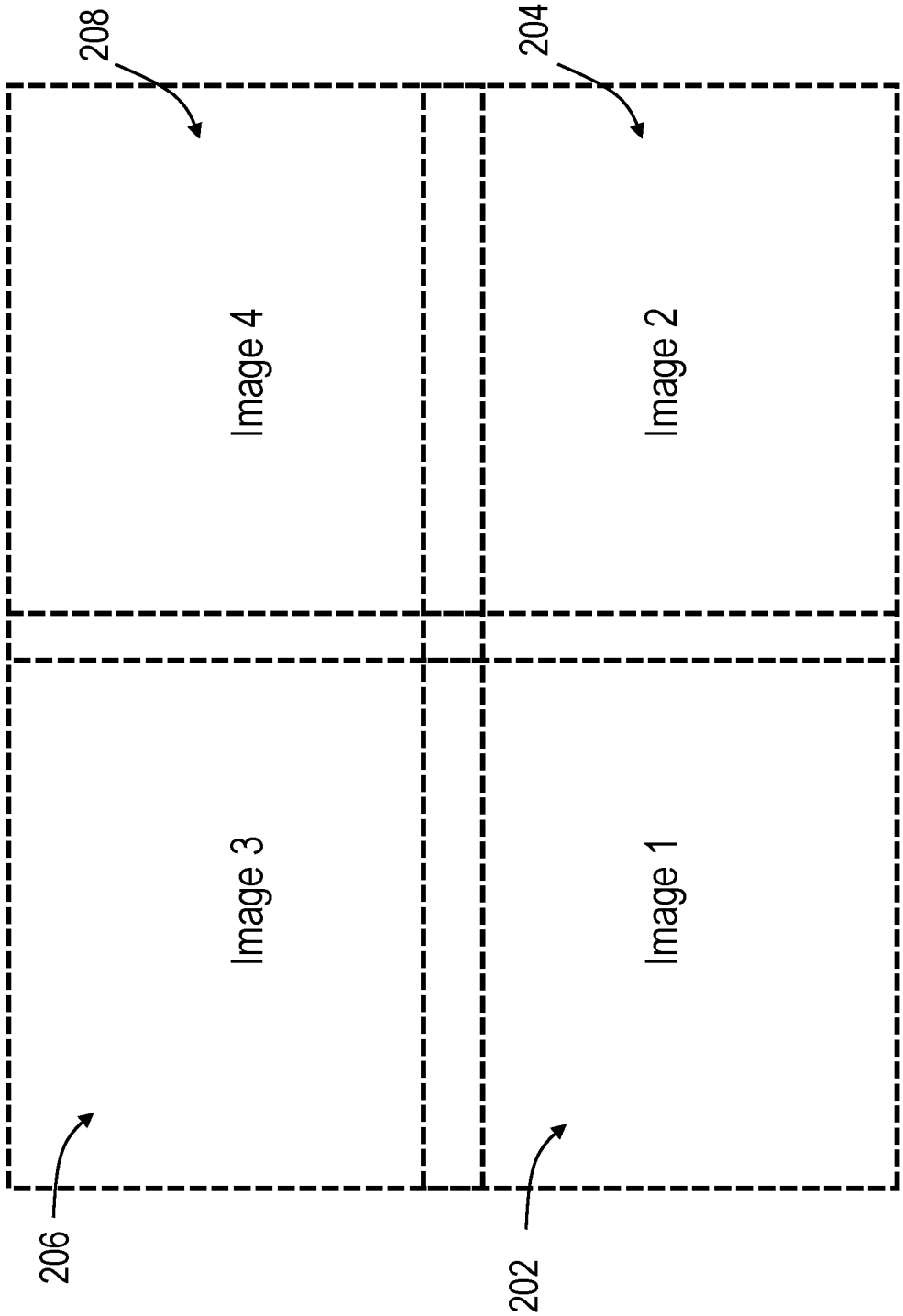


FIG. 7

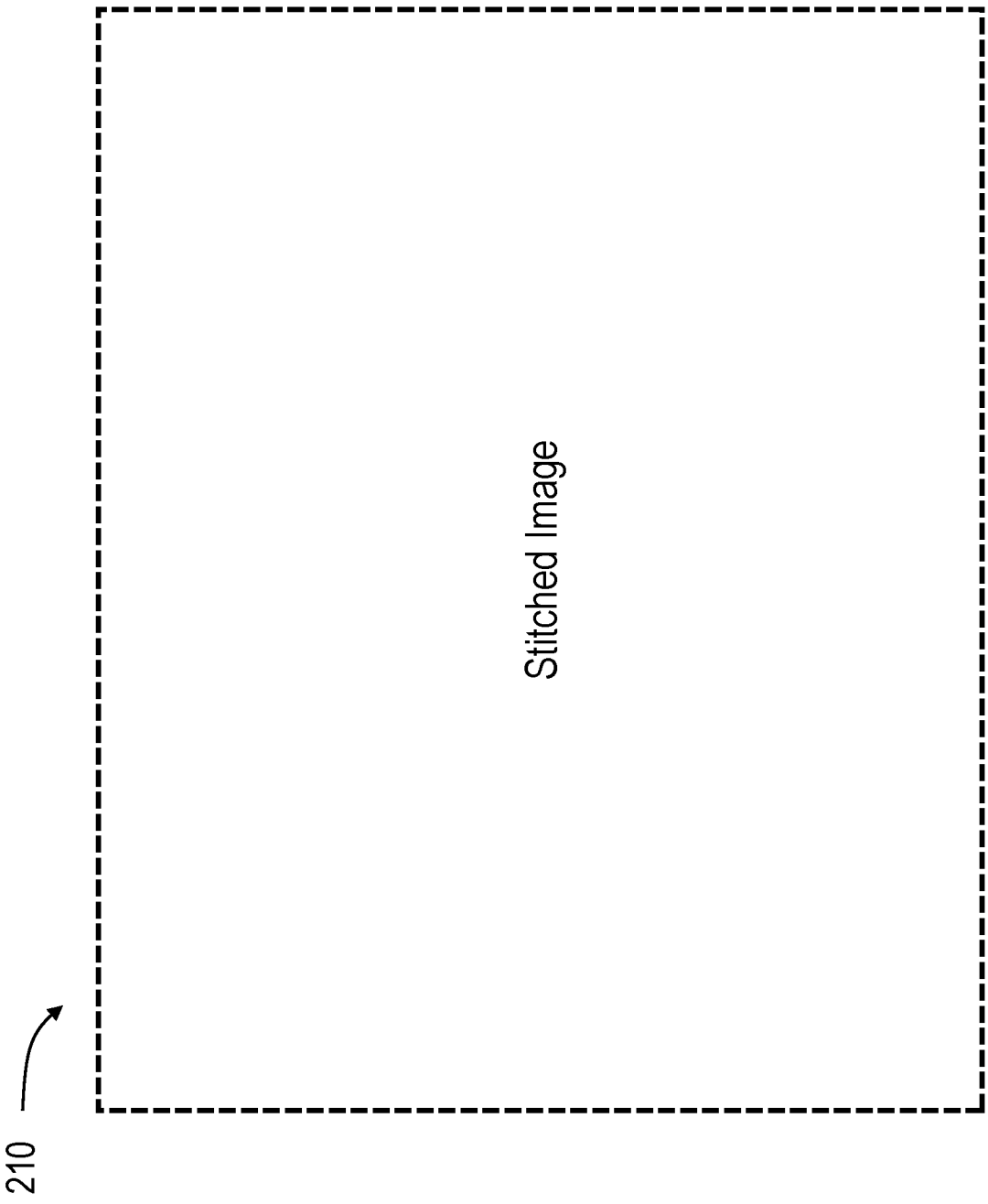


FIG. 8

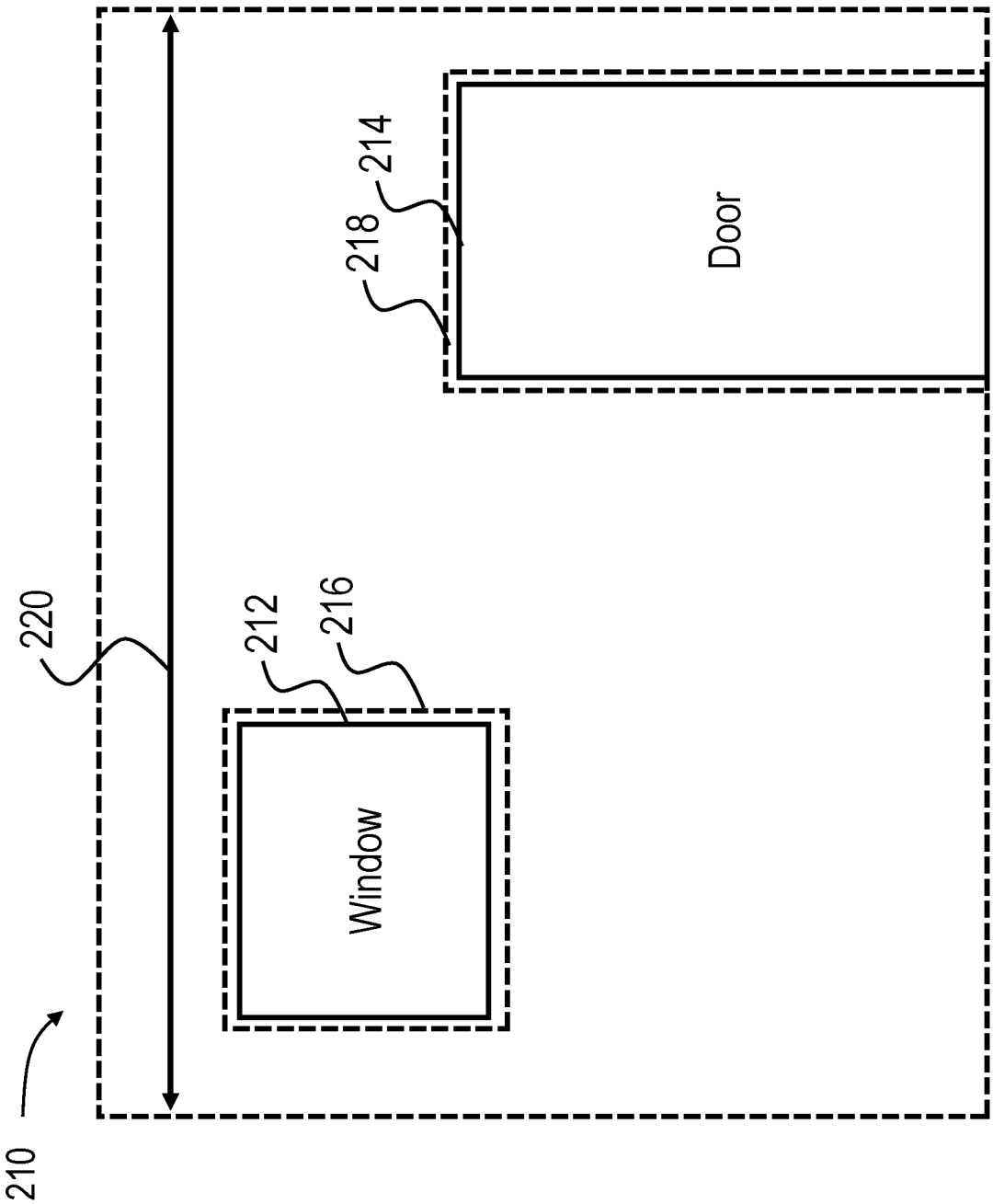


FIG. 9

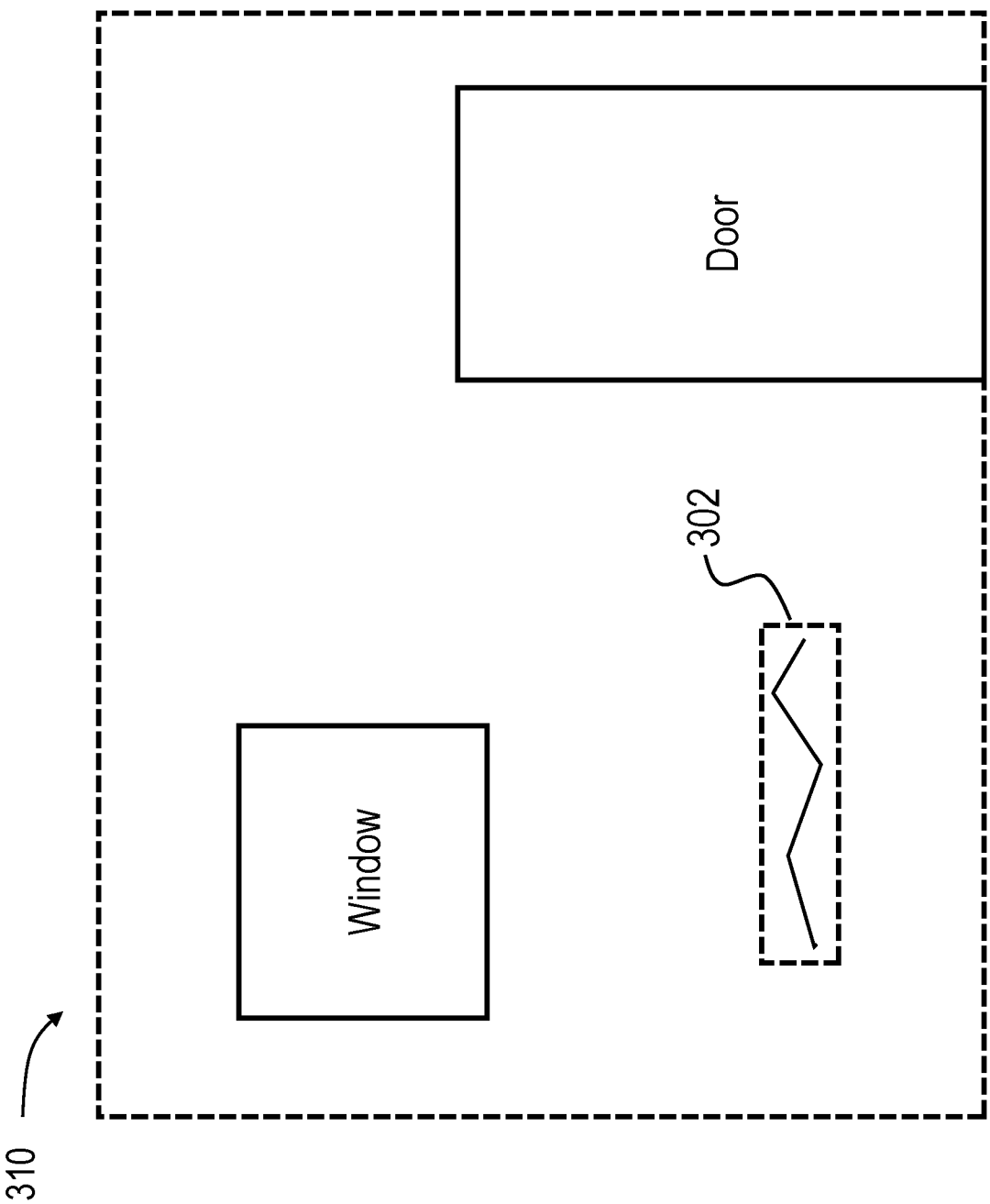


FIG. 10

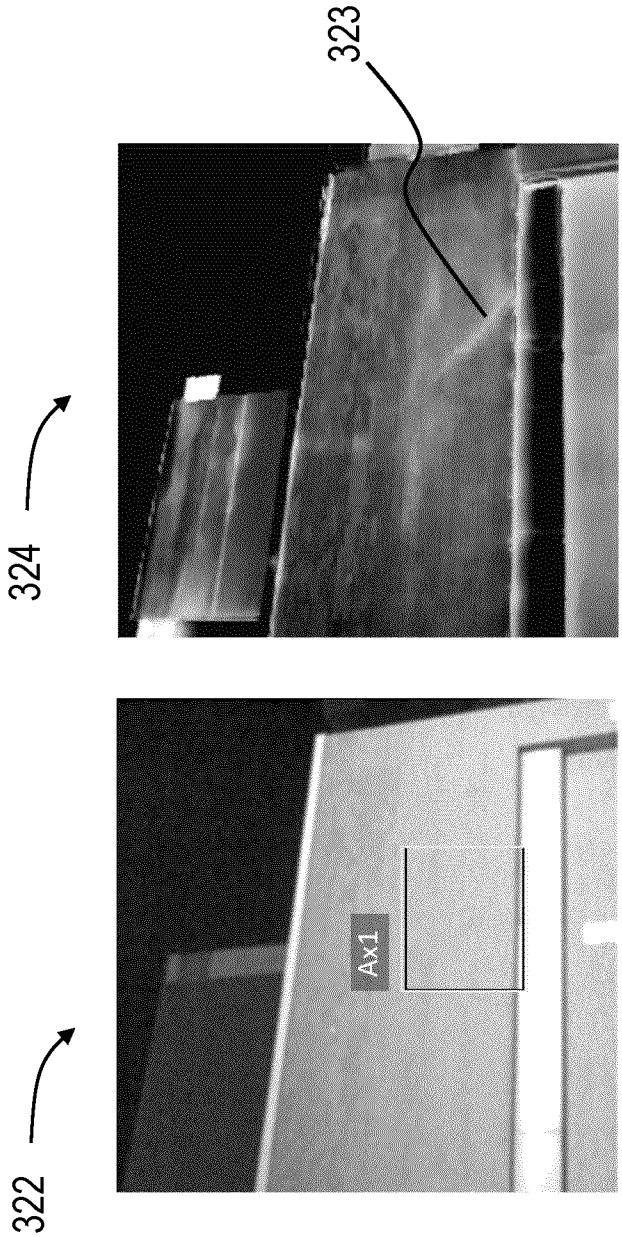


FIG. 11

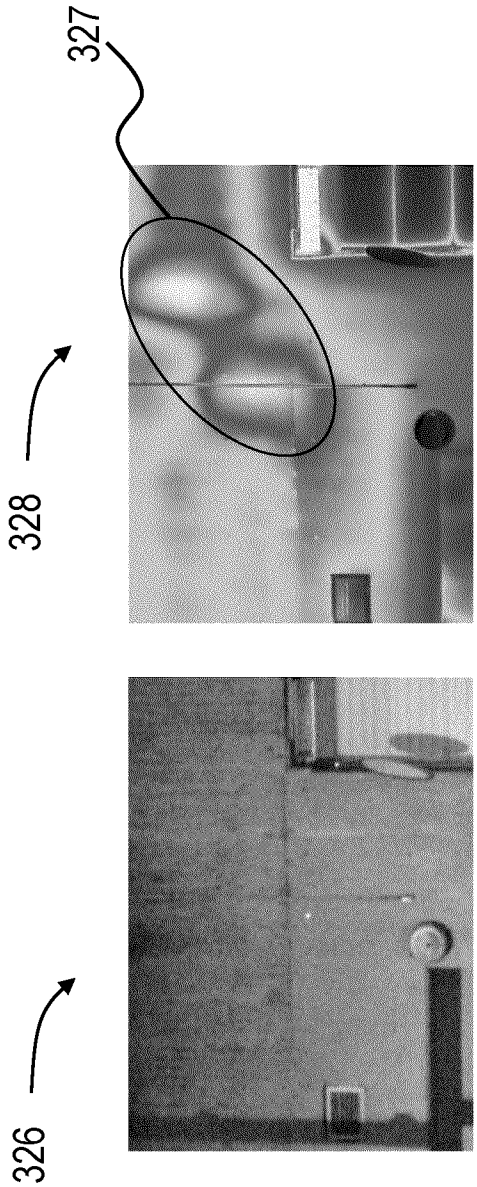


FIG. 12

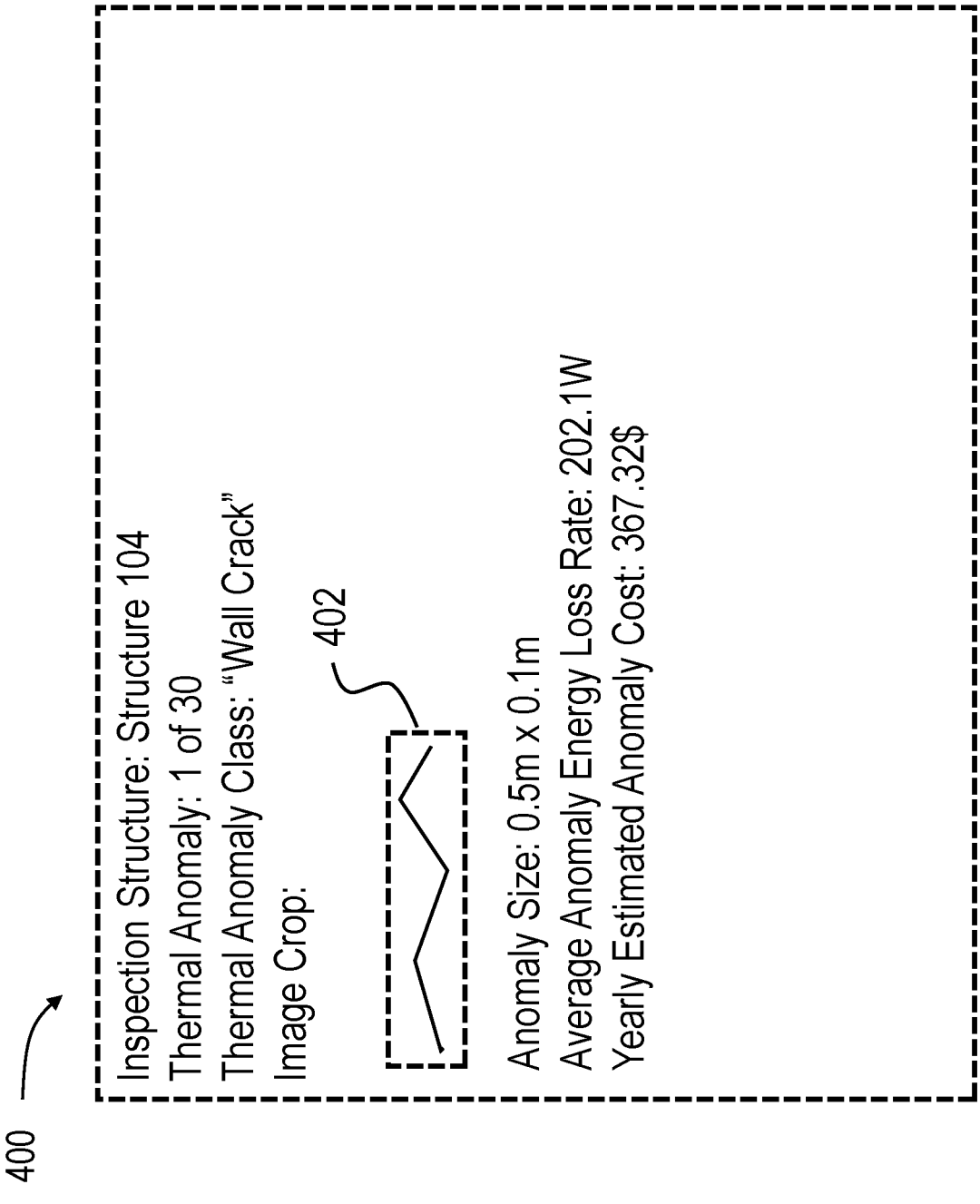

400
Inspection Structure: Structure 104
Thermal Anomaly: 1 of 30
Thermal Anomaly Class: "Wall Crack"
Image Crop:
402
Anomaly Size: 0.5m x 0.1m
Average Anomaly Energy Loss Rate: 202.1W
Yearly Estimated Anomaly Cost: 367.32$

FIG. 13

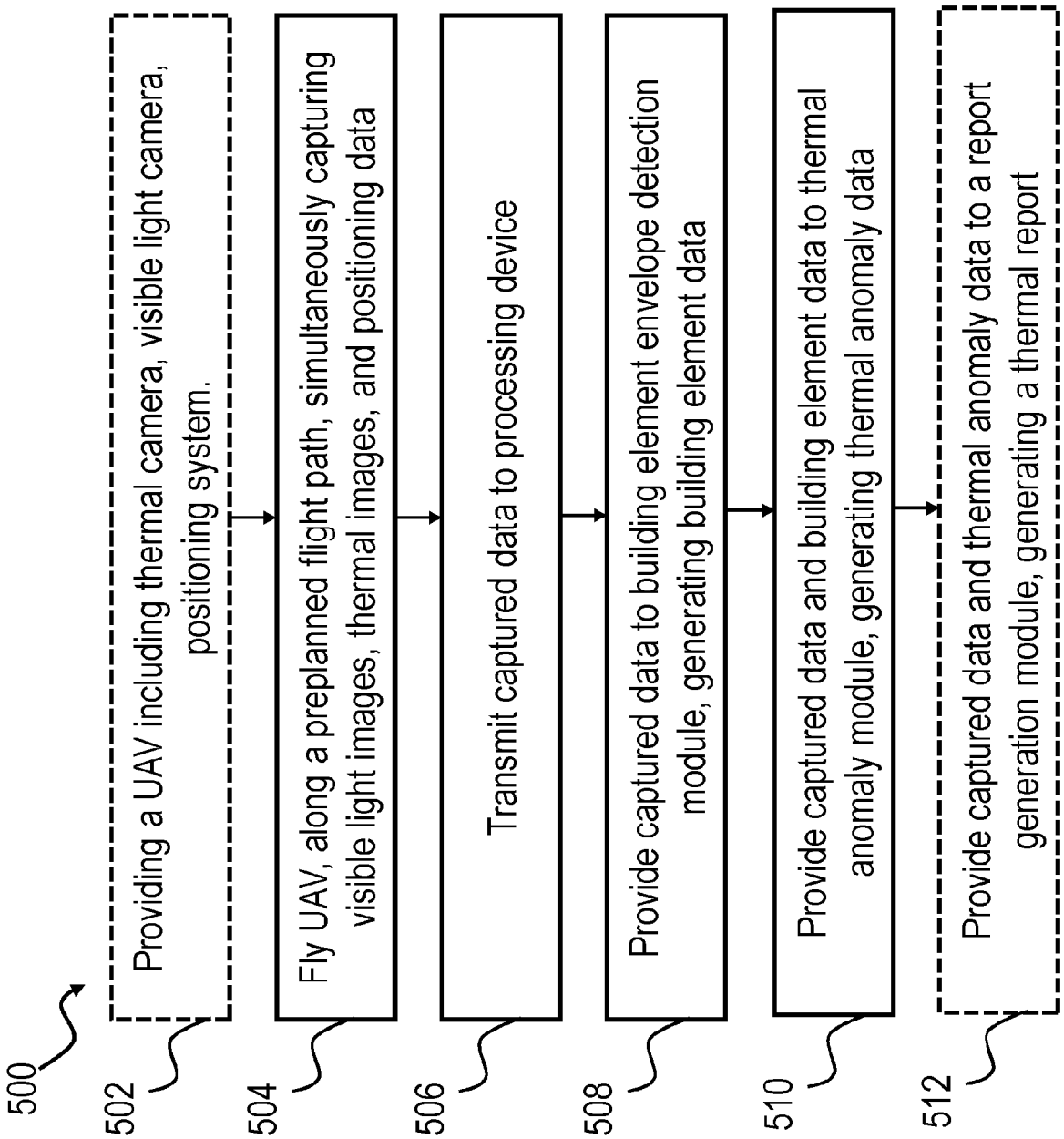

500
502
Providing a UAV including thermal camera, visible light camera, positioning system.
504
Fly UAV, along a preplanned flight path, simultaneously capturing visible light images, thermal images, and positioning data
506
Transmit captured data to processing device
508
Provide captured data to building element envelope detection module, generating building element data
510
Provide captured data and building element data to thermal anomaly module, generating thermal anomaly data
512
Provide captured data and thermal anomaly data to a report generation module, generating a thermal report

FIG. 14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2024/050196

A. CLASSIFICATION OF SUBJECT MATTER

IPC: ***G01N 21/88*** (2006.01) , *G01J 5/48* (2006.01)

CPC: **G01N 21/8851** (2020.01) , G01J 5/48 (2022.01) , G01N 2021/8854 (2020.01) , G01N 2201/10 (2020.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
Across all IPC classifications

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)

Database: Questel Orbit
Keywords: thermal, infrared, camera, UAV, drone, vehicle, building, window, door, envelope, anomaly, HVAC, detect, determine, assess, segmentation, and classify

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2019/0304078 A1 (ASRANI et al.) 3 October 2019 (03-10-2019) *paragraphs 0010, 0025, 0027, 0031, 0032, 0034, 0039-0042, 0044-0048, 0059, and 0060	1-6, 8, 9, 11, 13-15, 17, 18, 20, 22-24 --- 7, 10, 12, 16, 19, 21
Y	US 2022/0343769 A1 (MOTAHAR et al.) 27 October 2022 (27-10-2022) *paragraphs 0106, 0112, 0131, 0132 and 0136	7, 10, 12, 16, 19, 21

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"D"	document cited by the applicant in the international application	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"E"	earlier application or patent but published on or after the international filing date	"&"	document member of the same patent family
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)		
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 29 April 2024 (29-04-2024)	Date of mailing of the international search report 02 May 2024 (02-05-2024)
Name and mailing address of the ISA/CA Canadian Intellectual Property Office Place du Portage I, C114 - 1st Floor, Box PCT 50 Victoria Street Gatineau, Quebec K1A 0C9 Facsimile No.: 819-953-2476	Authorized officer Omer Ondun (819) 962-1518

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CA2024/050196

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
US2019304078A1	03 October 2019 (03-10-2019)	US11449981B2	20 September 2022 (20-09-2022)
		CA2999665A1	29 September 2019 (29-09-2019)
		CA3038434A1	29 September 2019 (29-09-2019)
US2022343769A1	27 October 2022 (27-10-2022)	None	