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Systems and Methods of Capturing Large Area Images in Detail Including Cascaded Cameras and/or Calibration Features

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ABSTRACT

Systems and methods are disclosed relating to acquisition of images regarding large area objects or large areas. In one exemplary embodiment, there is provided a method of obtaining or capturing, via a first system that includes one or more first image capturing devices, overview images, wherein the overview images depict first areas, as well as obtaining or capturing, via a second system that includes a plurality of image capturing devices, detail images characterized as being related to each other along an image axis. Moreover, the detail images may depict second areas that are subsets of the first areas, they may be arranged in strips parallel to the image axis, and they may have a higher resolution than corresponding portions of the first images.

A method and system are presented in which images are captured from overview and detail imaging devices such that overview images are created with a first degree of redundancy, and detail images are captured with less overlap and a second degree of redundancy.

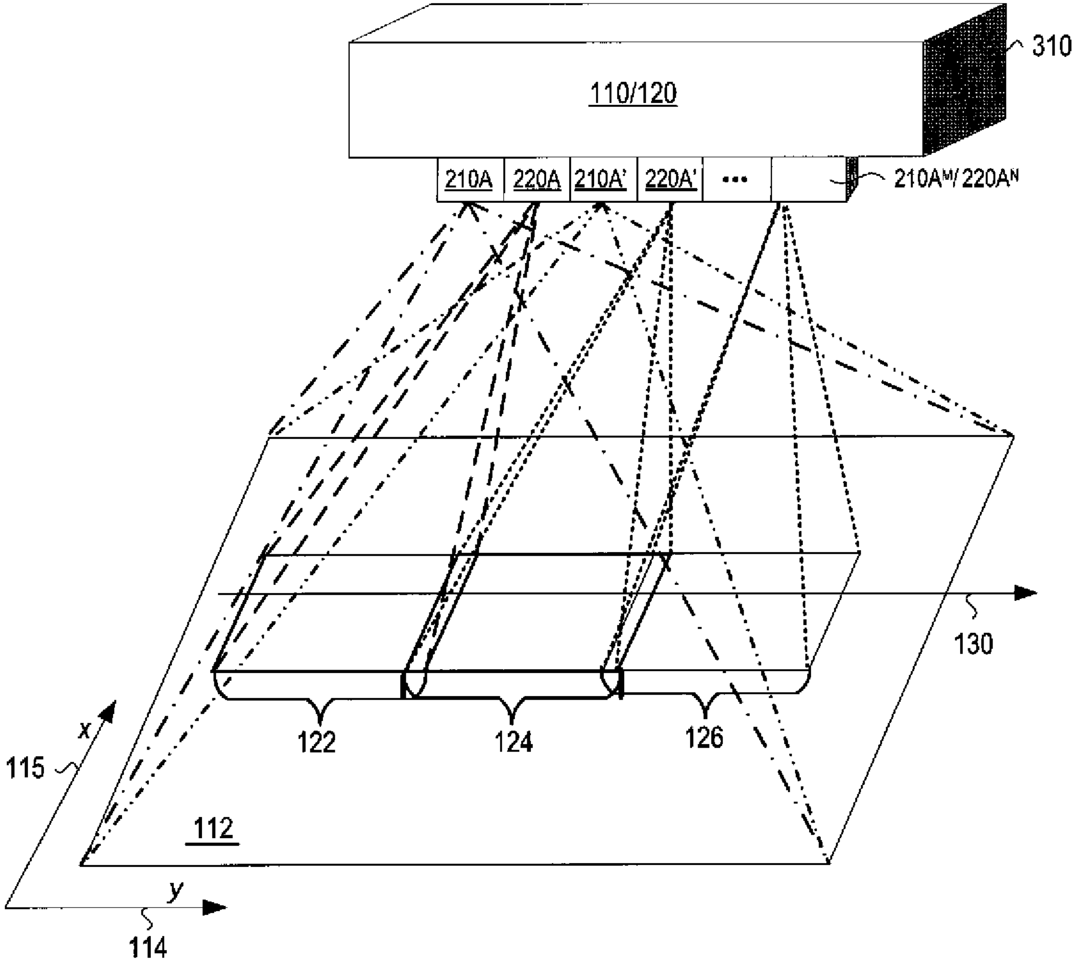
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Fig. 3

P/00/011 28/5/91
Regulation 3.2

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ORIGINAL

COMPLETE SPECIFICATION

STANDARD PATENT

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Invention Title: Systems and Methods of Capturing Large Area Images in Detail Including Cascaded Cameras and/or Calibration Features

The following statement is a full description of this invention, including the best method of performing it known to me:-

SYSTEMS AND METHODS OF CAPTURING LARGE AREA IMAGES IN DETAIL INCLUDING CASCADED CAMERAS AND/OR CALIBRATION FEATURES

FIELD OF THE INVENTION

The present invention relates to photogrammetry, and, more particularly, to systems and methods consistent with arrays of image capturing devices directed to the acquisition of images regarding large area objects or large areas.

BACKGROUND ART

Each document, reference, patent application or patent cited in this text is expressly incorporated herein in their entirety by reference, which means that it should be read and considered by the reader as part of this text. That the document, reference, patent application, or patent cited in this text is not repeated in this text is merely for reasons of conciseness.

The following discussion of the background to the invention is intended to facilitate an understanding of the present invention only. It should be appreciated that the discussion is not an acknowledgement or admission that any of the material referred to was published, known or part of the common general knowledge of the person skilled in the art in any jurisdiction as at the priority date of the invention.

Aerial and satellite imagery of the earth is used for a wide range of military, commercial and consumer applications. Recent innovations sometimes include components that process and compress large amounts of images and a number of emerging applications include serving photo imagery maps on the Internet, and services based on the generation of those photomaps (e.g. maps and directions, real estate values). In general, there is an increasing demand for photo imagery maps, and recently updated photomaps. However, existing systems for the generation of photomaps often involve overly complex components, require high capital expenditures, and/or have high operating costs, among other drawbacks. They are unable to yield imagery within short timeframes and operating regimes, or otherwise provide the high resolution, presently desired.

In general, existing photogrammetry imagery solutions fail to meet the increasing demand for more timely and higher resolution imagery because of their inability to capture sufficient amounts of the appropriate high resolution data in an efficient manner. According to principles consistent with certain aspects related to embodiments of the invention described herein, camera systems used for aerial photogrammetry desirably address two conflicting requirements.

First, it is desirable that the camera system's lens and focal system parameters (which may be referred to as interior orientation), as well as its position in space and look angle (which may be referred to as exterior orientation) are precisely calculated. A photogrammetric solution known as bundle adjustment may be used to calculate interior and exterior orientation information for the camera and for each photo taken by the camera. Such calculations often represent a pre-requirement for enabling merging of individual photos into seamless photomaps. One way of achieving the required level of accuracy is to take multiple photos or images, with a large amount of redundant overlap or data between photos. Common features, common elements, common points, or image elements visible in multiple photos can then be identified and used to calculate camera interior and exterior parameters. However, even with large amounts of redundant data between photos it can be difficult to identify common points or image elements if the photos have been taken at different times or under different conditions (e.g. different altitudes, different times of day) since the common points or image elements may have moved or may have differences in appearance (e.g. different shadowing due to changes in illumination) that makes correlation between those common points or image elements difficult.

Second, it is desirable that aerial surveys be completed quickly. This provides several advantages such as reduced operating costs and minimized delays stemming from unfavorable environmental or surveying conditions such as inclement weather. An effective way to increase the amount of ground area captured, measured in km^2 per hour, is to minimize the amount of redundancy between the detailed high resolution photos which are subsequently used to generate photomaps.

As such, the desire to increase redundancy between or among photos or images to enable accurate photogrammetric positioning of the photos or images must be balanced with the desire to decrease redundancy between photos to complete surveys at a lower cost.

One existing approach uses "push-broom" linear detector arrays to minimize redundant capture and maximize capture rate. This approach minimizes the amount of redundancy and so increases capture rate. However, one drawback of this approach is that it sacrifices positional accuracy calculated from redundancy in the photos themselves, and so other complex methods must be used to accurately calculate camera system position information.

Another existing approach is to increase the size of the camera system being used, i.e., in terms of the megapixel count for the cameras or camera arrays. Here, for example, multiple sensors and/or lenses may be combined in a single unit to maximize the megapixel count for the camera system. While this approach may increase the megapixel size of the camera system, it fails to address reduction of redundancy between photos.

Various systems are directed to minimizing amounts of redundant overlap between photos in a survey. Some existing camera systems, for example, are mounted in a fully gyroscopically stabilized platform which in turn is mounted in an aircraft. These systems may insulate the camera(s) from excessive yaw, pitch and/or roll, and enable a lesser amount of redundancy to be used between photos. However, such stabilization systems are expensive and heavy, and suffer from drawbacks like higher camera system costs and the need for larger aircraft to fly the survey.

Other existing systems adapted to estimating camera pose and reducing redundant photo overlap requirements sometimes include one or more IMU (Inertial Measurement Unit) systems with the camera system to provide measurement of the camera's yaw, pitch and roll. Such IMU systems, however, are complex and expensive, and the ability to utilize units of sufficient accuracy is often constrained by export restrictions that prohibit their use in many countries.

Certain other existing systems may include D-GPS (Differential GPS) units that enable estimation of the camera systems position when each photo is taken. These units, with appropriate post-survey (i.e., post-flight) processing, allow position to be estimated to centimetre accuracy. However, D-GPS units are expensive, and typically require a direct signal path to the GPS satellites in order to measure the signal phase later used to calculate precise position. Thus drawbacks of these systems include the requirement that aircraft must take very gradual/flat turns at the end of each flight line in a survey, to ensure that portions of the aircraft such as a wing do not block the D-GPS antennae's view of the satellites. These gradual/flat turns add significantly to the amount of time required to fly a survey.

Still other existing systems provide improved photogrammetric solution accuracy via use of industrial grade high quality lenses, which can minimize the amount of Interior orientation error induced by lens distortions. However, such high quality lenses add significantly to the cost of the camera system.

Even with such techniques, aerial surveys still require a significant amount of overlap between photos in order to ensure production of high quality photomaps. The amount of overlap between photos varies depending on the application and desired quality. A common overlap is 80/30, meaning 80% forward overlap with photos along a flight line and 30% side overlap with photos in adjacent parallel flight lines. This amount of overlap allows a feature to be identified on average in about 5 photos, which, in combination with the stability and position techniques discussed above, is sufficient to enable accurate photogrammetric bundle adjustment of photos.

However, forward overlap of 80% and side overlap of 30% means that only 14% of each photo covers new ground. About 86% of the photo information taken is redundant in terms of the final photomap product produces, so aerial surveys are fairly inefficient in terms of the amount of flying required to cover an area. Also, the redundant photo data must be stored and later processed, which further increases costs.

While greater levels of redundancy, or overlap, increase the ability to precisely calculate Exterior and Interior orientation for the camera system, such redundancy is largely wasted when creating a final photomap. This is because significantly more redundant imagery is captured than needed to create a photomap, which also increases the time and cost required to fly a survey. A satisfactory balance between these considerations is not available in a variety of other conventional systems, which all suffer from additional shortcomings.

For example, many existing systems for aerial photography require very expensive camera solutions that are typically purpose-built for the application. Such systems suffer the drawback that they cannot use COTS (Commercial Off The Shelf) cameras/hardware. Further, the heavy weight and high cost of these camera systems often requires the use of twin-engine turbo-prop aircraft, which further drives up operating costs since these aircraft are much more expensive to operate than common single engine commercial aircraft like the Cessna 210. Moreover, specific mounting requirements for such camera systems frequently require custom modification of the aircraft in order to mount the camera system.

Further, conventional large format aerial survey cameras are typically large, heavy and expensive. It is often impossible to configure systems of such cameras to take oblique photos at the same time as taking nadir photos. Oblique photography is very widely used in intelligence gathering and military applications, and has recently become popular for consumer applications. Oblique photomaps provide a view of objects such as houses from the side, where as nadir, or overhead, photomaps look from directly overhead and don't show the sides of objects. Oblique photography is also desirable to enable textures to be placed over 3D object models to increase realism. Existing systems that do provide oblique imagery often suffer additional limitations. For example, capture rates can be very low, and the aircraft typically must fly at low altitudes in order to capture high resolution oblique images. Moreover, minimal overlap is generally provided between photos from different obliques, making it difficult or impossible to create photogrammetrically accurate photomaps.

Furthermore, many existing systems have limited resolution (megapixels) per image and use much of their available resolution to capture redundant data used to accurately calculate camera position and pose. These systems suffer drawbacks when identification of smaller objects from the images is desired, such as the requirement that they fly surveys closer to the ground to capture images of high enough resolution to identify such objects. For example, a camera system must survey (fly) at 3,000 feet altitude to capture 7.5cm pixel resolution photos using a Vexcel UltraCam-D camera. Flying at such a low altitude causes multiple problems. First, turbulence and thermals are much worse at these lower altitudes which makes the flying rougher and more difficult for the pilot, and decreases the stability of the camera system. Secondly, flights over urban areas are more difficult at these altitudes, as ATC (Air Traffic Control) has to juggle the flight paths for the survey aircraft - which needs to fly a consistent set of flight lines - with incoming and outgoing flights from airports surrounding the urban area. Interruptions in survey flights at these altitudes cause significant delays in capturing the survey, further increasing costs.

Many existing systems also require large amounts of data storage onboard the platform or aircraft. These systems typically include local image capturing systems and/or storage devices, to which image data is transmitted or downloaded from the cameras. Often, the storage must be both fast enough to store photo data streaming from the cameras, and capable of storing enough data to enable a reasonable amount of flying time. Further, many such systems use RAID based hard disk storage systems to store in-flight captured data. However, hard disks are sensitive to low air pressure at higher altitudes, which can result in head crashes or other data losses or errors.

In sum, there is a need for systems and methods that may adequately capture and/or process large area images in detail by, for example, utilization of one or more camera systems or arrays having image capturing/processing configurations that provide features such specified overlap characteristics, the ability to create detail photomaps, among others.

DISCLOSURE OF THE INVENTION

The present invention seeks to overcome to at least some extent, or at least ameliorate, one or more of the deficiencies of prior art, or to provide the consumer with a useful or commercial choice.

Other advantages of the present invention will become apparent from the following description, taken in connection with the accompanying drawings, wherein, by way of illustration and example only, preferred embodiments of the present invention are disclosed.

According to a first broad aspect of the present invention, there is provided a method of capturing images comprising:

capturing, via a first system that includes one or more first image capturing devices, overview images, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of image capturing devices, detail images related to each other along a detail image axis, wherein the detail images depict second areas that:

are subsets of the first areas;

are arranged in strips parallel to the detail image axis; and

have a higher resolution than corresponding portions of the first images;

wherein the detail images are captured at a resolution sufficient to produce a detail photomap.

According to a second broad aspect of the present invention, there is provided a method of capturing images comprising:

capturing, via a first system that includes one or more first image capturing devices, overview images, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of image capturing devices, detail images related to each other along a detail image axis, wherein the detail images depict second areas that:

are subsets of the first areas;

are arranged in strips parallel to the detail image axis; and

have a higher resolution than corresponding portions of the first images;

wherein the detail images are captured with a resolution sufficient to produce a detail photomap having a ground-pixel resolution of at least about 10 cm.

According to a third broad aspect of the present invention, there is provided method of capturing images comprising:

capturing or obtaining, via a first system that includes one or more first image capturing devices, overview images, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of image capturing devices, detail images related to each other along a detail image axis, wherein the detail images depict second areas that:

are subsets of the first areas;

are arranged in strips parallel to the detail image axis; and

have a higher resolution than corresponding portions of the first images;

wherein the capturing of the detail images occurs from a small or UAV aircraft and the strips of the detail images correspond to a flightline of the small or UAV aircraft;

wherein the detail images are captured with a resolution sufficient to produce a detail photomap having a ground-pixel resolution of at least about 10 cm.

According to a fourth broad aspect of the present invention, there is provided a method of capturing images comprising:

capturing, via a first system that includes one or more first image capturing devices, overview images, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of image capturing devices, detail images related to each other along a detail image axis, wherein the detail images depict second areas that:

are subsets of the first areas;

are arranged in strips parallel to the detail image axis; and

have a higher resolution than corresponding portions of the first images;

wherein the overview images are captured with overlap between images such that a same image point is captured in a quantity of images sufficient to enable accurate bundle adjustment.

According to a fifth broad aspect of the present invention, there is provided a method of capturing images comprising:

capturing, via a first system that includes one or more first image capturing devices, overview images, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of image capturing devices, detail images related to each other along a detail image axis, wherein the detail images depict second areas that:

are subsets of the first areas;

are arranged in strips parallel to the detail image axis; and

have a higher resolution than corresponding portions of the first images;

wherein the overview images are captured with overlap between images such that a same image feature is captured in multiple images as required by bundle adjustment; and

wherein the detail images are captured with a resolution sufficient to produce a detail photomap having a ground-pixel resolution of at least about 10 cm.

According to a sixth broad aspect of the present invention, there is provided a method of capturing images comprising:

obtaining overview images, associated with one or more first image capturing devices of a first system, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of image capturing devices, detail images related to each other along a detail image axis, wherein the detail images depict second areas that:

are subsets of the first areas;

are arranged in strips parallel to the detail image axis; and

have a higher resolution than corresponding portions of the first images;

wherein the overview images are captured with overlap between images such that a same image point is captured in a quantity of images sufficient to enable accurate bundle adjustment;

wherein the detail images are captured such that side photo view overlap, of regions of the detail images that overlap laterally adjacent the detail image axis, is between about 0% and about 10%; and

wherein the detail images are captured at a resolution sufficient to produce a detail photomap.

According to a seventh broad aspect of the present invention, there is provided a method of capturing images comprising:

obtaining overview images, associated with one or more first image capturing devices of a first system, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of image capturing devices, detail images related to each other along a detail axis, wherein the detail images depict second areas that are subsets of the first areas and that have a higher resolution than corresponding portions of the first images;

wherein the overview images are captured with overlap between images such that a same image point is captured in a quantity of images sufficient to enable accurate bundle adjustment;

wherein side photo view overlap among the detail images is between about 0% and about 10%; and

wherein the detail images are captured at a resolution sufficient to produce a detail photomap.

According to an eighth broad aspect of the present invention, there is provided a method of capturing images comprising:

capturing, via a first system that includes one or more first image capturing devices, overview images related to each other along a first axis, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of second image capturing devices, detail images related to each other along a second axis, wherein the detail images depict second areas that are subsets of the first areas and that have a higher resolution than corresponding portions of the first images;

wherein the overview images are captured with overlap between images sufficient to enable accurate bundle adjustment; and

wherein the detail images are captured at a resolution sufficient to produce detailed photomaps.

According to a ninth broad aspect of the present invention, there is provided a method of capturing images comprising:

capturing, via a first system that includes one or more first image capturing devices, overview images related to each other along an overview axis, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of second image capturing devices, detail images related to each other along a detail axis, wherein the detail images depict second areas that are subsets of the first areas and that have a higher resolution than corresponding portions of the first images;

wherein the overview images captured have side overlap redundancy of between about 45% to about 65% with images that are laterally adjacent the first axis, as well as forward overlap redundancy between about 94% to about 99% with images that are longitudinally adjacent the first axis; and

wherein the detail images are captured at a resolution sufficient to produce detailed photomaps.

According to a tenth broad aspect of the present invention, there is provided a method of capturing images comprising:

capturing, via a first system that includes one or more first image capturing devices, overview images related to each other along an overview axis, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of second image capturing devices, detail images related to each other along a detail axis, wherein the detail images depict second areas that are subsets of the first areas and that have a higher resolution than corresponding portions of the first images;

wherein the overview images are captured with overlap between images such that a same imaged point is captured in a quantity of overview images greater than about 30 and less than about 100; and

wherein the detail images are captured at a resolution sufficient to produce detailed photomaps.

According to an eleventh broad aspect of the present invention, there is provided a method of capturing images comprising:

capturing, via a first system that includes one or more first image capturing devices, overview images related to each other along an overview axis, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of second image capturing devices, detail images related to each other along a detail axis, wherein the detail images depict second areas that are subsets of the first areas and that have a higher resolution than corresponding portions of the first images;

wherein the overview images are captured with overlap between images such that an imaged point is captured in an average of about 40 to about 60 overview images; and wherein the detail images are captured at a resolution sufficient to produce detailed photomaps.

According to a twelfth broad aspect of the present invention, there is provided a method of capturing images comprising:

capturing, via a first system that includes one or more first image capturing devices, overview images related to each other along an overview axis, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of second image capturing devices, wherein the detail images depict second areas that are subsets of the first areas and that have a higher resolution than corresponding portions of the first images;

wherein the overview images are captured having overlap between images greater than or equal to overlap required to calculate a bundle adjustment on the overview images;

wherein photo view overlap among the second image capturing devices is between about 0% and about 10%; and

wherein the detail images are captured at a resolution sufficient to produce detailed photomaps.

In one arrangement, the method further comprises removably mounting the image capturing devices in a modular platform such that individual image capturing devices are replaceable.

In one arrangement, the individual image capturing devices are off-the-shelf cameras, which may be individually removed for repair, replacement and/or upgrade.

In one arrangement, the method further comprises calculating interior orientation and exterior orientation of image capturing devices as a function of spatial/positional information determined among captured images, including one or both of the overview images and/or the detail images.

In one arrangement, the method further comprises adjusting, using data associated with spatial/positional relationship among the overview images and the detail images, in adjustment of orientation of one or more of a camera from which the images are derived, arrays of cameras from which the images are derived, and/or a camera system as a whole.

In one arrangement, the overlap redundancy is between about 50% to about 60% side overlap with images that are laterally adjacent the first axis, as well as between about 95% to about 99% forward overlap with images that are longitudinally adjacent the first axis.

In one arrangement, the overlap redundancy is between about 98% to about 99% forward overlap with images that are longitudinally adjacent the first axis.

In one arrangement, the overview images have overlap redundancy is about 50% side overlap with images that are laterally adjacent the first axis, as well as about 99% forward overlap with images that are longitudinally adjacent the first axis.

In one arrangement, the method further comprises capturing images corresponding to multiple different views, including one or more oblique views and/or one or more nadir views.

In one arrangement, the method further comprises processing the overview images to produce overview maps, wherein a first quantity of processing performed on the overview images to calculate interior orientation and exterior orientation is larger than a second quantity of processing performed on the overview images to produce overview maps.

In one arrangement, the method further comprises producing digital elevation models with the overview images;

wherein feature identification present within each photo is maximized to provide higher accuracy and/or robustness; and
wherein a first quantity of processing performed on the overview images to calculate interior orientation and exterior orientation is larger than a second quantity of processing performed on the overview images to produce digital elevation models.

In one arrangement, the method further comprises refining interior orientation and exterior orientation of individual cameras from which the images are derived, of arrays of cameras from which the images are derived, and/or of the camera system as a whole;
wherein a first quantity of processing performed on the detail images to produce detailed photomaps is larger than a second quantity of processing performed on the detail images to refine the interior orientation and the exterior orientation.

In one arrangement, the overview images and the detail images are obtained/acquired via/from a camera system in an externally-mountable housing (pod) of dimensions that are small enough to mount on a small or UAV aircraft.

In one arrangement, the overview images are obtained/acquired via a first system or platform that includes one or more first image capturing devices and the detail images are obtained/acquired via a second system or platform that includes a plurality of second image capturing devices.

In one arrangement, the image capturing devices are configured to all capture images at a same or nearly a same time.

In one arrangement, the method further comprises:
compressing image data local to each image capturing device; and
storing image data in parallel with regard to each image capturing device using a solid state data store local to the image capturing devices.

In one arrangement, performance of the compressing and the storing steps enables operation of image capturing aboard an aerial or space-borne platform without any requirement for transmission of photo image signal data or other camera event or state signal data to a remote processing device or a flight/control processing device.

In one arrangement, the method further comprises:

transmitting image data back to an image processing system that is remote from image capturing devices that capture one or both of the overview images and/or the detail images; and

storing image data in a data store associated with the remote image processing system.

In one arrangement, one or both of the first system or the second system are configured to include a removable mounting system such that the image capturing devices may be interchanged with different image capturing devices.

In one arrangement, the method further comprises:

detecting motion of the first system or the second system above a threshold via a MEMS accelerometer; and

increasing a rate of image capture as a function of the detected motion.

In one arrangement, the method further comprises orienting multiple overview image capturing devices at different poses to maximize the amount of ground feature observations contained within multiple images and thereby enable extraction of accurate photogrammetric bundle adjustment solutions during post processing.

In one arrangement, capturing the detail images is performed via the second system including about 9 second image capturing devices that capture strip-shaped sub-portions of overview images.

In one arrangement, capturing the detail images is performed via the second system including about 12 second image capturing devices composed of about 5 devices that provide a vertical view, about 4 devices that provide left oblique views and right oblique views, and about 3 devices that provide front oblique views and back oblique views from alternating image sequence (flight) lines.

In one arrangement, capturing the detail images is performed via the second system including about 3 sub-arrays of second image capturing devices, wherein a first sub-array captures nadir detail view images, a second sub-array captures first oblique detail view images, and a third sub-array captures second oblique detail view images.

According to a thirteenth broad aspect of the present invention, there is provided an image capturing system comprising:

a first system comprised of one or more first cameras and configured to capture overview images that are related to each other along an overview axis, wherein the overview images captured have side overlap redundancy of between about 45% to about 65% with images that are laterally adjacent the overview axis, as well as forward overlap redundancy between about 94% to about 99% with images that are longitudinally adjacent the overview axis; and

a second system comprised of a plurality of second cameras and configured to capture detail images, the detail images being related to each other along a detail axis, wherein the detail images are captured such that side photo view overlap, of regions of the detail images that overlap laterally adjacent the detail axis, is between about 0% and about 10%; and

wherein the one or more first cameras of the first system and cameras in the second system are configured/positioned such that interior orientation information and exterior orientation information may be determined from analysis of the overview images and the detail images; and

wherein the detail images are captured at a resolution sufficient to produce a detail photomap having a ground-pixel resolution of at least about 10 cm.

In one arrangement, interior orientation and exterior orientation is determined for one or more of individual cameras, groups of cameras, or a camera system as a whole.

In one arrangement, the first system and the second system are associated with a singular housing or platform.

In one arrangement, the second system includes about 9 second image capturing devices that capture strip-shaped sub-portions of overview images.

In one arrangement, the second system comprises about 12 or more second image capturing devices including about 5 devices that provide a vertical view, about 4 devices that provide left oblique views and right oblique views, and about 3 devices that provide front oblique views and back oblique views from alternating image sequence (flight) lines.

In one arrangement, the second system includes 3 sub-arrays of second image capturing devices, wherein a first sub-array captures nadir detail view images, a second sub-array captures first oblique detail view images, and a third sub-array captures second oblique detail view images.

In one arrangement, camera position, including interior orientation and/or exterior orientation, is set using data associated with spatial/positional relationship among the overview images and the detail images derived from one or more of individual cameras, arrays of cameras, or a camera system as a whole.

In one arrangement, the overlap redundancy is between about 50% to about 60% side overlap with images that are laterally adjacent the first axis, as well as between about 95% to about 99% forward overlap with images that are longitudinally adjacent the first axis.

In one arrangement, the overlap redundancy is between about 98% to about 99% forward overlap with images that are longitudinally adjacent the first axis.

In one arrangement, the overview images have overlap redundancy is about 50% side overlap with images that are laterally adjacent the first axis, as well as about 99% forward overlap with images that are longitudinally adjacent the first axis.

In one arrangement, the system is configured to capture images corresponding to multiple different view, including one or more oblique views and/or one or more nadir views.

In one arrangement, the system is configured to process the overview images to produce overview maps, wherein a first quantity of processing performed on the overview images to calculate interior orientation and exterior orientation is larger than a second quantity of processing performed on the overview images to produce overview maps.

In one arrangement, the first system is configured to take overview images that enable production of digital elevation models; and
feature identification present within each photo is maximized to provide higher accuracy and/or robustness.

In one arrangement, positioning to adjust orientation is refined as a function of one or more of individual cameras from which the images are derived, arrays of cameras from which the images are derived, and/or a camera system as a whole.

In one arrangement, the first system and the second system are fixed within an externally-mountable housing (pod) of dimensions that are small enough to mount on a small or UAV aircraft.

In one arrangement, the first system includes one or more first image capturing devices and the second system includes a plurality of second image capturing devices.

In one arrangement, the image capturing devices are configured to all capture images at a same or nearly a same time.

In one arrangement, the system further comprises:

a processing component that compresses image data local to each image capturing device; and

a solid state data store local to the image capturing devices that is configured to store image data in parallel with regard to each image capturing device.

In one arrangement, the system further comprises:

a processing component that compresses image data local to each image capturing device; and

a solid state data store associated with each of the image capturing devices, with each data store being configured to store image data in parallel with regard to each associated image capturing device.

In one arrangement, the processing component and the data store are configured to enable operation of image capturing aboard an aerial or space-borne platform without any requirement for transmission of photo image signal data or other camera event or state signal data to a remote processing device.

In one arrangement, the system further comprises a processing element or transceiver configured to transmit image data back to an image processing system that is remote from image capturing devices that capture one or both of the overview images and/or the detail images.

In one arrangement, one or both of the first system or the second system are configured to include a removable mounting system such that the image capturing devices may be interchanged with different image capturing devices.

In one arrangement, the system further comprises:

a MEMS accelerometer that detects motion of the first system or the second system above a threshold; and

a component that increases a rate of image capture as a function of the detected motion.

In one arrangement, multiple overview image capturing devices are arranged at different poses to maximize the amount of ground feature observations contained within multiple images taken by the overview image capturing devices, thereby providing data sufficient to extract accurate photogrammetric bundle adjustment solutions.

According to a fourteenth broad aspect of the present invention, there is provided an image capturing system comprising:

a first system including one or more first image capturing devices that capture overview images, wherein the overview images depict first areas; and

a second system including a plurality of second image capturing devices that capture detail images characterized as being related to each other along a detail image axis;

wherein the second image capturing devices are configured to capture the detail images such that the detail images:

depict second areas that are subsets of the first areas;

are arranged in strips parallel to the detail image axis; and

have a higher resolution than corresponding portions of the first images;

wherein the second image capturing devices capture the detail images at a resolution sufficient to produce a detail photomap.

According to a fifteenth broad aspect of the present invention, there is provided an image capturing system comprising:

a first system including one or more first image capturing devices that capture overview images, wherein the overview images depict first areas; and

a second system including a plurality of second image capturing devices that capture detail images characterized as being related to each other along a detail image axis;

wherein the second image capturing devices are configured to capture the detail images such that the detail images:

depict second areas that are subsets of the first areas;

are arranged in strips parallel to the detail image axis;

have a higher resolution than corresponding portions of the first images; and

have a resolution sufficient to produce a detail photomap having a ground-pixel resolution of at least about 10 cm.

In one arrangement, the first image capturing devices and the second image capturing devices are configured to capture images having overlap among the overview images and the detail images sufficient to enable bundle adjustment.

In one arrangement, the second system is located on a small or UAV aircraft, and the second image capturing devices capture detail images in strips that correspond to a flight line of the small or UAV aircraft.

In one arrangement, the system is configured to capture overview and detail images having overlap redundancy sufficient to enable accurate bundle adjustment.

In one arrangement, the system is configured to capture overview and detail images with overlap between the images characterized in that a same image point is captured in a quantity of images sufficient to enable accurate bundle adjustment.

In one arrangement, the overview images are characterized as being positioned along an overview axis, and the first image capturing devices are configured to capture the overview images having side overlap redundancy between about 45% to about 65% with images that are laterally adjacent the overview axis, as well as forward overlap redundancy between about 94% to about 99% with images that are longitudinally adjacent the overview axis.

In one arrangement, the overview images are characterized as being positioned along an overview axis, and the first image capturing devices are configured to capture the overview images having side overlap redundancy between about 50% to about 60% with images that are laterally adjacent the overview axis, as well as forward overlap redundancy between about 98% to about 99% with images that are longitudinally adjacent the overview axis.

In one arrangement, the overview images are characterized as being positioned along an overview axis, and the first image capturing devices are configured to capture the overview images having side overlap redundancy of about 50% with images that are laterally adjacent the overview axis, as well as forward overlap redundancy of about 99% with images that are longitudinally adjacent the overview axis.

In one arrangement, the second system includes between 3 and 15 second image capturing devices that capture strip-shaped sub-portions of the overview images.

In one arrangement, the second system includes between 5 and 13 second image capturing devices that capture strip-shaped sub-portions of the overview images.

In one arrangement, the second system includes between 7 and 11 second image capturing devices that capture strip-shaped sub-portions of the overview images.

In one arrangement, the second system includes about 9 second image capturing devices that capture strip-shaped sub-portions of the overview images.

In one arrangement, the second system comprises about 12 or more second image capturing devices including about 5 devices that provide a vertical view, about 4 devices that provide left oblique views and right oblique views, and about 3 devices that provide front oblique views and back oblique views from alternating image sequence (flight) lines.

In one arrangement, the second system includes 3 sub-arrays of second image capturing devices, wherein a first sub-array captures nadir detail view images, a second sub-array captures first oblique detail view images, and a third sub-array captures second oblique detail view images.

According to a sixteenth broad aspect of the present invention, there is provided an image capturing system comprising:

a first system including one or more first image capturing devices that capture overview images, wherein the overview images depict first areas; and

a second system including a plurality of second image capturing devices that capture detail images related to each other along a detail image axis, wherein the second system includes 3 sub-arrays of second image capturing devices, wherein a first sub-array captures nadir detail view images, a second sub-array captures first oblique detail view images, and a third sub-array captures second oblique detail view images;

wherein the second image capturing devices are located on a small or UAV aircraft and configured to capture the detail images such that the detail images:

depict second areas that are subsets of the first areas;

are taken along a flight line of the small or UAV aircraft and arranged in strips parallel to the detail image axis;

have a higher resolution than corresponding portions of the first images; and

have a resolution sufficient to produce a detail photomap; and

wherein the first image capturing devices and the second image capturing devices are configured/arranged to capture overview and detail images having overlap among the overview and detail images sufficient to enable bundle adjustment.

According to a seventeenth broad aspect of the present invention, there is provided an image capturing system comprising:

a first system including one or more first image capturing devices that capture overview images, wherein the overview images depict first areas; and

a second system including a plurality of second image capturing devices that capture detail images characterized as being related to each other along a detail image axis, wherein the second system includes 3 sub-arrays of second image capturing devices, wherein a first sub-array captures nadir detail view images, a second sub-array captures first oblique detail view images, and a third sub-array captures second oblique detail view images;

wherein the second image capturing devices are located on a small or UAV aircraft and configured to capture the detail images such that the detail images:

depict second areas that are subsets of the first areas;

are taken along a flight line of the small or UAV aircraft and arranged in strips parallel to the detail image axis;

have a higher resolution than corresponding portions of the first images; and

have a resolution sufficient to produce a detail photomap having a ground-pixel resolution of at least about 10 cm; and

wherein the first image capturing devices and the second image capturing devices are configured/arranged to capture overview and detail images having overlap among the overview and detail images sufficient to enable bundle adjustment.

According to an eighteenth broad aspect of the present invention, there is provided a method of capturing images comprising:

capturing, via a first system that includes a plurality of first image capturing devices arranged on a platform in different poses, overview images having overlap redundancy characterized in that a same ground point is visible and measurable on at least about 500 images of the overview images captured;

capturing, via a second system that includes a plurality of second image capturing devices, detail images characterized as being related to each other along a second axis;

determining spatial/positional relationship information among the overview images and the detail images; and

calculating interior orientation and exterior orientation as a function of the spatial/positional information determined;

wherein the detail images are captured at a resolution sufficient to produce detailed photomaps.

In one arrangement, the method further comprises assisting, using the data indicative of spatial/positional relationship among the overview images and the detail images, in adjustment of interior orientation and exterior orientation of individual cameras from which the images are derived, arrays of cameras from which the images are derived, and/or the camera system as a whole.

In one arrangement, the overlap redundancy is between about 50% to about 60% side overlap with images that are laterally adjacent the first axis, as well as between about 95% to about 99% forward overlap with images that are longitudinally adjacent the first axis.

In one arrangement, the overlap redundancy is between about 98% to about 99% forward overlap with images that are longitudinally adjacent the first axis.

In one arrangement, the overview images have overlap redundancy is about 50% side overlap with images that are laterally adjacent the first axis, as well as about 99% forward overlap with images that are longitudinally adjacent the first axis.

In one arrangement, the method further comprises capturing images corresponding to multiple different view, including one or more oblique views and/or one or more nadir views.

In one arrangement, the method further comprises processing the overview images to produce overview maps, wherein a first quantity of processing performed on the overview images to calculate interior orientation and exterior orientation is larger than a second quantity of processing performed on the overview images to produce overview maps.

In one arrangement, the method further comprises producing digital elevation models with the overview images;
wherein feature identification present within each photo is maximized to provide higher accuracy and/or robustness; and
wherein a first quantity of processing performed on the overview images to calculate interior orientation and exterior orientation is larger than a second quantity of processing performed on the overview images to produce digital elevation models.

In one arrangement, the method further comprises refining interior orientation and exterior orientation of individual cameras from which the images are derived, of arrays of cameras from which the images are derived, and/or of the camera system as a whole;
wherein a first quantity of processing performed on the detail images to produce detailed photomaps is larger than a second quantity of processing performed on the detail images to refine the interior orientation and the exterior orientation.

In one arrangement, the overview images and the detail images are obtained/acquired from a camera system fixed within an external pod of dimensions that are small enough to mount on a small or UAV aircraft.

In one arrangement, the overview images are obtained/acquired via a first system or platform that includes one or more first image capturing devices and the detail images are obtained/acquired via a second system or platform that includes a plurality of second image capturing devices.

In one arrangement, the method further comprises configuring the image capturing devices to capture images at a same or nearly a same time.

In one arrangement, the method further comprises:

compressing image data local to each image capturing device; and

storing image data in parallel with regard to each image capturing device using a solid state data store local to the image capturing devices.

In one arrangement, performance of the compressing and the storing steps enables operation of image capturing aboard an aerial or space-borne platform without any requirement for transmission of photo image signal data or other camera event or state signal data to a remote processing device or flight/control processing device.

In one arrangement, the method further comprises:

transmitting image data back to an image processing system that is remote from image capturing devices that capture one or both of the overview images and/or the detail images; and

storing image data in a data store associated with the remote image processing system.

In one arrangement, the method further comprises configuring one or both of the first system or the second system to include a removable mounting system such that the image capturing devices may be interchanged with different image capturing devices.

In one arrangement, the method further comprises:

detecting motion of the first system or the second system above a threshold via a MEMS accelerometer; and

increasing a rate of image capture as a function of the detected motion.

In one arrangement, the method further comprises orienting multiple overview image capturing devices at different poses to maximize the amount of ground feature observations contained within multiple images and thereby enable extraction of accurate photogrammetric bundle adjustment solutions during post processing.

In one arrangement, capturing the detail images is performed via the second system including about 9 second image capturing devices that capture a strip sub-portion of each overview image.

In one arrangement, capturing the detail images is performed via the second system including 12 second image capturing devices composed of 5 devices that provide a vertical view, 4 devices that provide left oblique views and right oblique views, and 3 devices that provide front oblique views and back oblique views from alternating image sequence (flight) lines.

In one arrangement, capturing the detail images is performed via the second system including 3 sub-arrays of second image capturing devices, wherein a first sub-array captures nadir detail view images, a second sub-array captures first oblique detail view images, and a third sub-array captures second oblique detail view images.

According to a nineteenth broad aspect of the present invention, there is provided a method of capturing and processing images, the method comprising:

obtaining/acquiring overview images having a first axis, wherein the overview images have overlap redundancy including between about 45% to about 65% side overlap with images that are laterally adjacent the first axis, as well as between about 94% to about 99% forward overlap with images that are longitudinally adjacent the first axis;

obtaining/acquiring detail images having a second axis, wherein the overview images have overlap redundancy including between about 2% to about 5% side overlap with images that are laterally adjacent, as well as about 5% to about 10% forward overlap with images that are longitudinally adjacent, the first axis;

processing or utilizing data indicative of spatial/positional relationship among one or more of the overview images, the detail images, and/or fields of view thereof;

processing overview image data to calculate interior orientation and exterior orientation; and

processing the detail images to produce detailed photomaps.

According to a twentieth broad aspect of the present invention, there is provided a system that captures images via aerial or space-borne surveying, the system comprising:

a first system comprised of one or more first cameras and configured to capture overview images, wherein the overview images provide overview data sufficient to calculate interior orientations and exterior orientations of the one or more cameras; and

a second system comprised of a plurality of second cameras and configured to capture detail images, wherein photo view overlap among the second cameras is between about 0% and about 10%;

wherein the one or more first cameras of the first system are positioned in an arrangement that is set in relation to positioning of cameras in the second system, such that camera interior orientation information and camera exterior orientation information may be determined from interrelated field of view information derived from the overview images and the detail images.

In one arrangement, the second system is located on a small or UAV aircraft, and the second image capturing devices capture detail images in strips that correspond to a flight line of the small or UAV aircraft.

In one arrangement, the second system includes between 5 and 13 second image capturing devices that capture strip-shaped sub-portions of the overview images.

In one arrangement, interior orientation and exterior orientation is determined for one or more of individual cameras, groups of cameras, or a camera system as a whole.

In one arrangement, the first system and the second system are associated with a singular housing or platform.

In one arrangement, the overlap redundancy is between about 98% to about 99% forward overlap with images that are longitudinally adjacent the first axis.

In one arrangement, the system is configured to capture images corresponding to multiple different view, including one or more oblique views and/or one or more nadir views.

In one arrangement, the first system and the second system are fixed within an externally-mountable housing (pod) of dimensions that are small enough to mount on a small or UAV aircraft.

In one arrangement, the system further comprises:

a processing component that compresses image data local to each image capturing device; and

a solid state data store local to the image capturing devices that is configured to store image data in parallel with regard to each image capturing device.

In one arrangement, one or both of the first system or the second system are configured to include a removable mounting system such that the image capturing devices may be interchanged with different image capturing devices.

In one arrangement, multiple overview image capturing devices are arranged at different poses to maximize the amount of ground feature observations contained within multiple images taken by the overview image capturing devices, thereby providing data sufficient to extract accurate photogrammetric bundle adjustment solutions.

In one arrangement, the second system includes 3 sub-arrays of second image capturing devices, wherein a first sub-array captures nadir detail view images, a second sub-array captures first oblique detail view images, and a third sub-array captures second oblique detail view images.

In one arrangement, multiple overview image capturing devices are arranged at different poses to maximize the amount of ground feature observations contained within multiple images taken by the overview image capturing devices, thereby providing data sufficient to extract accurate photogrammetric bundle adjustment solutions.

In one arrangement, the second image capturing devices capture detail images in strips that correspond to a flight line of the small or UAV aircraft.

In one arrangement, the second system includes between 5 and 13 second image capturing devices that capture strip-shaped sub-portions of the overview images.

In one arrangement, the detail images are captured with a resolution sufficient to produce a detail photomap having a ground-pixel resolution of at least about 10 cm.

In one arrangement, the first image capturing devices and the second image capturing devices are configured/arranged to capture overview and detail images having overlap among the overview and detail images sufficient to enable bundle adjustment.

In one arrangement, the method further comprises removably mounting the image capturing devices in a modular platform such that individual image capturing devices are replaceable.

In one arrangement, the individual image capturing devices are off-the-shelf cameras, which may be individually removed for repair, replacement and/or upgrade.

In one arrangement, images captured correspond to multiple different views, including one or more oblique views and/or one or more nadir views.

In one arrangement, the overview images and the detail images are obtained via a camera system in an externally-mountable housing (pod) of dimensions that are small enough to mount on a small or UAV aircraft.

In one arrangement, capturing the detail images is performed via the second system including 3 sub-arrays of second image capturing devices, wherein a first sub-array captures nadir detail view images, a second sub-array captures first oblique detail view images, and a third sub-array captures second oblique detail view images.

In one arrangement, interior orientation and exterior orientation is determined for one or more of individual cameras, groups of cameras, or a camera system as a whole.

In one arrangement, the first system and the second system are associated with a singular housing or platform.

In one arrangement, the second system includes 3 sub-arrays of second image capturing devices, wherein a first sub-array captures nadir detail view images, a second sub-array captures first oblique detail view images, and a third sub-array captures second oblique detail view images.

In one arrangement, the method further comprises maintaining forward overlap redundancy between about 98% to about 99% in the overview images with images that are longitudinally adjacent the first axis.

In one arrangement, the method further comprises capturing images corresponding to multiple different views, including one or more oblique views and/or one or more nadir views.

In one arrangement, the first system and the second system are fixed within an externally-mountable housing (pod) of dimensions that are small enough to mount on a small or UAV aircraft.

In one arrangement, the method further comprises:

compressing image data local to each image capturing device; and

storing image data in parallel with regard to each image capturing device via a solid state data store local to the image capturing devices.

In one arrangement, the method further comprises arranging multiple overview image capturing devices at different poses to maximize the amount of ground feature observations contained within multiple images taken by the overview image capturing devices, thereby providing data sufficient to extract accurate photogrammetric bundle adjustment solutions.

In one arrangement, the second image capturing devices capture detail images in strips that correspond to a flight line of the small or UAV aircraft.

In one arrangement, the second system captures strip-shaped sub-portions of the overview images using between 5 and 13 second image capturing devices.

According to a twenty-first broad aspect of the present invention, there is provided a method of capturing images comprising:

capturing, via a first system that includes one or more first image capturing devices, overview images, wherein the overview images depict first areas; and

capturing, via a second system that includes a plurality of image capturing devices, detail images characterized as being related to each other along a detail image axis, wherein the detail images depict second areas that:

are subsets of the first areas;

are arranged in strips parallel to the detail image axis; and

have a higher resolution than corresponding portions of the first images;

wherein the capturing of the detail images occurs from a small or UAV aircraft and the strips of the detail images correspond to a flightline of the small or UAV aircraft;

wherein the overview images are captured with overlap between images characterized in that a same image point is captured in a quantity of images sufficient to enable accurate bundle adjustment.

According to a twenty-second broad aspect of the present invention, there is provided an image capture system comprising:

a first image capture subsystem comprising a first imaging device configured for capturing, at a first instance in time, at least one overview image of an overview area; and

a second image capture subsystem comprising a second imaging device configured for capturing, substantially concurrent with the first instance in time, at least one detail image of at least a portion of the overview area, the first and second image capture subsystems being configured such that a plurality of overview images results in an overview redundancy of image elements among the plurality of overview images and a plurality of detail images results in a detail redundancy of image elements among the plurality of detail images.

In one arrangement, the first image capture subsystem includes a plurality of imaging devices arranged to capture the plurality of overview images.

In one arrangement, the plurality of imaging devices is arranged to substantially simultaneously capture the plurality of overview images.

In one arrangement, the plurality of imaging devices is arranged in an adjacent manner to capture the plurality of overview images.

In one arrangement, the first and second image capture subsystems are proximately located to each other.

In one arrangement, the redundancies represent the degree to which image elements appear in multiple images.

In one arrangement, the image elements include one or more identifiable features, areas or markings corresponding to the area captured in the at least one overview image and the at least one detail image.

In one arrangement, the overview redundancy is greater than 10.

In one arrangement, the detail redundancy is less than or equal to 10.

According to a twenty-third broad aspect of the present invention, there is provided an image capture system comprising:

a first image capture subsystem comprising a first imaging device configured for capturing, at a first instance in time, at least one overview image of an overview area at a first ground resolution; and

a second image capture subsystem comprising a second imaging device configured for capturing, substantially concurrent with the first instance in time, at least one detail image of at least a portion of the overview area, the at least one detail image being at a second ground resolution that is higher than the first ground resolution.

In one arrangement, the first and second image capture subsystems are configured such that a plurality of overview images results in a redundancy of image elements among the plurality of overview images and a plurality of detail images results in a redundancy of image elements among the plurality of detail images.

In one arrangement, the first image capture subsystem includes a plurality of imaging devices arranged to capture a plurality of overview images of one or more overview areas.

In one arrangement, the plurality of imaging devices is arranged to capture the plurality of overview images substantially simultaneously.

In one arrangement, the plurality of imaging devices is arranged in an adjacent manner to capture the plurality of overview images.

In one arrangement, the first plurality of imaging devices is arranged in a cascaded manner to capture the plurality of overview images.

In one arrangement, the second image capture subsystem includes a plurality of imaging devices arranged to capture a plurality of detail images of one or more detail areas.

In one arrangement, the plurality of imaging devices is arranged to capture the plurality of detail images substantially simultaneously.

In one arrangement, the second plurality of imaging devices is arranged in an adjacent manner to capture the plurality of detail images.

In one arrangement, the plurality of imaging devices is arranged in a cascaded manner to capture the plurality of detail images.

In one arrangement, the first and second image capture subsystems are located proximately to each other.

In one arrangement, the first and second image capture subsystems are mounted in or on an aircraft.

In one arrangement, the first and second image capture subsystems are arranged within a housing on the aircraft.

In one arrangement, the housing is removably attached to the aircraft.

In one arrangement, the at least one second imaging device is a digital camera.

In one arrangement, the at least one second imaging device is a CMOS sensor.

In one arrangement, the at least one second imaging device is a push broom sensor.

In one arrangement, the at least one second imaging device is a whisk broom sensor.

In one arrangement, the overview images are stored locally within the first image capture subsystem.

In one arrangement, the detail images are stored locally within the second image capture subsystem.

According to a twenty-fourth broad aspect of the present invention, there is provided a method of capturing images, the method comprising:

(a) capturing, by a first image capture subsystem, a first overview image of an overview area, the first overview image being at a first ground resolution; and

(b) capturing, by a second image capture subsystem, substantially simultaneously with the capture of the first overview image, a first detail image of at least a portion of the overview area, the first detail image being at a second ground resolution that is higher than the first ground resolution.

In one arrangement, the method further comprises:

(c) translating the first and second image capture subsystems along a first axis;

(d) capturing, by the first image capture subsystem, a second overview image of a second overview area at the first ground resolution, wherein the first and second overview images have at least one overlapping overview portion with respect to each other; and

(e) capturing, by the second image capture subsystem, a second detail image at a second ground resolution, wherein the first and second detail images have at least one overlapping detail portion with respect to each other that is substantially smaller than the overlapping overview portion of the first and second overview images.

In one arrangement, at least one of the overlapping overview portion and the overlapping detail portion results in an overview redundancy with respect to the first and second overview images and a detail redundancy with respect to the first and second detail images.

In one arrangement, the redundancies represent the degree to which image elements appear in multiple images.

In one arrangement, the image elements include one or more identifiable features, areas or markings corresponding to an area captured in the overview image and the at least one detail image.

In one arrangement, the overview redundancy is greater than 10.

In one arrangement, the detail redundancy is less than or equal to 10.

In one arrangement, the overview redundancy is greater than 10 and the detail redundancy is less than or equal to 10.

In one arrangement, the area of the at least one overlapping overview portion along the first axis is greater than or equal to 50% of the area of one of the first and second overview images.

In one arrangement, the area of the at least one overlapping detail portion along the first axis is less than or equal to 20% of the area of one of the first and second detail images.

According to a twenty-fifth broad aspect of the present invention, there is provided a method of capturing images from one or more moving platforms, comprising:

a. capturing a strip of overview images which are related to each other along an overview image axis and depict overview areas; and
b. capturing a strip of detail images which are related to each other along a detail image axis and depict detail areas that:
    i. are subsets of the overview areas; and
    ii. have a higher resolution than corresponding portions of the overview images, sufficient to produce detailed photomaps.

In one arrangement, the method includes capturing the overview images in sequentially overlapping strips along or substantially parallel to the overview image axis.

In one arrangement, the method includes capturing the detail images in sequentially overlapping strips along or substantially parallel to the detail image axis.

In one arrangement, the method includes capturing the detail images with a resolution sufficient to produce a detail photomap having a ground-pixel resolution of at least about 10 cm.

In one arrangement, the method includes capturing a common ground point in a quantity of overlapping overview images sufficient to enable accurate bundle adjustment.

In one arrangement, the method includes capturing a common ground point which is visible and measurable on at least about 30 to about 500 overview images.

In one arrangement, the method includes acquiring sequentially overlapping overview images in longitudinal strips along and substantially parallel to the overview image axis and having:

a. between about 94% to about 99% forward overlap between adjacent overview images in strips along or substantially parallel to said axis; and/or
b. between about 45% to about 65% side overlap between substantially parallel strips of overview images transverse to said axis.

In one arrangement, the method includes acquiring detail images that have:

a. greater than 0% to about 10% forward overlap between adjacent detail images in strips along or substantially parallel to the detail image axis; and /or
b. greater than 0% to 10% side overlap between substantially parallel strips of detail images transverse to the detail image axis.

In one arrangement, detail image axis and/or overview image axis substantially correspond to the direction of movement of the platform.

In one arrangement, the method further comprises calculating the interior orientation and exterior orientation of image capture devices as a function of spatial and/or positional information determined among captured overview and/or detail images.

In one arrangement, the method further comprises adjusting the orientation of one or more of:

- a. an image capture device from which the images are derived;
- b. arrays of image capture devices from which the images are derived; and/or
- c. an image capture system as a whole;

using data associated with the spatial and/or positional relationships among overview and detail images.

In one arrangement, the method further comprises capturing images for multiple different views, including one or more oblique views and/or one or more nadir views.

In one arrangement, the method includes capturing the detail images by a detail system, which includes:

- a. a first sub-array capturing nadir view detail images;
- b. a second sub-array capturing first oblique view detail images; and
- c. a third sub-array capturing second oblique view detail images.

In one arrangement, the method further comprises:

- a. detecting motion of the overview system or the detail system above a threshold via a MEMS accelerometer; and
- b. increasing the rate of image capture as a function of the detected motion.

In one arrangement, the method further comprises configuring the image capture devices to capture sets of substantially contemporaneous overview and detail images.

In one arrangement, the method further comprises:

- a. detecting motion of the overview system and/or the detail system above a threshold with a MEMS accelerometer; and

b. increasing the rate of image capture as a function of the detected motion.

According to a twenty-sixth broad aspect of the present invention, there is provided a moving image capture system comprising:

a. an overview system, comprising one or more overview image capture devices that are configured to capture overview images which are related to each other along an overview axis and depict overview areas; and
b. a detail system, comprising a plurality of detail image capture devices that are configured to capture detail images which are related to each other along a detail axis and depict detail areas within the overview image areas; and

wherein the overview image capture devices and detail image capture devices are configured and/or positioned such that interior orientation information and exterior orientation information may be determined from analysis of the overview and detail images.

In one arrangement, the detail images are captured at a resolution sufficient to produce a detail photomap having a ground-pixel resolution of at least about 10 cm.

In one arrangement, the image capture devices are cameras.

In one arrangement, the image capture devices are off-the-shelf digital cameras, which are each mounted for removal for repair, replacement and/or upgrade.

In one arrangement, one or more of the detail image capture devices are configured to capture detail images that:

a. are arranged such that each detail strip overlaps the adjacent detail strips; and

b. have a higher resolution than corresponding portions of the overview images.

In one arrangement, the detail image capture devices are configured to capture strips of detail images that have greater than 0% to about 10% forward overlap between adjacent detail images.

In one arrangement, the overview image capture devices are configured to capture strips of overview images along the overview image axis that have between about 94% to about 99% forward overlap between adjacent overview images.

In one arrangement, the image capture devices are configured to capture overview images with between about 98% to about 99% forward overlap between adjacent overview images.

In one arrangement, the overview system and the detail system are mounted on one or more structures adapted to be mounted on a moving platform.

In one arrangement, the system is configured to capture images corresponding to multiple different views, including one or more oblique views and/or one or more nadir views.

In one arrangement, the detail system comprises:

a. a first sub-array of detail image capture devices to capture nadir view detail images;
b. a second sub-array of detail image capture devices to capture first oblique view detail images, and
c. a third sub-array of detail image capture devices to capture second oblique view detail images.

In one arrangement, the system further comprises:

a. a processing component in each image capture device that compresses image data from the device; and

b. a solid state data store in each image capture device that is configured to store the compressed image data for that device.

In one arrangement, the overview and detail image capture devices are configured and/or arranged to capture overview and detail images having sufficient overlap among overview and detail images to enable bundle adjustment.

In one arrangement, the overview and detail image capture systems are fixed in or on one or more externally-mountable structures of dimensions that are small enough to mount on a small or UAV aircraft.

In one arrangement, one or both of the overview and detail image capture systems includes a removable mounting system such that each image capture device may be interchanged with another image capture device.

In one arrangement, the detail image capture system is located on a small or UAV aircraft, and the detail image capture devices capture detail images in strips that correspond substantially to the flight line of the aircraft.

In one arrangement, multiple overview image capture devices are arranged at different poses to maximize the number of ground feature observations contained within multiple images taken by the overview image capture devices, thereby providing data sufficient to extract accurate photogrammetric bundle adjustment solutions.

In one arrangement, the detail image capture system includes between 3 and 15 detail image capture devices to capture strip-shaped sub-portions of areas within the overview images.

According to a twenty-seventh broad aspect of the present invention, there is provided one or more computer readable media containing computer readable and/or executable instructions, including instructions adapted to cause one or more processors to execute and/or implement the functionality of at least one of the methods according to broad aspects of the present invention as hereinbefore described.

According to a twenty-eighth broad aspect of the present invention, there is provided a system that captures images via aerial or space-borne surveying, the system comprising:

a. an overview system comprised of one or more overview image capture devices configured to capture overview images which provide overview data sufficient to calculate interior and exterior orientations of the one or more image capture devices; and

b. a detail system comprised of a plurality of detail image capture devices configured to capture detail images with overlap between adjacent detail images that is greater than 0% to about 10%;

wherein the one or more image capture devices of the overview system are positioned in relation to the image capture devices in the detail system such that image capture devices' interior orientation information and exterior orientation information may be determined from interrelated field of view information derived from the overview and the detail images.

In one arrangement, the processing component and the data store are configured to enable image capture aboard an aerial or space-borne platform without any requirement to transmit image signals or other image capture device events or state signal data to a remote processing device.

According to a twenty-ninth broad aspect of the present invention, there is provided a processor-readable storage medium on which is stored instructions that, when executed by a processor, cause the processor to perform at least one of the methods according to broad aspects of the present invention as hereinbefore described.

According to a thirtieth broad aspect of the present invention, there is provided a processor programmed to carry out at least one of the methods according to broad aspects of the present invention as hereinbefore described.

Systems and methods consistent with embodiments of the present invention are directed to arrays of image capturing devices, and processes associated therewith, that acquire/process images of large area objects or large areas.

In one exemplary embodiment, there is provided a method of capturing, via a first system that includes one or more first image capturing devices, overview images, wherein the overview images depict first areas, and capturing, via a second system that includes a plurality of image capturing devices, detail images characterized as being related to each other along an image axis. In one or more further embodiments, the detail images depict second areas that are subsets of the first areas, are arranged in strips parallel to the image axis, and have a higher resolution than corresponding portions of the first images.

According to a thirty-first broad aspect of the present invention, there is provided a method of creating a photomap of a survey area, the method comprising:

(a) moving a vehicle relative to the survey area along a set of substantially parallel survey paths;

(b) capturing, during vehicle movement and via a first imaging system carried by the vehicle, a sequence of overview images, each overview image depicting an overview area of the survey area, consecutive overview areas along each survey path having a degree of forward overlap of the overview areas, adjacent overview areas associated with adjacent survey paths having side overlap;

(c) capturing, during vehicle movement and via a second imaging system carried by the vehicle, a sequence of detail image strips, each detail image strip comprising at least one detail image, each detail image depicting at least a portion of an overview area, each detail image having a higher resolution than the resolution of the overview image corresponding to the overview area, consecutive detail image strips along each survey path having a degree of forward overlap of the detail image strips, the degree of overlap of the overview areas being higher than the degree of overlap of the detail image strips, adjacent detail image strips associated with adjacent survey paths having side overlap, adjacent detail images within each strip having side overlap;

(d) identifying, in a plurality of the overview images and detail images, common features corresponding to common ground points;

(e) estimating, via bundle adjustment and using locations of the identified ground points in the plurality of overview images and detail images, data comprising an exterior orientation associated with each detail image, and a position associated with each ground point; and

(f) merging, using at least some of the estimated data, the detail images to create the photomap.

Preferably, the second imaging system views vertically, and the photomap contains a substantially vertical view.

Preferably, the method also comprises capturing, via one or more oblique groups of cameras, a sequence of oblique detail image strips, and creating, from the oblique detail image strips, an oblique photomap of the survey area.

Preferably, the vehicle is one of a spacecraft, an airborne vehicle, an aircraft, a balloon, an unmanned aerial vehicle (UAV), a seagoing vessel, and a submarine.

Preferably, at least one of the imaging systems comprises at least one sensor, the at least one sensor being one of a digital camera, a push broom sensor, and a whisk broom sensor.

Preferably, at least one of the imaging systems comprises at least one sensor, the at least one sensor being one of an electromagnetic imager, a visible electromagnetic imager, an infrared electromagnetic imager, a thermographic imager, and an ultrasound imager.

According to a thirty-second broad aspect of the present invention, there is provided a system for creating a photomap of a survey area, the system comprising:

(a) a vehicle configured to move relative to the survey area along a set of substantially parallel survey paths;

(b) a first imaging system disposed on the vehicle and configured to capture, during vehicle movement, a sequence of overview images, each overview image depicting an overview area of the survey area, consecutive overview areas along each survey path having a degree of forward overlap of the overview areas, adjacent overview areas associated with adjacent survey paths having side overlap;

(c) a second imaging system disposed on the vehicle and configured to capture, during vehicle movement, a sequence of detail image strips, each detail image strip comprising at least one detail image, each detail image depicting at least a portion of an overview area, each detail image having a higher resolution than the resolution of the overview image corresponding to the overview area, consecutive detail image strips along each survey path having a degree of forward overlap of the detail image strips, the degree of overlap of the overview areas being higher than the degree of overlap of the detail image strips, adjacent detail image strips associated with adjacent survey paths having side overlap, adjacent detail images within each strip having side overlap;

(d) a computer system including at least a computer and a computer-readable medium that stores computer-readable instructions that, when executed by the computer cause the computer to perform a method including:

identifying, in a plurality of the overview images and detail images, common features corresponding to common ground points;

estimating, via bundle adjustment and using locations of the identified ground points in the plurality of overview images and detail images, data comprising an exterior orientation associated with each detail image, and a position associated with each ground point; and

merging, using at least some of the estimated data, the detail images to create the photomap.

Preferably, the second imaging system views vertically, and the photomap contains a substantially vertical view.

Preferably, the system also comprises one or more oblique groups of cameras configured to capture a sequence of oblique detail image strips, wherein the computer system is further configured to create, from the oblique detail image strips, an oblique photomap of the survey area.

Preferably, they system also comprises an enclosure or housing within which the imaging systems are mounted.

Preferably, each imaging system is removably mounted within the enclosure or housing.

Preferably, the enclosure or housing is configured to be mounted external to the vehicle.

Preferably, the enclosure or housing is configured to be removably mounted external to the vehicle.

Preferably, each of the imaging systems comprises one or more image capturing devices.

Preferably, the system further comprises a plurality of data storage devices, each data storage device associated with a respective one of the image capturing devices and configured to store images captured by the image capturing device.

Preferably, each data storage device is a flash memory data storage device.

Preferably, the vehicle is one of a spacecraft, an airborne vehicle, an aircraft, a balloon, an unmanned aerial vehicle (UAV), a seagoing vessel, and a submarine.

Preferably, at least one of the imaging devices comprises at least one sensor, the at least one sensor being one of a digital camera, a push broom sensor, and a whisk broom sensor.

Preferably, at least one of the imaging devices comprises at least one sensor, the at least one sensor being one of an electromagnetic imager, a visible electromagnetic imager, an infrared electromagnetic imager, a thermographic imager, and an ultrasound imager.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention, as described. Further features and/or variations may be provided in addition to those set forth herein. For example, the present invention may be directed to various combinations and subcombinations of the disclosed features and/or combinations and subcombinations of several further features disclosed below in the detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the present invention may be more fully understood and put into practice, preferred embodiments thereof will now be described with reference to the accompanying drawings, It should be understood, however, that the various embodiments of the present invention disclosed are not limited to the precise arrangements and instrumentalities shown in the drawings.

In the drawings:

FIG. 1 depicts a block diagram of an exemplary embodiment of a system for capturing overview and detail images in accordance with aspects of the present invention;

FIGs. 2A-2B depict block diagrams of other exemplary embodiments of systems for capturing overview and detail images in accordance with aspects of the present invention;

FIG. 3 depicts a block diagram of another exemplary embodiment of a system for capturing overview and detail images in accordance with aspects of the present invention;

FIG. 4 depicts a representative diagram of a camera pod system of an exemplary embodiment of a system including overview and detail image capturing devices in accordance with aspects of the present invention;

FIG. 5A depicts an illustration of one exemplary embodiment or implementation including an external pod mounted on a small single engine aircraft in accordance with aspects of the present invention;

FIG. 5B depicts an illustration of one exemplary embodiment or implementation of image capturing subsystems mounted within an external pod of an image capturing system in accordance with aspects of the present invention;

FIG. 5C depicts an illustration of exemplary utilization of an aircraft for data collection of overview and detail images in accordance with aspects of the present invention;

FIG. 5D depicts an illustration of an exemplary flight plan for the collection of overview and detail images in accordance with aspects of the present invention;

FIGs. 6A1, 6B1, 6A2 and 6B2 depict diagrams illustrating exemplary overview and detail image representations in accordance with aspects of the present invention;

FIGs. 7A1, 7B1, 7A2 and 7B2 depict diagrams illustrating further exemplary overview and detail image representations in accordance with aspects of the present invention;

FIGs. 8A-8C depict tables illustrating representative camera configurations for two embodiments of exemplary systems for capturing overview and detail images in accordance with aspects of the present invention;

FIG. 9 depicts an illustration of an aircraft outfitted with a computing/processing system, a navigation/flight plan system, a flight plan display, and a camera pod system in accordance with aspects of the present invention;

FIG. 10 depicts an illustration of a block diagram for a notebook/laptop computer working in conjunction with a controller and GPS system as described in one embodiment in accordance with aspects of the present invention;

FIG. 11 depicts a block diagram of an exemplary embodiment of a system for capturing overview and detail images in accordance with aspects of the present invention;

FIGs. 12A-12B depict block diagrams of other exemplary embodiments of systems for capturing overview and detail images in accordance with aspects of the present invention;

FIG. 13 depicts a block diagram of another exemplary embodiment of a system for capturing overview and detail images in accordance with aspects of the present invention; and

FIG. 14 depicts a representative diagram of a camera pod system of an exemplary embodiment of a system including overview and detail image capturing devices in accordance with aspects of the present invention.

BEST MODE(S) FOR CARRYING OUT THE INVENTION

DETAILED DESCRIPTION OF SOME EXEMPLARY EMBODIMENTS

Reference will now be made in detail to the invention, examples of which are illustrated in the accompanying drawings. The embodiments or implementations set forth in the following description do not represent all embodiments or implementations consistent with the present invention claimed herein. Instead, they are merely some examples consistent with certain aspects related to the present invention.

Certain terminology is used herein for convenience only and is not to be taken as a limitation on the embodiments of the present invention disclosed. In the drawings, wherever possible, the same reference letters and numerals have been used to reference or designate the same or like elements, features or parts of the different embodiments throughout the several figures.

The words "right", "left", "lower" and "upper" designate directions in the drawings to which reference is made. The words "forward" and "sideways" refer to directions of travel of a vehicle, aircraft, spacecraft, submarine or other platform which is translated with respect to the ground. The terminology includes the words above specifically mentioned, derivatives thereof and words of similar import.

The term “resolution” when used herein with respect to an image refers to the ability to distinguish imaged objects, with the resolution typically being given in cm and in reference to object(s) on the ground. When used in that context, resolution can be variously termed ground sample distance, resolution cell, ground resolution, or ground pixel resolution. When used with respect to a camera or other imaging device, the resolution may refer to the density of pixels of that imaging device. As will be understood by one of skill in the art, the resolution of the image (ground sample distance, resolution cell, ground resolution, or ground pixel resolution) is dependent on many parameters, including not only the resolution of the camera but other variables including without limitation the imaging system (e.g. lenses) and operating conditions (e.g. altitude) at which the images are captured.

Many systems and image capturing devices are used in terrestrial, airborne and space-borne platforms to acquire images of large area objects or large areas. These systems and platforms can be implemented with a variety of components, including cameras, processing components, data stores, telescopes, lenses or other devices having specialized components for capturing and/or processing images.

Collection of aerial photomap data can be accomplished by flying an aircraft equipped with aerial imaging devices (e.g. cameras) along a flight plan which involves flying along a relatively straight path, banking and turning the aircraft to turn 180° to fly a parallel return path with some sideways displacement from the original path, and repeating this pattern until a designated area of the ground has been photographed. As will be understood by one of skill in the art, images or photographs are captured at periodic intervals along the straight part of the flight plan to create photographs with forward overlap, and the flight plan is designed such that the images captured have side-to-side overlap.

Overlap in images can be created by a number of mechanisms. For example, an imaging system that is being translated along an axis or generally moved above the ground in a vehicle (e.g. an aircraft) can capture images periodically. The timing between the images (photos) captured can be arranged such that the photos have overlap in the direction of travel. Overlap resulting from the forward direction of travel is commonly referred to as forward overlap. Photos that are taken one after another in such a system and which have the aforementioned forward overlap can be referred to as sequential or adjacent photos. In a flight plan with a forward path and a return path, sideways overlap is created by spacing the forward path and return path such that images captured along those paths have a desired degree of overlap. Overlap resulting from the spacing of the forward and return paths in the flight path is commonly referred to as side overlap. Finally, imaging systems or cameras can be arranged within an image capturing system such that they point at different areas of the ground below, with overlap between the captured images being created due to the mechanical arrangement of the imaging capture (e.g. camera) systems.

Although the amount of forward and side overlap may vary from application to application, as hereinbefore described under the heading Background Art, a common overlap of current aerial mapping systems is 80/30, indicating 80% forward overlap with sequential photos along a flight line and 30% side overlap with photos in adjacent parallel flight lines. In such a configuration, capturing sequential images during forward translation in one flight line would result in only 20% of each image containing new information. Collecting data in this manner allows a feature, image element or common point to be identified within about 5 images. In terms of redundancy for the aforementioned example, any point, pixel, set of pixels, element, image element, object, or feature in that common area has a redundancy of 4 (original plus four more identifiable images of that point or object). As such a set of sequential images having 80% overlap could be considered to have a redundancy of 4. In general, redundancy can be described as the number of images (in a set of images) in which a point appears on average, minus one. The points which are captured redundantly may or may not be used as image elements, but such points or pixels appear in multiple images within the set. As will be understood by one of skill in the art, for high values of redundancy the number of images in which a point appears in on average (*n*), which approximates the redundancy (*n-1*). The amount of redundant information in the sets of images would be further increased by side overlap, resulting in only about 14% of each image containing new information and about 86% of the image information being redundant in terms of the final photomap. As will be understood by one of skill in the art, increasing overlap, whether it be forward overlap, side overlap, or overlap generated by other operations or mechanical configurations, will increase the redundancy in the sets of images.

In one embodiment of systems and methods of the present invention, at least two imaging systems/subsystems are used to capture overview images and detail images. In another embodiment, at least two imaging systems/subsystems are used to capture overview images at a first level of resolution, and detail images at a second level of resolution, the second level of resolution being higher (more image detail) than the first level of resolution. As illustrated in FIG. 1, detail images 122, 124 and 126, captured by second system 120, fall partially or completely within the capture area of an overview image 112, captured by first system 110. The first and second systems 110 and 120 can be translated, typically along X-axis 115. FIGs. 5C and 5D illustrate capture of detail and overview images from a plane and along a typical flight survey path respectively.

Images are collected such that significant overlap exists in the overview images, but overlap in the detail images is significantly reduced or minimized with respect to the amount of overlap in the overview images. Similarly, the amount of overlap of the detail images in one or more embodiments of the present systems and methods is greatly reduced with respect to images obtained in other traditional photomap imaging systems. By having a significant amount of overlap in the overview images, high redundancy exists in those low resolution images, that redundancy being used for image processing related to photomap generation. The detail images, which are at the desired resolution for the photomaps, have a much lower amount of redundancy, thus reducing storage and processing requirements for those images.

Greater levels of redundancy or overlap increase the ability to precisely calculate exterior and interior orientation for the camera system. However, increased redundancy is largely wasted when creating a final photomap, as significantly more image data is captured than is needed to create the final photomap. Collection of this excess data increases the time and costs involved in flying the survey. For example, if a traditional aerial imaging system is flown at an altitude sufficient to produce a 10 cm ground pixel size photomap using an 80/30 overlap, approximately 100 Terabytes (TB) of image data would need to be collected to generate a final photomap that is approximately 14 TB in size. As such, the 10 cm ground pixel resolution images will have a redundancy of about 6 (corresponding to only about 14% new information in each image) and those images will serve both for calculation of the exterior and interior orientation of the camera system, as well as for the generation of the final photomap.

Alternatively, use of embodiments of methods and systems in accordance with aspects of the present invention would allow the use of a first camera system providing 100 cm ground pixel size at a high redundancy (e.g. 98) with a very low unique area covered per photo (approximately 1%) and a second camera system providing high resolution at 10 cm with a high unique area per photo of 80%. Using this technique and system would require about 15 TB for the high redundancy photo set and about 15TB for the low redundancy photo set, for a total storage requirement of less than 30 TB. Furthermore, because of the high redundancy (98) in the low resolution photos, the post processing can achieve higher robustness (fewer errors) and higher accuracy than with lower redundancy images at higher resolution. For example, if the traditional system has a Root Mean Square (RMS) error of 0.5 pixels, the absolute ground error would be 5 cm (0.5 * 10 cm). Using the present methods and systems, the high redundancy photos may enable a post processing RMS of 0.1 pixels, for an absolute ground error of 0.1 * 100 cm = 10 cm. This can be further improved by locating the high detail images within the high redundancy images, resulting in the ability to achieve absolute ground error levels that are comparable to or less than previous systems.

One embodiment of methods and systems of the present invention employs the use of multiple camera sets, each camera set potentially comprising multiple cameras. As such, resolution is not limited to that of current camera systems. For example, current camera systems such as those offered by the Vexcel Corporation can have a resolution of 300 megapixels, but this is achieved through the use of multiple cameras that are mounted in an extremely rigid platform and pre-calibrated. Using the present methods and systems it is possible to create a virtual camera system of extremely high resolution (e.g. 10 gigapixels).

As described previously under the heading Background Art, because of the demanding requirements for aerial photography the camera systems are typically custom built for the particular aerial photography application. Traditional systems cannot take advantage of Commercial Off The Shelf (COTS) components, and as such cannot easily take advantage of advanced in digital photography, such as the relatively low (and continually decreasing) cost of professional Digital Single Lens Reflex (D-SLR) cameras. The heavy weight and high cost of the camera systems required using traditional approaches encourages or requires the use of twin-engine turbo-prop aircraft, which further drives up operating costs, as such aircraft are significantly more expensive to operate than common single engine commercial aircraft such as the Cessna 210. In addition, use of traditional systems common requires custom modifications to the aircraft for camera mounting. In contrast, the present methods and systems allow, in certain embodiments of the invention, the ability to use single engine aircraft, having lower operating costs than twin-engine aircraft, and do not require modification to the aircraft frame.

Using embodiments of methods and systems in accordance with aspects of the present invention, high resolution digital images can be captured over large areas for airborne or space-borne photomap surveys. Data collection times can be significantly reduced over current systems. As such, capital and operating costs can be reduced, and flight surveys can be rapidly conducted when weather permits. In certain embodiments high resolution surveys can be captured from high altitudes, thus reducing the impact on Air Traffic Control, providing smoother flying conditions for the flight survey crew, and generally reducing pilot workload.

Additionally, different types of cameras, or cameras used at different angles, can be utilized to collect the images of different resolutions and with different degrees of redundancy. For example, in the collection of image data for photogrammetry applications, overhead cameras can be used to collect overview images at a relatively low resolution with a high degree of redundancy, and oblique cameras can be used to collect high resolution data with a low degree of redundancy. Other combinations of cameras and resolutions/redundancies are possible, both for photogrammetric applications as well as in other applications. Using embodiments of methods and systems in accordance with aspects of the present invention, different types of cameras may be combined to generate nadir photo maps, oblique photomaps, infrared photomaps, or other combinations as dictated by the survey requirements.

Although described herein as systems of detail and overview cameras, additional sets of cameras (or other types of image capturing devices) can be incorporated to form cascades of image capturing systems operating with different resolutions and different amounts of redundancy. By having higher degrees of redundancy in lower resolution images than in the higher resolution images, it is possible to have the appropriate amount of redundancy for image processing (e.g. bundle adjustment, digital elevation map generation) while at the same time minimizing the amount of redundancy in the higher resolution images. For example, embodiments of the method and system of the invention described herein can be utilized with three sets of cameras, the first set of cameras operating at a low resolution with high redundancy, the second set of cameras operating at a medium resolution with a medium redundancy, and the third set of cameras operating at a high resolution with low redundancy. In general, cascading can be performed using multiple sets of cameras which capture images with differing degrees of overlap, resolution and/or redundancy, such that the resulting sets of lower resolution images have higher redundancy than sets of images taken at a higher resolution. As will be understood by one of skill in the art, the cascade of cameras can be extended to *n* cameras or *n* sets of cameras, without limitations to specific physical arrangements. The cascade of cameras can produce images with a spectra of resolutions, consistent with the redundancy being lower in the higher resolution images. A set of cameras, whether organized in a linear fashion, in an array (row and column format), or in a hierarchy of magnifications can be considered to be organized in a cascaded manner when the result is a plurality of captured images having different ground resolutions. As an example, a set of four cameras arranged as an array can be organized in a cascaded manner by capturing images at different ground resolutions, or at different ground resolutions with different magnifications. If the cameras are organized to cover the same or overlapping ground areas, there will be redundant image data between the captured images.

As understood by one skilled in the art, after the imagery has been captured, whether through these or prior art methods, it can be processed using photogrammetry tools in order to produce a number of applications such as photomaps or digital elevation maps. Common software programs used for such processing include, but are not limited to, one or more of the following programs: Match-AT triangulation software sold by the Inpho Corporation; digital mapping software sold under the trademark Socet Set® by

BAE Systems®; Socet Set® software which is integrated with photogrammetric bundle adjustment software sold as BINGO by GIP mbH; and ERDAS ER Mapper image processing software sold by ERDAS®. Additionally, a wide variety of image processing and triangulation software sold by a variety of vendors may be used to process the data.

The imaging systems/subsystems for overview and detail image capture can be co-located on a suitable vehicle for image capture (e.g. aircraft, spaceship, submarine, balloon) or may be located on separate platforms. In several embodiments the overview and detail imaging systems are co-located in a housing (e.g. pod) which attaches to a small aircraft. In one or more embodiments, the overview and detail images are captured substantially simultaneously. An image capture signal can be generated from a timing system/subsystem (e.g. a system controller) which facilitates the near simultaneous capture of the detail and overview images.

In one or more embodiments of the systems and methods of the present invention, the overview images are collected such that there is an overlap of sequentially captured overview images (hereafter referred to as sequential overview images) of greater than or equal to 50% in the forward direction. In an alternate embodiment, the overlap of sequential overview images in the forward direction is at least 90%. In one embodiment the overlap of the sequential detail images in the forward direction is in the range of 0% to 20%. Other embodiments with other combinations of overlap are possible as will be understood by one of skill in the art, and consistent with having the degree of overlap in the sequential detail images significantly lower than the degree of overlap in the sequential overview images.

In one embodiment of the methods and systems of the present invention, a first image capture system is used to capture an overview image of an overview area, while a second image capture system captures, at substantially the same time, a detail image of at least a portion of the overview area, with redundancy existing between the overview images, and redundancy existing between the detail images.

In terms of redundancy, in one embodiment the redundancy in the overview images is greater than 10, whereas the redundancy in the detail images is less than or equal to 10. In another embodiment the redundancy in the detail images approaches zero. In yet another embodiment the redundancy in the detail images is occasionally less than zero (negative) indicating gaps in the captured images. Because of the high redundancy in the overview images, the gaps in the detail images can be recreated or filled in through subsequent image processing.

As will be appreciated by one of skill in the art, the degree of redundancy can be varied depending on the environment or conditions under which the images are being collected. In poor visibility or rapidly changing environments, the degree of redundancy will need to be extremely high. For example, in foggy/dusty conditions, or in underwater applications, the solution can be biased towards greater redundancy. This can be accomplished through various mechanisms including the use of more overview cameras or by having more frequent image capture (even approaching video frame rates). In the case of underwater applications, multiple 270° sensors, running at close to video frequency, could be used to collect overview type images with very high redundancy, while a single camera could be used to take very high resolution/low redundancy images. Conversely, in an environment which changes less over time (e.g. viewing of an entire planet from space) the degree of redundancy in the overview images could be reduced.

In one application, overview and detail images are collected simultaneously, hence insuring that redundant images contain a sufficient number of potential common features, common elements, common points, or image elements, and minimizing the effects of movements of objects or changes in illumination. In another embodiment the overview and detail images are captured from approximately the same location. In yet another embodiment, the overview and detail images are captured simultaneously from approximately the same location.

In one or more embodiments of the systems and methods of the present invention, the image capture systems/subsystems utilize digital cameras. In one or more embodiments the digital cameras are CMOS based cameras or sensors. In an alternate embodiment a push broom sensor is used, and in yet another embodiment a whisk broom sensor is used for image capture. Other mechanisms for image capture of both overview and detail images can be utilized, including but not limited to analog film systems, point or linear scanners, CCD imaging arrays, other III-V or II-VI based imaging devices, ultrasound imagers, infrared (thermographic) imagers. The imagers operate on the basis of receipt of electromagnetic rays and can operate in the infrared, visible, or other portions of the electromagnetic spectrum. Large format and multiple lens, multiple detector, and multiple detector/lens systems such as those described in U.S. Patent No. 7,009,638 to Gruber et al., and U.S. Patent No. 5,757,423 to Tanaka et al., the entire disclosures of which are incorporated herein by reference, can also be used to capture overview or detail images. Additionally, multiple image collection systems such as the Multi-cameras Integrated Digital Acquisition System (MIDAS) offered by the TRACK'AIR Corporation, and other systems configured to provide detailed metric oblique views can be adopted to and incorporated into the methods and systems of the present invention.

In one or more embodiments of the systems and methods of the present invention, a timing system/subsystem is utilized to generate image capture signals which are fed to the image capture systems/subsystems and cause capture of the overview and detail images. In one or more embodiments the timing system/subsystem is based on a microcontroller or microprocessor with appropriate software, firmware, and accompanying hardware to generate electronic or optical signals which can be transmitted, via cabling or through space (e.g. wirelessly) to the image capturing systems/subsystems. Alternatively, a specialized electronic hardware device, working in conjunction with a navigation system, such as a GPS based navigation system, or alone, can act as the timing system/subsystem to generate image capture signals. In one or more embodiments, the image capture signals are generated at a system controller in the form of a computer (e.g. laptop or ruggedized computer) and are received by digital cameras which form the imaging systems for the overview and detail cameras. There is inherent skew in the transmission of the signals over cables (typically having different lengths) and delays inherent to the digital cameras such that there are variations in the actual capture time of the images, although use of one or more synchronized image capture signals results in the substantially simultaneous capture of the images.

In one or more embodiments, the image capture signal is a one-way signal emanating from the timing system/subsystem, and no return signals from the image capture systems/subsystems are needed. Similarly, the image capture data can be stored locally in the imaging devices (e.g. digital cameras) and no image data needs to be returned from the imaging devices to the controller or other data storage devices. Data storage used for the storage of the images includes, but is not limited to: solid state memory devices such as flash memory, Static Random Access Memory (SRAM), Dynamic Random Access Memory, (DRAM); magnetic storage devices including but not limited to tapes, magnetic drums, core memory, core rope memory, thin film memory, twistor memory, and bubble memory; electro-magnetic storage devices including but not limited to hard or disk drives and floppy drives; optical storage devices including but not limited to photographic film, holographic memory devices and holograms, and optical disks; and magneto-optic drives and data storage devices.

FIG. 1 is a block diagram of an exemplary system 100 consistent with certain aspects related to the methods and systems of the present invention. Referring to FIG. 1, system 100 may comprise a first system 110 that acquires at least one overview image 112, and a second system 120 that acquires detail images 122, 124, 126. The system can be oriented in an *x-y* coordinate system as illustrated in FIG. 1 and in accordance with *x-axis* 115 and *y-axis* 114. In one embodiment, imaging capture devices (e.g. cameras) are arranged to capture detail images 122, 124, 126 in strips along a detail axis 130, with detail axis 130 being generally parallel with *y-axis* 114.

First and second systems 110 and 120 may each include one or more image capturing devices, for example, cameras (throughout this disclosure, the broad term "image capturing device" is often referred to as "camera" for purpose of convenience, not limitation). Furthermore, an imaging array can be created through an arrangement of individual sensors that are used to capture an image, and can act as an individual image capturing device or camera. Individual cameras or image capture devices can be arranged in a linear arrangement, arranged along an axis and set at varying angles to capture different areas of the ground, or arranged in a matrix or array (row and column) format. When arranged such that the image capturing devices capture adjacent or proximate image areas, whether overlapping or not overlapping, the devices can be considered to be arranged in an adjacent manner.

In one embodiment first system 110 and second system 120 are translated in an *x* direction with images captured periodically such that a high degree of overlap is created in the sequential overview images captured by first system 110, and a lesser degree of overlap is created in the sequential detail images captured by the second system 120. In several embodiments the overview images have a lower resolution than the detail images, in order to produce a high redundancy within the overview images without creating unnecessary data storage and processing requirements.

As illustrated in FIG. 1, due to the physical arrangement of the imaging systems or cameras, detail image 122 has some overlap with detail image 124, and detail image 124 has some overlap with detail image 126 in the direction of detail axis 130. As will be understood by one of skill in the art, translation of first system 110 and second system 120 along the *x-axis* 115 with periodic capturing of images allows for a swath or strip of ground to be imaged in detail images 122, 124, and 126, with the overlap insuring that the detail images capture a contiguous strip corresponding to a swath of ground. Movement or translation of the first system 110 and second system 120 along with periodic capture of images results in the capture of contiguous strips/swaths having a first degree of forward overlap at the detail image level, and capture of overview images having a second degree of forward overlap, the second degree of overlap being higher than the first degree of overlap.

In alternate embodiments, first system 110 and second system 120 are translated along *y-axis* 114. In yet another embodiment, first system 110 is translated separately from second system 120. In yet another embodiment overview image 112 and detail images 122, 124 and 126 are captured at separate times from first system 110 and second system 120 respectively.

Further, first and second systems 110, 120 may include arrays of digital image capturing devices, such as cascaded or adjacent groups of multiple cameras mounted in rigid or semi-rigid mounts. Persons of ordinary skill in the art will appreciate that such mounting details are exemplary. For instance, the term rigid or semi-rigid mounting system can describe any apparatus capable of accurately defining the relative position of an imaging system such as a single camera or a plurality of cameras. Such a mounting system can be constructed in a number of ways. For example, the mounting system may be comprised of a rigid structure, such as mounting the cameras into a pod enclosure; it may comprise cameras held in independent but accurate positions relative to one another, such as cameras mounted in multiple distinct aerial or satellite systems with a local referencing system to define relative camera positioning between the satellites. Alternatively, first system 110 may consist of a low-resolution imaging array, and second system 120 may consist of one or more high-resolution imaging arrays, with the arrangement and the imaging of the arrays selected such that the low-resolution imaging array of first system 110 captures overview image 112, and the high-resolution imaging arrays capture detail images 122, 124 and 126.

System 100 of FIG. 1 is also exemplary with regard to various configurations that may be present between or among systems 110, 120 and/or their image capturing devices. For example, FIGs. 2A-2B are block diagrams illustrating differing arrangements of the first system 110 and the second system 120 consistent with the methods and systems disclosed herein. In both FIGs. 2A and 2B imaging systems 210A and 220A are used with the first system 110 and second system 120 respectively. FIG. 2A illustrates an implementation wherein the first system 110 and the second system 120 are located in one fixed location, such as on an aerial platform, in or on an aircraft including without limitation a fixed wing aircraft or helicopter, in a satellite, high altitude or spaced based observation platform, or in or on an ocean going craft, such as a ship, submarine, or other undersea vessel. In this embodiment, first system 110 and second system 120 are located near each other and are moved together. In other applications the proximately located first system 110 and second system 120 are used for ground observations, earth-sky observations, undersea imaging, or microscopic imaging.

FIG. 2B illustrates an embodiment where first system 110 is positioned separately from second system 120. In this embodiment the first and second systems are kept independent but the locations of the two (or more) systems relative to one another are precisely known or calculated. In a physical structure this can be accomplished through rigid mounting such as in a pod enclosure. Alternatively, tracking of the relative position between first system 110 and second system 120 will allow for use of two completely independent platforms. In one embodiment a first aircraft or other type of vehicle may create overview images using first system 110, while a second aircraft or other type of vehicle may create detail images using second system 120. Navigational or inertial guidance systems can utilized to determine the relative positioning of the systems. In yet another embodiment the systems are mounted in multiple distinct satellite systems with a local referencing system used to define relative camera positioning between satellites.

FIG. 3 is a block diagram of another exemplary system consistent with certain aspects related to embodiments of the invention herein. As shown in FIG. 3, a unitary platform or module 310 may include or embody both the first system 110 and the second system 120. The unitary platform can be any arrangement or configuration in which first system and second system are fixedly attached and can be translated or moved together. According to further implementations, the platform 310 may also include various arrangements and/or arrays of first and second image capturing devices or cameras. With respect to FIG. 3, image capturing systems 210A and 210A' represent first imaging systems which capture overview images at a first resolution. The number of image capturing systems which capture the overview images at a first resolution can be extended as illustrated by image capturing system 210A^M, and as such a plurality of cameras or other imaging devices can be used to create the overview image 112. In one embodiment each of the first imaging systems 210A, 210A' through 210A^M is used to take the complete overview image 112, while in an alternate embodiment the first imaging systems 210A, 210A', through 210A^M are arranged to take segments of overview image 112 and as such support the assembly of an entire overview image. In one embodiment the first imaging systems 210A, 210A', through 210A^M are arranged along detail axis 130. In alternate embodiments first imaging systems 210A, 210A', through 210A^M are arranged along *x-axis* 115, in an array format, or in any other arrangement which provides for coverage of the overview area to be captured in overview image 112. As previously discussed, the arrangements and/or arrays of imaging devices can be configured to create a cascade of imaging systems producing a spectra of resolutions with redundancy generally decreasing with increasing resolution.

Referring again to FIG. 3, detail images 122, 124, and 126, having a higher resolution than overview image 112, are captured with second imaging systems 220A, 220A', and 220A^N respectively. In one embodiment the detail images 122, 124, and 126 are overlapping detail images aligned along detail axis 130, detail axis 130 being substantially parallel to *y-axis* 114. In other embodiments second imaging systems 220A, 220A', and 220A^N are all arranged along *x-axis* 115, in an array format, or in any other overlapping or non-overlapping format which allows for the capture of detail images such as detail images 122, 124 and 126.

In one embodiment first imaging systems 210A, 210A', through 210A^M and second imaging systems 220A, 220A' and 220A^N are all based on the same type of imaging system, such as a digital camera operating in the visible portion of the spectrum. In an alternate embodiment, the individual imaging systems within first imaging systems 210A, 210A' through 210A^M and second imaging systems 220A, 220A', and 220A^N are different. For example, first imaging system 220A may operate in the visible region of the spectrum, while second imaging system 220A' can operate in the infrared portion of the spectrum. Similarly, second imaging systems 220A, 220A' and 220A^N may be of different types (e.g. visible and infrared) and can be organized such that detail image 122 is captured twice or more, once by each of two or more imaging systems. As will be understood by one of skill in the art, detail images 122, 124 and 126 can be captured by multiple types of imaging systems (e.g. visible or infrared), or with each detail image being captured by a single type of imaging system.

Referring to FIG. 4, a unitary module 400 is disclosed, including a first overview camera 410A subtending a first overview camera view 411A, a second overview camera (not shown in FIG. 4) subtending a second overview camera view 411B, a first detail camera 420A subtending a first detail view 421A, a second detail camera 420B subtending a second detail camera view 421B, a third detail camera 420C subtending a third detail camera view 421C, a fourth detail camera 420D subtending a fourth detail camera view 421D, a fifth detail camera 420E subtending a fifth detail camera view 421E, a sixth detail camera 420F subtending a sixth detail camera view 421F, a seventh detail camera 420G subtending a seventh detail camera view 421G, an eighth detail camera 420H subtending an eight detail camera view 421H, a ninth detail camera 420I subtending a ninth detail camera view 421I, a tenth detail camera 420J subtending a tenth detail camera view 421J, and an eleventh detail camera 420K subtending an eleventh detail camera view 421K. Local data storage may be used with each camera, thus eliminating the need to write back to a central memory or storage location. The local data storage can be comprised of any type of digital memory including but not limited to flash or other type of nonvolatile memory, volatile memory and associated systems for retaining information in that memory, disk drives, or other types of digital storage media or systems. Alternatively, cameras may share local memory. With regard to the latter, some of the embodiments of the invention herein include features of compressing and/or storing images in association with each camera, rather than requiring captured photos to be transmitted to and stored in a central storage system. Further, features directed to parallel compression and storage of photos on or with each camera increases the maximum throughput and storage for the camera system, which allows surveys to be flown at a faster rate, enabling more data to be stored and flight time to be increased. Such parallel compression and storage on or with each camera also increases storage reliability, as it allows use of compact flash or other solid-state media on or with each camera.

Existing digital imaging and other systems typically store the raw linear sensor as 12 to 16 bit data stored in or to a central storage system. In contrast, by performing compression on each camera in parallel, embodiments of the invention herein allow the data to be converted to a gamma color space such as YCbCr. This allows data to be stored as 8 bit data, since increased bit depth is typically only needed for raw linear data, and further allows compression of images prior to storage on each camera's data store. Conversion to a gamma color space and compression can enable about a 10-fold reduction in storage space requirements. For example, in a system having 14 cameras, each with its own 32GB compact flash memory card, the total of 448GB of storage can be equivalent to upwards of about 4,500GB or 4.5TB of storage of raw uncompressed photo data. Further advantages relate to features of parallel operation and avoiding transmissions. Particularly, parallel operation eliminates the need to transmit image data or any other signals from the cameras to the flight control computer system, and as such increases the capture rate for the camera system, thus reducing post-processing requirements and increasing robustness by reducing cabling and signaling requirements, among others.

A flight plan and image capture timing subsystem can be used to generate one or more capture signals to be sent to the cameras such as those illustrated in FIG. 4. In one embodiment, a single capture signal is sent from the flight plan and image capture timing subsystem to each camera. However, differences in cable lengths, delay times in the cameras, and other variables may result in the photos being taken at slightly different times. Furthermore, the local clocks of the cameras may be inexact or exhibit drift.

In one embodiment, digital cameras, typically containing CMOS imaging sensor arrays, are used to capture the overview and detail images. In an alternate embodiment, push broom sensors, comprised of a linear array of optical sensors, can be used to capture the detail images and serve as the detail image capture system. In another embodiment, a whisk broom or spotlight sensor can be used to generate the detail images. When using a whisk broom sensor a mirror-based or other type of scanning system creates the image by imaging a single spot onto the sensor. The scanning system can be integrated with the timing and navigational systems such that the scanning rate is appropriately synchronized with the forward motion of the vehicle carrying the camera systems and creates the appropriate resolution detail image.

One of ordinary skill in the art would recognize that the quantities (i.e., of both the cameras and of the arrays) of detail cameras may be adjusted to provide for image results desired. Advantages consistent with such implementations include the ability to configure and/or reconfigure module 400 to target different survey requirements, such as the collection of vertical or oblique (high or low) images, or combinations thereof. As understood by one of skill in the art, vertical or nadir images or photographs are those taken with the camera axis directed as nearly vertically as possible, whereas oblique images or photos refer to those images or photographs taken with the camera axis intentionally tilted away from the vertical. Also, one of skill in the art will understand that high oblique images or photographs generally include the horizon, whereas low oblique images or photographs generally do not include the horizon.

Referring to FIG. 4, the plurality of cameras can be arranged in unitary module 400 such that the cameras generally align along module axis 450. In one embodiment module axis 450 is substantially parallel to *x-axis* 115 of FIG. 3, which is typically in the direction of forward travel of the aircraft or other vehicle. In this embodiment detail axis 130 (not shown in FIG. 4) is substantially perpendicular to module axis 450 and the detail cameras are arranged to create an imaging swath which is substantially parallel to *y-axis* 114 of FIG. 3.

FIGs. 8A and 8B provide examples of the details of camera arrangements which may be used in one embodiment. The specific examples disclosed herein are not to be taken as limiting and do not in any way restrict the use of the methods and systems according to aspects of the present invention disclosed herein, which can be applied to many types and configurations of imaging systems. For example, although the exemplary arrangement details reference Canon or Nikon equipment, other types of imaging equipment or combinations thereof, or different combinations of camera groups, layouts, or lenses, may be utilized. In one embodiment the cameras are grouped such that the overview cameras (Canon or Nikon brand cameras) are comprised of a vertical overview camera in the form of a camera with a 28mm lens pointing vertically down, as noted in Table I of FIG. 8A, and a rear overview camera with a 28mm lens pointing aft (or opposite the direction of movement of the aircraft or other vehicle) at an angle of 35 degrees from the vertical. In this embodiment the Canon high resolution cameras are comprised of a vertical group of five cameras with 200 mm lenses and with a group spacing of -19°, -9.5°, 0°, 9.5°, 19°, and 28.5°; a side oblique group is comprised of three cameras having 200 mm lenses and a group spacing of 38°, 47.5°, 57°; and a rear oblique group comprised of three cameras with 135mm lenses with a group spacing of -14.5°, 0°, 14.5° inclined 50° off vertical. In the case of Nikon high resolution cameras, a vertical group of 6 cameras having 180 mm lenses has a group spacing of -21°, -10.5°, 0°, 10.5°, 21°, 31.5°; a side oblique group of 3 cameras having 180 mm lenses having a group spacing of 42°, 52.5°, and 63°; and a rear oblique group of 3 cameras having 135 mm lenses with a group spacing of -14.5°, 0°, 14.5° inclined 50° off vertical.

In an alternate embodiment a first set of cameras is configured with wide-angle lenses and are used to capture photos with a very large amount of overlap such as 50/99 (50% side and 99% forward). Photos captured by these cameras cover a large area per photo, and the high degree of overlap and redundancy results in common features, common elements, common points, or image elements points being visible in many more photos than previous systems, thus enabling precise determination of interior and exterior orientation even without the use of a stabilized platform. A second set of cameras can be configured with longer focal length lenses and used to capture detail imagery to generate the detailed photomaps for the survey. A low amount of overlap is used in these cameras to minimize redundancy and to maximize use of the photo imagery for the detail survey, significantly reducing the overall costs and time required to complete the survey.

FIG. 11 illustrates a block diagram of an exemplary system 100 consistent with certain aspects related to the present invention. Referring to FIG. 11, system 100 may comprise a first system 110 that acquires overview images 112, and a second system 120 that acquires detail images 122, 124, 126. According to some embodiments, the overview images may be characterized by a first or overview axis 116. Similarly, the detail images 122, 124, 126 may be arranged in strips along a second or detail axis 130. Further, the first and second systems 110, 120 may each include one or more image capturing devices, for example, cameras. As set forth in more detail below, embodiments of the present invention consistent with the arrangements herein provide systems and methods having numerous advantages, including the ability to accurately capture high resolution digital images over large areas for airborne or space-borne photomap surveys at a much faster rate and shorter survey flight time than existing systems.

Further, according to some aspects of the invention herein, first and second systems 110, 120 may include arrays of digital image capturing devices, such as cascaded groups of multiple cameras mounted in rigid or semi-rigid mounts. As hereinbefore described, a rigid or semi-rigid mounting system can describe any apparatus capable of accurately defining relative position of the multiple and cascaded groups of cameras. Such a mounting system might be embodied via a variety of permutations, for example, it might comprise a physical rigid structure, such as mounting the cameras into a pod enclosure, it might comprise cameras keeping independent but accurate station relative to one another, such as cameras mounted in multiple distinct aerial or satellite systems with a local referencing system to define relative camera positioning between satellites, etc.

System 100 of FIG. 11 is also exemplary with regard to various configurations that may be present between or among systems 110, 120 and/or their image capturing devices. For example, FIGs. 12A-12B are block diagrams illustrating differing arrangements of the first system 110 and the second system 120 consistent with aspects related to the invention herein. FIG. 12A shows an implementation wherein the first system 110 and the second system 120 are located in one fixed location, such as on an aerial platform, in a satellite, etc. FIG. 12B shows another implementation wherein the invention resides in just one of system, specifically, here, in the second system 120. In this exemplary embodiment or implementation, aspects of the invention consistent with acquisition/processing of particular images may occur primarily via the second system 120. Here, relationship information between the first system 110 and the second system 120, among arrays of cameras located therein, or among images obtained therefrom, is determinable, however, the aspects of the invention described herein are resident on or associated primarily with the second system 120. This arrangement may be useful, for example, when certain images, such as overview images, are obtained from a third party provider, while the remaining images are obtained via the second system 120. Lastly, while FIG. 12B illustrates the aspects of the invention residing in the second system 120, a similar arrangement may also exist with respect to the first system. As also depicted for purpose of illustration in FIGs. 12A-12B, the first system 110 may include one or more first image capturing devices or cameras 210A and the second system 120 may include one or more second image capturing devices or cameras 220A.

Such exemplary camera arrays may be configured such that one or more cameras capture photos with very high amounts of overlap, e.g., to help facilitate accurate calculation of camera system interior and exterior orientation. Further, a second cascaded sub-groups of cameras may be arranged to capture images with minimal overlap but high detail, e.g., to help facilitate processes such as refining the photogrammetric interior and exterior orientation, providing the photo image data needed to create detail photomap surveys, etc. Persons of ordinary skill in the art will appreciate that such delineations are exemplary, and configurations of cascaded cameras can be changed or tuned to specific applications. For example, cameras used to capture high-redundancy photos for calculating exterior and interior orientation can also be used to create lower-resolution overview photomaps for the survey. Further, cameras used for capturing low-redundancy high detail photos used to create detailed photomaps may also be used to refine exterior and interior estimates for the camera system.

In certain embodiments or implementations, some cameras may be configured to maximize the amount of redundancy and overlap between photos, or otherwise enable more precise calculations of the interior and exterior orientations related to the camera systems. In further embodiments or implementations, other cameras may be arranged to minimize the amount of redundancy and overlap between photos, or otherwise configured to enable creation of final detail photomap surveys with a minimum amount of wasted redundant photo imagery.

FIG. 13 is a block diagram of another exemplary system consistent with certain aspects related to the invention herein. As shown in FIG. 13, a unitary platform or module 310 may include or embody both the first system 110 and the second system 120. According to further implementations, the platform 310 may also various arrangements and/or arrays of first and second image capturing devices or cameras 210A, 210A’, 220A, 220A’, etc. Such arrangements and arrays of cameras may be configured to provide the various types of images described herein. One exemplary embodiment or implementation of such an arrangement is set forth in more detail in connection with FIG. 14, below. Advantages of implementations consistent with these arrangements include the ability to mount the systems in an external camera pod, enabling use of the camera systems in standard aircraft without custom modifications, as well as reduced weight and size for the camera system, enabling it to be used in a “small” aircraft (e.g., a single engine aircraft of lesser expense, such as a Cessna 210 or Diamond DA42 Twin Star), and also to enable it to be used in UAV (Unmanned Airborne Vehicle) aircraft.

Aspects of the invention herein are also directed to overlap features existing between the cameras, the images, or both, as well as interrelationship of several such overlap features. In one embodiment or implementation, with respect to overview images captured by the first system, exemplary cameras may be configured with wide-angle lenses and used to capture photos with a very large amount of overlap. Photos captured by these cameras cover a larger area per photo. This very high amount of overlap redundancy results in ground points being visible in many more photos than prior art camera systems, enabling precise positioning of interior and exterior orientation even without the use of a stabilised platform. For example, overlap of such overview images may be characterized in the range of 45-65/94-99 (45%-65% side overlap and 94%-99% forward overlap with regard to an axis), or narrower. Specifically, captured overview images may have side overlap redundancy of between about 45% to about 65% with images that are laterally adjacent the first axis, as well as forward overlap redundancy between about 94% to about 99% with images that are longitudinally adjacent the first axis. Narrower ranges include between about 50% to about 60% side overlap and between about 95% to about 99% forward overlap, between about 98% and about 99% forward overlap, about 50% side overlap and about 99% forward overlap, among others consistent with the parameters set forth herein. According to additional expressions of overlap consistent with the invention herein, overview images may also be captured such that the images have overlap redundancy characterized in that a same imaged point is captured: in a quantity of overview images greater than about 30 and less than about 100, in an average of about 40 to about 60 images, in an average of about 50 images, or in a maximum of about 100 images, depending upon the systems and processes involved. A further expression of overlap may also include characterization in that a same imaged point is captured in a quantity of about 500 images, as explained in connection with FIG. 7A, below.

Further aspects of the invention herein may also include arrays of one or more cameras configured with longer focal length lenses and are used to capture detail imagery to generate the detailed photomaps for the survey. Low amounts of overlap on these cameras may minimize redundancy and so maximize use of the photo imagery for the detail survey, and may provide other advantages such as significantly reducing the overall costs and time required to complete a survey. Here, for example, one measure of overlap of such detail images consistent with the invention herein is characterized by a photo view overlap among the second image capturing devices is between about 0% and about 10%.

FIG. 14 is a diagram of an exemplary system including overview camera arrays and detail camera arrays consistent with certain aspects related to the invention herein. Referring to FIG. 14, a unitary module 400 is disclosed including a plurality of overview cameras 410, at least one data store 430/430A, a first array of detail cameras 420A, a second array of detail cameras 420B, a third array of detail cameras 420C, and a fourth array of detail cameras 420D, etc. These arrays of detail cameras may be used, for example, to obtain images of the various views set forth below at the same time while flying a single survey, such as multiple oblique views, overhead nadir views, etc. One of ordinary skill in the art would recognize that the quantities (i.e., of both the cameras and of the arrays) of detail cameras may be adjusted according to the specifications known to an ordinary artisan to provide for image results desired. Advantages consistent with such implementations include the ability to configure and/or reconfigure a module 400 to target different survey requirements, such as nadir photo maps, oblique photo maps, infrared photomaps, or any combination of these or other requirements that may arise. Further, embodiments of the invention consistent with modules like that of FIG. 14 provide for improved initial estimates of the look angle for the detail cameras relative to the overview cameras.

Further, embodiments or implementations consistent with Fig. 14 allow for the use of low-cost COTS (Commercial Off The Shelf) cameras, rather than requiring industrial quality and expensive camera systems as do many existing systems. According to some aspects of the invention herein, systems and methods may include image capturing devices that are removably/modularly mounted in a platform such that individual image capturing devices are replaceable. For example, one or both of the first system or the second system may be configured/designed with removable mounting systems such that the image capturing devices may be interchanged with different image capturing devices. Exemplary image capturing devices, here, may include COTS cameras installed such that they may be individually removed for repair, replacement and/or upgrade. This provides particular advantages, such as the ability to quickly take advantage of new advances in digital photography, like rapid developments in and the low cost of next generation professional D-SLR (Digital Single Lens) cameras. Use of such cameras has advantages such as reducing the cost of the camera system in total, and also enables ready and rapid upgrade as new D-SLR cameras are released with increased resolution, higher performance, and/or lower cost.

As shown in FIG. 14, platforms or modules 400 consistent with embodiments of the invention may also include a data store 430 or a plurality of such components, one associated with each camera 430A.

Systems consistent with the exemplary embodiments or implementations of FIGs. 11-14 may be utilized to implement image capturing methodologies consistent with certain aspects related to the invention herein. These systems may include the image capturing devices from which the images described herein are obtained or captured, as well as other elements that process and store such images. According to some processes performed by these systems, exemplary methods may include obtaining or capturing overview images, wherein the overview images depict first areas, as well as obtaining or capturing detail images characterized as being related to each other along an image axis. Here, the overview images may be obtained or captured via a first system or array including first image capturing devices. Further, the detail images may be obtained or captured via a second system or array including second image capturing devices. Moreover, the detail images captured may depict second areas that are subsets of the first areas, they may be arranged in strips parallel to the image axis, and/or they may have a higher resolution than corresponding portions of the first images.

With regard to the detail images, some of the image capturing processes herein are directed to capturing detail images at a resolution sufficient to produce a detail photomap. Regarding the capture of these detail images and/or the detail images themselves, determination of sufficient resolution, here, is well known to those skilled in the art. Such determinations being consistent, for example, with those of U.S. patent Nos. 6,078,701, 6,694,064, 6,928,194, 7,127,348, and 7,215,364, and/or U.S. patent application publication Nos. 2002/0163582A1, 2005/0265631A1, and 2007/0188610A1, which are incorporated herein by reference in their entirety. Further, some aspects of the embodiments of the invention herein are particularly well suited to creation of detail photomaps of much higher resolution than comparable systems, i.e., wherein the detail images are captured at a resolution sufficient to produce a detail photomap having a ground-pixel resolution of at least 10 cm. Embodiments of the invention herein consistent with the above enable advantages such as one or more of enabling high-resolution surveys to be captured from higher altitudes, reducing impacts associated with Air Traffic Control restrictions, providing smoother flying conditions, and/or reducing pilot/operator workload.

With regard to the overview images, some of the image acquisition processes herein are directed to capturing images having overlap between images characterized in that a same image point is captured in a quantity of images sufficient to enable accurate bundle adjustment. Other image acquisition processes herein are directed to capturing images having overlap between images characterized in that a same feature is captured in a quantity of images as required by bundle adjustment. Further, the bundle adjustment solution may derived as a function of both the overview images and the detail images.

Bundle adjustment is a mathematical manipulation used to precisely calculate the position, referred to as exterior orientation, and camera calibration, referred to as interior orientation for each photo taken for a terrestrial, airborne or space-borne survey using camera systems.

The bundle adjustment referred to herein simultaneously refines estimates for ground point positions and for each photo's exterior and interior orientation. A ground point position is identified as a feature in each photo. A requirement for bundle adjustment is to maximize the average and maximum number of photos in which a ground point is or can be identified. If a ground point is identified in too few photos, then the solution is not very rigid and suffers both from accuracy errors and from an increased risk of blunders, where incorrectly identified ground points have been used in the bundle solution. Bundle adjustment is also capable of refining photos that have different poses, for example photos or images having different oblique angles, or vertically oriented or otherwise oriented differently.

Further information regarding bundle adjustment can be found in references such as “Elements of Photogrammetry with Applications in GIS, 3rd edition,” by Paul Wolf and Bon Dewitt (McGraw Hill, 2000), “Manual of Photogrammetry, 3rd Edition”, American Society of Photogrammetry, 1966, U.S. Patent No. 6,996,254 to Zhang, et. al, and “Bundle adjustment – a modern synthesis” by Bill Triggs, Philip McLauchlan, Richard Hartley and Andrew Fitzgibbon, appearing in Lecture Notes in Computer Science, vol. 1882 (Springer Verlag, January 2000), all of which are incorporated herein by reference.

According to embodiments of the invention herein, use of cascaded cameras allows the interior and exterior orientation of photos taken by the detail cameras be further refined through bundle adjustment. Using known bundle adjustment techniques, this may be achieved by identifying ground points visible in images captured by overview cameras and in images captured by detail cameras. As the overview cameras provide very high redundancy and thus accuracy in the bundle adjustment process, this serves as the basis for calculating accurate interior and exterior orientation for photos taken with detail cameras, despite the limited amount of redundancy and overlap provided by detail cameras. Advantages related hereto include the ability to enable self-calibration of camera interior orientation parameters, such as lenses focal length and distortions, allowing lower cost professional grade lenses to be used and affording automation of the photomap photogrammetry process.

Further aspects of embodiments of the invention herein allow for all or a plurality of cameras in the camera system(s) to have their shutters triggered at the same time or at nearly the same time. In this context, 'at nearly the same time' refers to a period of about 100 milliseconds given stable platform (i.e., flying, pitch, yaw, etc.) conditions. This provides further rigidity to the bundle adjustment solution, as the camera system can be modelled more accurately, for example, by using known bundle adjustment methods for multiple-camera interior and exterior orientation refinement.

FIG. 5A illustrates one exemplary embodiment or implementation including an external pod mounted on a small single engine aircraft 510. Referring to FIG. 5A, in one embodiment of the invention the cameras for the camera system are mounted into a pod or removable enclosure or housing 520, which serves as the unitary module 400. As such it is possible to use the camera system on a standard small aircraft 510, such as a Cessna 210 without requiring modifications to the airframe. FIG. 5B illustrates an exemplary embodiment or implementation of an image capturing system. As shown in FIG. 5B, the pod or removable enclosure or housing 520 may include a plurality of overview and detail cameras 410 and 420, which may be grouped or arranged, e.g., in arrays, as previously described and with respect to FIGs. 4, 8A and 8B. Implementations as shown in FIGs. 5A and 5B provide high accuracy without requiring a stabilized mounting platform, and also enable sufficient weight and size reduction allowing the camera system to be mounted in an Unmanned Aerial Vehicle (UAV).

Flight surveys can be performed at different altitudes and with different flight times, with different resulting resolutions. For example, and in correspondence with the camera configurations illustrated in FIGs. 8A and 8B, a flight survey performed with 1 vertical

Canon 1Ds MkIII camera with a 28 mm focal length lens and 5 vertical Canon 1Ds MkIII cameras with 200 mm focal length lenses at an altitude of 8,000 ft. can generate data for a final photomap with a resolution of 7.5 cm. In this example, with a capture rate of 330 km^2/hr, a typical city of 50 km x 40 km can be captured in a flight time of 6 hours.

In another embodiment, in correspondence with the camera configurations illustrated in FIG. 8C, with 1 vertical overview Canon 1Ds MkIII camera with a 28 mm focal length lens and 9 detail Canon 1Ds MkIII cameras with 300 mm focal length lenses and at an altitude of 10,000 ft., a capture rate of 500 km^2/hr can be obtained, resulting in a flight time of 4 hours to capture a typical city of 50km x 40km with a resulting resolution of 6.5 cm.

Higher resolutions can be captured using the same embodiments discussed above, or in other embodiments by using longer flight times (e.g. 3.5 cm resolution captured in a flight survey of 9 hours) at lower altitudes. The aforementioned flight surveys are representative examples only and are not given to limit the scope of the invention, which may be practiced under a wide variety of conditions. For underwater applications, altitude can be understood to be comparable to the distance above the ocean floor.

As will be appreciated by one of skill in the art, various configurations of imaging systems can be used with differing relationships between altitude and resolution, all of those configurations being within the spirit and the scope of the invention. In one embodiment, 1 cm resolution is produced for every 1,000 ft. of altitude (e.g. 3 cm resolution at 3,000 ft. altitude, 7 cm resolution at 7,000 ft. altitude). In a second embodiment, the ground point resolution in cm is the altitude in ft. divided by 900. In a third embodiment, the ground point resolution in cm is the altitude in ft. divided by 800, and in a fourth embodiment the ground resolution in cm is the altitude in ft. divided by 2,000.

Referring to FIG. 5C, use of the method and system in one embodiment is illustrated in which aircraft 510 is equipped with the pod or removable housing 520 and travels at a given altitude h 530 (represented along *z-axis* 117), at a velocity v 532, the travel being generally performed in the x-y plane as defined by *x-axis* 115 and *y-axis* 114.

FIG. 5D is a flight plan for a survey in the *x-y* plane, that flight plan having a first long segment 560, followed by a turn 564, followed by return long segment 568. Repeated combinations of long segments, turns, and return long segments can be used to create the flight plan for the survey area.

Embodiments of the method and system of the invention described herein can also incorporate a flight plan and timing system/subsystem which generates a flight plan suitable for generating a photomap of a particular area, as well as for capturing signals indicating to the overview and detail image capture systems which respective images should be captured. In one embodiment, the flight plan contains parameters such as altitude, direction of travel, airspeed, waypoints and turnaround locations. As will be understood by one of skill in the art, the flight plan directs the pilot (or vehicle in the case of an unmanned or auto controlled craft) to fly in a pattern that allows the creation of images having the appropriate degree of sideways overlap. Although the overlap in the forward direction is controlled by the timing of the image capture signals, the overlap in the side direction is controlled primarily by the path of the aircraft/vehicle in relation to previous parallel paths in the flight.

In one embodiment the flight plan and timing system/subsystem receives input signals from navigational equipment including ground based (e.g. VOR, LORAN) and satellite systems (e.g. GPS and WAAS) to determine position. Signals generated from inertial systems can be used in conjunction with the location determining signals to determine changes in velocity as well as changes in pitch, yaw and roll of the aircraft. In one embodiment, rapid changes in direction can be determined using Micro-Electrical-Mechanical Systems (MEMS). Both short term and long term deviations from the proposed flight plan can be incorporated by the flight plan and image capture timing subsystem to indicate corrections to the flight plan or adjust the capture signals being sent to the overview and detail image capture systems.

In one embodiment the flight plan and image capture timing subsystem is based on a personal computer with additional navigational equipment (e.g. GPS, D-GPS), displays, and programming which enables a flight plan to be developed and generates timing signals for image capture consistent with the desired overlap. In an alternate embodiment specialized hardware is used for flight plan development and image capture signal generation.

FIGs. 6A1, 6A2, 6B1, and 6B2 are diagrams illustrating exemplary overview and detail image representations. FIGs. 6A1 and 6A2 show exemplary representations wherein multiple cameras are configured to maximize the amount of detail image data 610 obtained in the unique (non overlapped) area through the use of multiple detail cameras, while (preferably at the same time) ensuring that sufficient (and preferably significant) overlap exists between overview images 612 to create the desired redundancy to enable successful processing into photomaps, which may include accurate bundle adjustment.

The representation of FIGs. 6A1 or 6A2 may be achieved, for example, using one overview camera (see, e.g., representative images 612, 616, 620, 624 thereof) to capture interior and exterior orientation, and a one group of nine cameras organized or arranged in an adjacent manner, or cascaded, to capture detailed strips or a strip of detailed photos 610, 614, 618, 622 or sub-portions of each overview photo in very high detail or in higher resolution than the overview resolution. As set forth above, aspects of the invention herein may include rigid or fixed or semi-rigid or partially adjustable alignment of cameras in the camera system, which allows photos to be taken with minimal overlap between photos within, or detail images forming, the strip. Further, images may be taken often enough to ensure that overlap exists between consecutive photos or sequential images taken along a flight line, and flight lines may be organized to ensure that there is overlap between strips of photos or detail images, taken along adjacent flight lines. Unlike existing systems where significant overlap is required to perform accurate bundle adjustment, embodiments of the present invention enable use of a minimal amount of overlap to exist between subsequent, sequential, or adjacent photo strip details or strips of detail images, which only need to be sufficient to later perform creation of a seamless photomap. As a result, the redundancy required for a strip of photos from detail cameras is much less than with existing systems, which significantly decreases survey time and costs.

Moreover, as many additional detail cameras as required may be configured in an adjacent or cascaded fashion to capture detailed sub-portions of the overview images for specific views, such as nadir overhead (vertical) images or oblique images from different look angles. These images can be subsequently processed to produce the corresponding nadir overhead photomaps or oblique photomaps, and preferably from different look angles. Because a single detail camera may not have sufficient resolution to capture a sub-portion in sufficient resolution for the desired survey, a group of detail cameras for a specific view perspective may be organized in a strip to capture a wider swath of the desired perspective. FIGs. 7A1, 7A2, 7B1 and 7B2 illustrate further exemplary overview and detail image representations. FIGs. 7A1 and 7A2 illustrate the results of three adjacent or cascaded groups of detail cameras in which five cameras produce images corresponding to the detailed vertical view (e.g., images 730, 730A-E), four cameras produce images corresponding to the detailed left and right oblique views from alternating flight lines (e.g. images 740), and three cameras produce images corresponding to detailed front and back oblique views from alternating flight lines (e.g. images 750, 750A-C). FIGs. 7B1 and 7B2 illustrate image capture through movement of the vehicle or aircraft, wherein multiple oblique views are provided by flying flight lines in alternating directions, for example, by obtaining four oblique views from two groups of oblique cameras.

As previously discussed with respect to FIGs. 8A, 8B, and 8C, particular types of cameras can be geometrically arranged to achieve the imaging configurations illustrated in FIGs. 7A1and 7B1. One of skill in the art will be able to determine alternate configurations to those disclosed herein suitable for capture of aerial data from various airborne vehicles or aircraft, or in the case of ocean floor mapping, from seagoing vessels.

Images collected using embodiments of the methods and systems of the present invention have overlap with each other, resulting in the appearance of points common to two or more images or photographs. Such points may be referred to as common features, common elements, common points, or image elements, ground points, feature points, ground feature points, tie points, stereopairs or other terms referring to the repeated appearance of a point or object in a plurality of images. In some instances, the points may contain objects with known locations, those objects commonly referred to as control points. Common points can be used to develop an appropriate analytical stereomodel through the steps of interior orientation, relative orientation, and absolute orientation. Interior orientation generally recreates the geometry that existed in the camera (or other imaging system) when the image or photograph was taken. Analytical relative orientation is the process of determining the relative angular attitude and positional displacement between the photographs that existed when the photos were taken. The process of analytical absolute stereorientation results in relating the coordinates of control points to their three-dimensional coordinates in a ground-based system.

Generally speaking, given a set of images depicting a number of points from different viewpoints, the traditional process of bundle adjustment can be used to adjust all photogrammetric measurements to ground control values (ground points or common points) in a single solution. Bundle adjustment can include determining the object space coordinates of all object points, and the exterior orientation parameters of all photographs.

The representation of FIG. 7A2 also illustrated another feature where multiple overview cameras 710, 720 are used, each oriented at a different pose. This exemplary feature increases the amount of overlap between photos considerably, allowing overlap between images that might be several flight lines away. As such, redundancy and rigidity of the feature matching solution may be significantly increased between images. Further, combining multiple overview cameras with different poses enables the same ground point to be visible and measured on 500 or more photos. This compares favourably with existing methods having 30%/80% overlap, which result in a ground point being captured in an average of 5 photos.

Turning back to FIGs. 6B2 and 7B2, these drawings illustrate the amount of overlap between images. Here, the overlap amounts to 50%/95%. Each of these figures show images or group of images in a sequence taken during a survey and adjacent images or groups of images in the previous and next flight line for the survey. The large amount of redundancy allows bundle adjustment to accurately refine photo interior and exterior position to sub-pixel accuracy for the overview cameras.

FIG. 7A2 illustrates other exemplary features of the invention, such as using two overview cameras 710, 720 to capture interior and exterior orientation, and three cascade groups of detail cameras 730, 740 and 750 to capture a nadir detail view and two oblique detail views. When the aircraft survey is flown in alternating directions for each flight line, then the two oblique views alternate direction, resulting in a total of four oblique detail views being captured in addition to the overview detail view. Indeed, the ability to configure the camera system to specific survey mission requirements enables the simultaneous capture of detail photomaps from different look angles, at the same time. FIG. 7A2, for example, allows production of a detail overhead photomap and four detail oblique photomaps through a combination of multiple cascaded camera groups and the use of alternative flight lines.

Arranging strips of detail cameras into arrays or groups gives the camera system a high virtual megapixel count. With respect to an exemplary system consistent with FIG. 7A2, e.g., one implementation uses 14 cameras, each being a 21 megapixel 35mm D-SLR camera, yielding an effective camera system resolution of several gigapixels in size. In this exemplary implementation, one overview camera 710 provides a nadir overhead view connected to another overview camera 720 to provide a rear oblique overhead view. One cascade group of a plurality of detail cameras 730 may provide a detailed nadir survey imagery referenced within the first overview camera 710. Another cascade group of a plurality of detail cameras 750 may provide along track detailed oblique survey imagery referenced within the overview camera 720. Another cascaded group of a plurality of detail cameras 740 may provide across track detailed oblique survey images which are referenced using a rigid camera system body and/or referenced using overview camera imagery from adjacent survey flight lines as shown in FIG. 7B2.

In one embodiment an imaging capturing system is mounted in or on an aircraft to take the appropriate raw images using the methods and systems described herein and to guide the pilot of the aircraft to the correct coordinates. FIG. 9 illustrates an exemplary aircraft outfitted with the necessary equipment in accordance with this embodiment. Aircraft 510 is prepared with the pod or removable housing 520 which is rigidly mounted to aircraft 510. In one embodiment the mounting is performed through removal of the passenger side aircraft door, and replacement of the door with a door/pod mount.

The pod or removable housing 520 contains a plurality of cameras as described above with respect to FIG. 4. In one embodiment, a series of movable doors cover the cameras in pod or removable housing 520 to protect the cameras during portions of the flight including takeoff and landing. In one embodiment sensors are incorporated into the camera doors, such that the status of the door can be monitored. In one embodiment cameras and doors of the pod or removable housing 520 are connected to a computer 1000. In this embodiment, computer 1000 runs software developed to control and operate elements of the system during flight. Although pictured as a laptop, the computer 1000 may be any computer including a laptop, ruggedized personal computer, a system embedded into the aircraft, a specialized computer, a portable device such as a Personal Digital Assistant or a cellular telephone.

Referring again to FIG. 9, computer 1000 is connected to a Global Positioning System (GPS) unit 1010, which produces a feed to track the plane's current position and log the current position in storage on the computer 1000. The camera control unit 1030 controls the camera array in the pod or removable housing 520, including sending signals to autofocus and take photographs. In the embodiment illustrated in FIG. 10, GPS unit 1010 serves as a navigation system/subsystem, while computer 1000 serves as a timing system/subsystem. In an alternate embodiment, computer 1000 incorporates the functionality of the navigation system and can include GPS unit 1010. In yet another embodiment, a dedicated unit has subsystems providing the navigation and timing functions.

Flight display 1020 is connected to computer 1000 and in one embodiment displays details of the flight. In an alternate embodiment, flight display 1020 shows the status of the system as a whole including status of the doors and activity of the cameras in acquiring images. The flight display 1020 may be the monitor from the personal computer 1000, an additional external monitor or a monitor embedded into the aircraft. The flight display 1020 may be a touch sensitive monitor and allow for the input of commands into the system. Alternatively, a mouse, keyboard or other input device (not shown) may be used to receive user input.

In one embodiment, the system displays a variety of information to the pilot of aircraft 510. This information may be displayed on the flight display 1020, the display of computer 1000 or in another display available to the pilot. The system displays flight lines of a projected area, defined geographic areas and survey data which define the actual area within the map to capture.

FIG. 10 illustrates a block diagram for computer 1000 working in conjunction with a controller 1120 and a GPS device 1122. In one embodiment computer 1000 includes at least one Universal Serial Bus (USB) port 1100 which is connected to a USB hub 1112. USB hub 1112 has a plurality of additional USB ports which allow for devices to be connected to and communicate with the computer 1100. The USB port 1114 is connected to a controller 1120. As will be understood by one of skill in the art, other types of buses, wired or wireless, serial or parallel, can be used to interconnect the components of FIG. 10. In one embodiment controller 1120 is a camera control unit (e.g. camera control unit 1030) and controls the camera[s] in the pod or removable housing 520, enacting auto focus command 1130 and shutter command 1132 in the camera[s]. The controller 1120 also reads from a door sensor 1134 to determine if the doors protecting the cameras in the pod or removable housing 520 are open or closed. The door may be opened or closed as appropriate in response to the controller 1120 reading the door sensor 1134. The GPS device 1122 is connected to the USB hub 1112 through USB ports 1116, 1118. The GPS device 1122 reads the current geographic location of the device and transmits this data to the computer 1000. The controller 1120 is enabled to send a signal causing a photograph to be taken from removable housing 520.

Features herein associated with minimizing overlap between photos captured by detail cameras have advantages such as maximizing use of imagery in resulting photomaps. This allows surveys to be flown at higher altitudes and in less time. Flying surveys at higher altitude reduces impact on Air Traffic Control in busy urban areas, and generally provides for smoother flying conditions and lower pilot/operator work-load. Flying surveys in less time reduces the operating costs for the survey, and allows a survey to flown as soon as weather clears, rather than waiting for larger blocks of time with clear weather. Accordingly, embodiments of the invention consistent with the above may also greatly increase the likelihood of capturing a survey despite inclement weather.

Further, aspects of the invention herein that provides a high amount of overlap between photos captured by overview cameras enable "self-calibration", or accurate modelling of interior orientation lens and sensor characteristics using existing bundle adjustment self-calibration techniques. For example, as images are captured by the cascaded detail cameras are in turn mapped into the overview photos, such self-calibration modelling can be performed for detail cameras as well as for overview cameras. Because embodiments of the invention herein enable accurate self-calibration, low-cost COTS professional grade lenses can be used in the camera system, instead of requiring the use of much more expensive industrial grade lenses.

Aspects of the invention herein also allow the use of IMU, D-GPS, stabilized platforms or other complex or expensive ancillary systems, which decreases the capital and operating cost for the camera system, and may reduce overall complexity.
Still other advantages of the embodiments of the invention herein allow for an increase the accuracy of calculated camera position and pose, without the need for expensive D-GPS, stabilisation or IMU ancillary sub-systems.

As may be appreciated in connection with the strip of detail images 610 in FIG. 6A, embodiments of the invention herein also relate to the concept of the field of view for a group of detail cameras being very wide but very narrow. If the camera sensor platform pitches quickly enough in the direction of the narrow aspect of the field of view, it's possible that detail views of the ground might be missed. Although the risk of this happening is mitigated because the systems and methods herein may be practiced at higher (and, typically, much smoother) altitudes, embodiments of the invention may also include use of low-cost MEMS (Micro-Electro-Mechanical Systems) accelerometers to detect rapid changes in pitch. MEMS accelerometers are very cheap (they are used in air-bags), though are not suitable for many IMU measurements as they drift over time. However, implementations of MEMS with platform or aircraft acceleration, rapid pitch, etc and related image capturing devices afford particularized advantage to the presently described systems and methods. Embodiments of the invention herein involve the use of MEMS accelerometers to measure rapid short-term pitch, yaw or or roll changes, and to use this information to increase the number of shutter events and photos taken during these times of rapid change to ensure that detail cameras with narrow fields of view still cover all the required ground area even during rapid changes of sensor platform pose.

Finally, Digital Elevation Models (DEMs) are a common by-product from the photogrammetric bundle adjustment process. DEMs are useful in their own right for applications such as flood and fire modelling, and are also required to produce ortho-rectified photomaps using the usual prior-art methods as present in applications such as ER Mapper [Nixon, Earth Resource Mapping, www.ermapper.com]. The overall accuracy of DEMs is commonly much more important than the density of measurements for the DEM itself. Ortho-rectification commonly uses DEMs that are 1/10th or less resolution than the photo imagery being rectified. Aspects of the invention herein provide a high level of overlap between images captured by overview cameras. A single ground point can typically be observed in several orders of magnitude more photos than possible in existing camera systems. As such, the redundancy of observations of ground points provided by embodiments of the invention herein also enables production of robust and accurate DEMs.

US 12/565,232 and PCT/IB2009/006228 are incorporated herein by reference.

In the present description, the terms component, module, and functional unit, may refer to any type of logical or functional process or blocks that may be implemented in a variety of ways. For example, the functions of various blocks can be combined with one another into any other number of modules. Each module can be implemented as a software program stored on a tangible memory (e.g., random access memory, read only memory, CD-ROM memory, hard disk drive) to be read by a processing unit to implement the functions of the embodiments of the invention herein. Or, the modules can comprise programming instructions transmitted to a general purpose computer or to graphics processing hardware via a transmission carrier wave. Also, the modules can be implemented as hardware logic circuitry implementing the functions encompassed by the embodiments of the inventions herein. Finally, the modules can be implemented using special purpose instructions (SIMD instructions), field programmable logic arrays or any mix thereof which provides the desired level performance and cost.

The embodiments of the present disclosure may be implemented with any combination of hardware and software. If implemented as a computer-implemented apparatus, the present disclosure is implemented using means for performing all of the steps and functions described above.

As disclosed herein, embodiments and features of the invention may be implemented through computer-hardware, software and/or firmware. For example, the systems and methods disclosed herein may be embodied in various forms including, for example, a data processor, such as a computer that may also include a database, digital electronic circuitry, computer-readable media, firmware, software, or in combinations of these elements. Further, while some of the disclosed implementations describe components such as software, systems and methods consistent with embodiments of the invention herein may be implemented with any combination of hardware, software and/or firmware. Moreover, the above-noted features and other aspects and principles of the invention herein may be implemented in various environments. Such environments and related applications may be specially constructed for performing the various processes and operations according to the invention or they may include a general-purpose computer or computing platform selectively activated or reconfigured by code to provide the necessary functionality. The processes disclosed herein are not inherently related to any particular computer, network, architecture, environment, or other apparatus, and may be implemented by a suitable combination of hardware, software, and/or firmware. For example, various general-purpose machines may be used with programs written in accordance with teachings of the invention, or it may be more convenient to construct a specialized apparatus or system to perform the required methods and techniques.

The embodiments of the present disclosure can be included in an article of manufacture (e.g., one or more computer program products) having, for instance, computer useable or computer readable media. The media has embodied therein, for instance, computer readable program code means, including computer-executable instructions, for providing and facilitating the mechanisms of the embodiments of the present disclosure.

The article of manufacture can be included as part of a computer system or sold separately.

Aspects of the method and system described herein may be implemented as functionality programmed into any of a variety of circuitry, including programmable logic devices ("PLDs"), such as field programmable gate arrays ("FPGAs"), programmable array logic ("PAL") devices, electrically programmable logic and memory devices and standard cell-based devices, as well as application specific integrated circuits. Some other possibilities for implementing aspects include: memory devices, microcontrollers with memory (such as EEPROM), embedded microprocessors, firmware, software, etc. Furthermore, aspects may be embodied in microprocessors having software-based circuit emulation, discrete logic (sequential and combinatorial), custom devices, fuzzy (neural) logic, quantum devices, and hybrids of any of the above device types. The underlying device technologies may be provided in a variety of component types, e.g., metal-oxide semiconductor field-effect transistor ("MOSFET") technologies like complementary metal-oxide semiconductor ("CMOS"), bipolar technologies like emitter-coupled logic ("ECL"), polymer technologies (e.g., silicon-conjugated polymer and metal-conjugated polymer-metal structures), mixed analog and digital, and so on.

It should also be noted that the various functions disclosed herein may be described using any number of combinations of hardware, firmware, and/or as data and/or instructions embodied in various machine-readable or computer-readable media, such as via one or more computer readable media containing computer readable/executable instructions including instructions adapted to cause one or more processors to execute and/or otherwise implement the functionality, features and/or aspects set forth herein,
in terms, by way of example and not limitation, of their behavioural, register transfer, logic component, and/or other characteristics. Computer-readable media in which such formatted data and/or instructions may be embodied include, but are not limited to, non-volatile storage media in various forms (e.g., optical, magnetic or semiconductor storage media) and carrier waves that may be used to transfer such formatted data and/or instructions through wireless, optical, or wired signalling media or any combination

thereof. Examples of transfers of such formatted data and/or instructions by carrier waves include, but are not limited to, transfers (uploads, downloads, e-mail, etc.) over the Internet and/or other computer networks via one or more data transfer protocols (e.g., HTTP, FTP, SMTP, and so on).

Throughout the specification, unless the context requires otherwise, the word “comprise” or variations such as “comprises” or “comprising”, will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers.

Furthermore, throughout the specification, unless the context requires otherwise, the word “include” or variations such as “includes” or “including”, will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers.

Additionally, throughout the specification, unless the context requires otherwise, the words "substantially" or "about" will be understood to not be limited to the value for the range qualified by the terms.

Words using the singular or plural number also include the plural or singular number respectively. Additionally, the words “herein,” “hereunder,” “above,” “below,” and words of similar import refer to this application as a whole and not to any particular portions of this application. When the word “or” is used in reference to a list of two or more items, that word covers all of the following interpretations of the word: any of the items in the list, all of the items in the list and any combination of the items in the list.

While specific embodiments have been described in detail in the foregoing detailed description and illustrated in the accompanying drawings, it will be appreciated by those skilled in the art that various modifications and alternatives to those details could be developed in light of the overall teachings of the disclosure and the broad inventive concepts thereof. It is understood, therefore, that the scope of the present disclosure is not limited to the particular examples and implementations disclosed herein, but is intended to cover modifications within the spirit and scope thereof as defined by the appended claims and any and all equivalents thereof.

It will be appreciated by those skilled in the art that variations and modifications to the invention described herein will be apparent without departing from the spirit and scope thereof. The variations and modifications as would be apparent to persons skilled in the art are deemed to fall within the broad scope and ambit of the invention as herein set forth.

It is to be understood that the foregoing description is intended to illustrate and not to limit the scope of the invention, which is defined by the scope of the appended claims. Other embodiments are within the scope of the following claims.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A method of creating a photomap of a survey area, the method comprising:

(a) moving a vehicle relative to the survey area along a set of substantially parallel survey paths;

(b) capturing, during vehicle movement and via a first imaging system carried by the vehicle, a sequence of overview images, each overview image depicting an overview area of the survey area, consecutive overview areas along each survey path having a degree of forward overlap of the overview areas, adjacent overview areas associated with adjacent survey paths having side overlap;

(c) capturing, during vehicle movement and via a second imaging system carried by the vehicle, a sequence of detail image strips, each detail image strip comprising at least one detail image, each detail image depicting at least a portion of an overview area, each detail image having a higher resolution than the resolution of the overview image corresponding to the overview area, consecutive detail image strips along each survey path having a degree of forward overlap of the detail image strips, the degree of overlap of the overview areas being higher than the degree of overlap of the detail image strips, adjacent detail image strips associated with adjacent survey paths having side overlap, adjacent detail images within each strip having side overlap;

(d) identifying, in a plurality of the overview images and detail images, common features corresponding to common ground points;

(e) estimating, via bundle adjustment and using locations of the identified ground points in the plurality of overview images and detail images, data comprising an exterior orientation associated with each detail image, and a position associated with each ground point; and

(f) merging, using at least some of the estimated data, the detail images to create the photomap.

2. The method of Claim 1, wherein the second imaging system views vertically, and the photomap contains a substantially vertical view.

3. The method of any one of Claims 1 to 2 comprising:

capturing, via one or more oblique groups of cameras, a sequence of oblique detail image strips, and creating, from the oblique detail image strips, an oblique photomap of the survey area.

4. The method of any one of Claims 1 to 3, wherein the vehicle is one of a spacecraft, an airborne vehicle, an aircraft, a balloon, an unmanned aerial vehicle (UAV), a seagoing vessel, and a submarine.

5. The method of any one of Claims 1 to 4, wherein at least one of the imaging systems comprises at least one sensor, the at least one sensor being one of a digital camera, a push broom sensor, and a whisk broom sensor.

6. The method of any one of Claims 1 to 5, wherein at least one of the imaging systems comprises at least one sensor, the at least one sensor being one of an electromagnetic imager, a visible electromagnetic imager, an infrared electromagnetic imager, a thermographic imager, and an ultrasound imager.

7. A system for creating a photomap of a survey area, the system comprising:

(a) a vehicle configured to move relative to the survey area along a set of substantially parallel survey paths;

(b) a first imaging system disposed on the vehicle and configured to capture, during vehicle movement, a sequence of overview images, each overview image depicting an overview area of the survey area, consecutive overview areas along each survey path having a degree of forward overlap of the overview areas, adjacent overview areas associated with adjacent survey paths having side overlap;

(c) a second imaging system disposed on the vehicle and configured to capture, during vehicle movement, a sequence of detail image strips, each detail image strip comprising at least one detail image, each detail image depicting at least a portion of an overview area, each detail image having a higher resolution than the resolution of the overview image corresponding to the overview area, consecutive detail image strips along each survey path having a degree of forward overlap of the detail image strips, the degree of overlap of the overview areas being higher than the degree of overlap of the detail image strips, adjacent detail image strips associated with adjacent survey paths having side overlap, adjacent detail images within each strip having side overlap;

(d) a computer system including at least a computer and a computer-readable medium that stores computer-readable instructions that, when executed by the computer cause the computer to perform a method including:

identifying, in a plurality of the overview images and detail images, common features corresponding to common ground points;

estimating, via bundle adjustment and using locations of the identified ground points in the plurality of overview images and detail images, data comprising an exterior orientation associated with each detail image, and a position associated with each ground point; and

merging, using at least some of the estimated data, the detail images to create the photomap.

8. The system of Claim 7 wherein the second imaging system views vertically, and the photomap contains a substantially vertical view.

9. The system of any one of Claims 7 to 8, comprising:

one or more oblique groups of cameras configured to capture a sequence of oblique detail image strips, wherein the computer system is further configured to create, from the oblique detail image strips, an oblique photomap of the survey area.

10. The system of any one of Claims 7 to 9, further comprising:

an enclosure or housing within which the imaging systems are mounted.

11. The system of Claim 10, wherein each imaging system is removably mounted within the enclosure or housing.

12. The system of any one of Claims 10 to 11, wherein the enclosure or housing is configured to be mounted external to the vehicle.

13. The system of any one of Claims 10 to 12, wherein the enclosure or housing is configured to be removably mounted external to the vehicle.

14. The system of any one of Claims 7 to 13, wherein each of the imaging systems comprises one or more image capturing devices.

15. The system of Claim 14, further comprising:

a plurality of data storage devices, each data storage device associated with a respective one of the image capturing devices and configured to store images captured by the image capturing device.

16. The system of Claim 15, wherein each data storage device is a flash memory data storage device.

17. The system of any one of Claims 7 to 16, wherein the vehicle is one of a spacecraft, an airborne vehicle, an aircraft, a balloon, an unmanned aerial vehicle (UAV), a seagoing vessel, and a submarine.

18. The system of any one of Claims 14 to 16, wherein at least one of the imaging devices comprises at least one sensor, the at least one sensor being one of a digital camera, a push broom sensor, and a whisk broom sensor.

19. The system of any one of Claims 14 to 16 and 18, wherein at least one of the imaging devices comprises at least one sensor, the at least one sensor being one of an electromagnetic imager, a visible electromagnetic imager, an infrared electromagnetic imager, a thermographic imager, and an ultrasound imager.

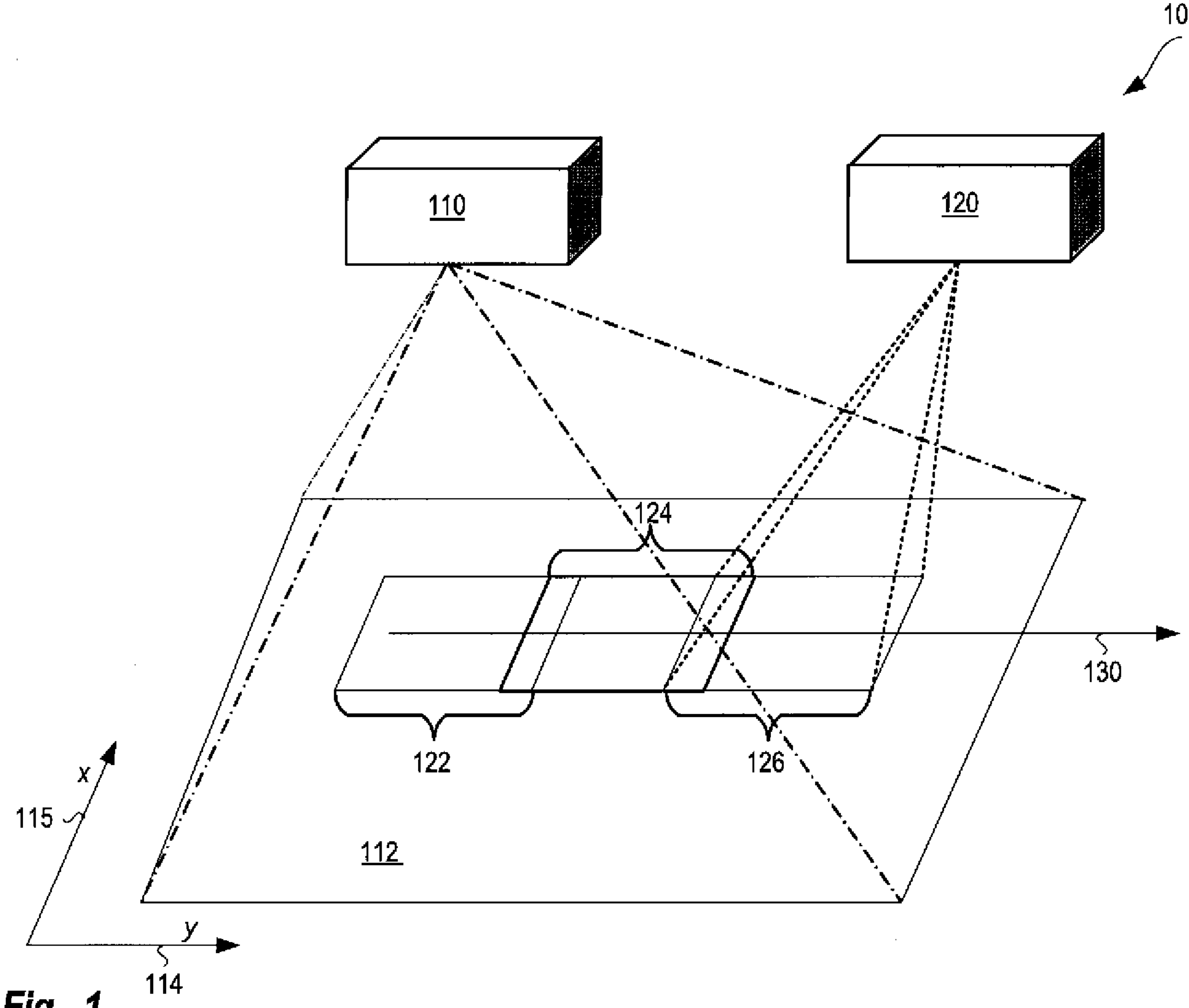


Fig. 1

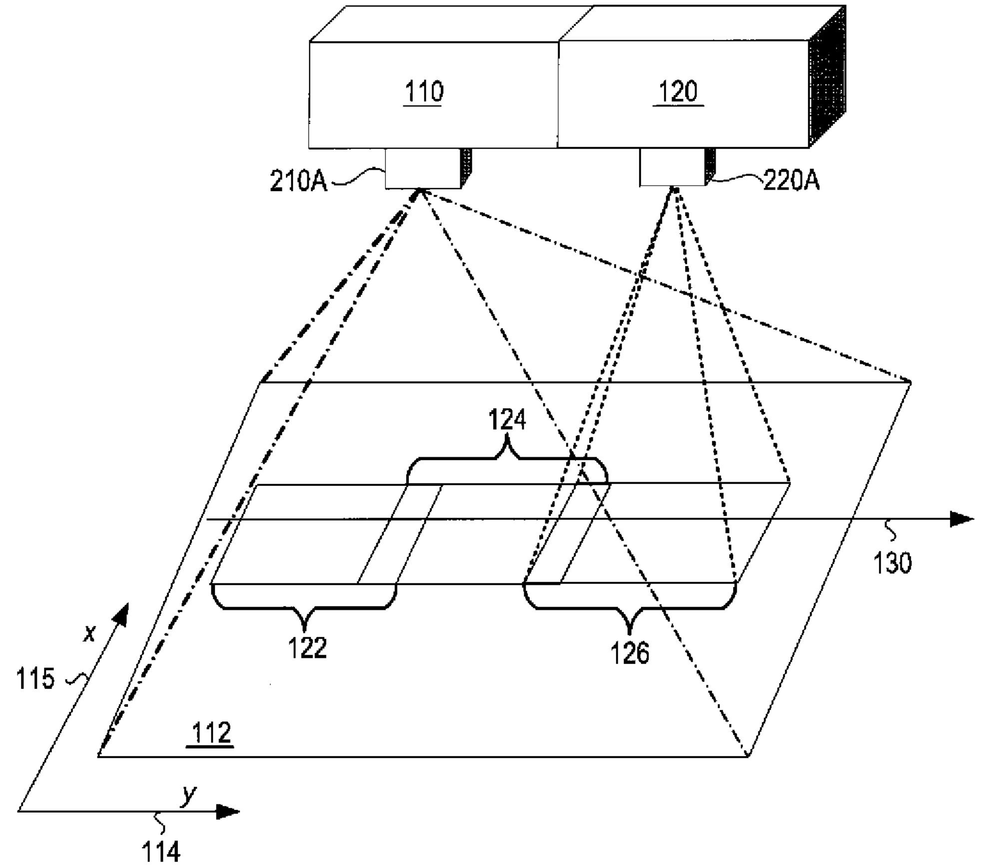


Fig. 2A

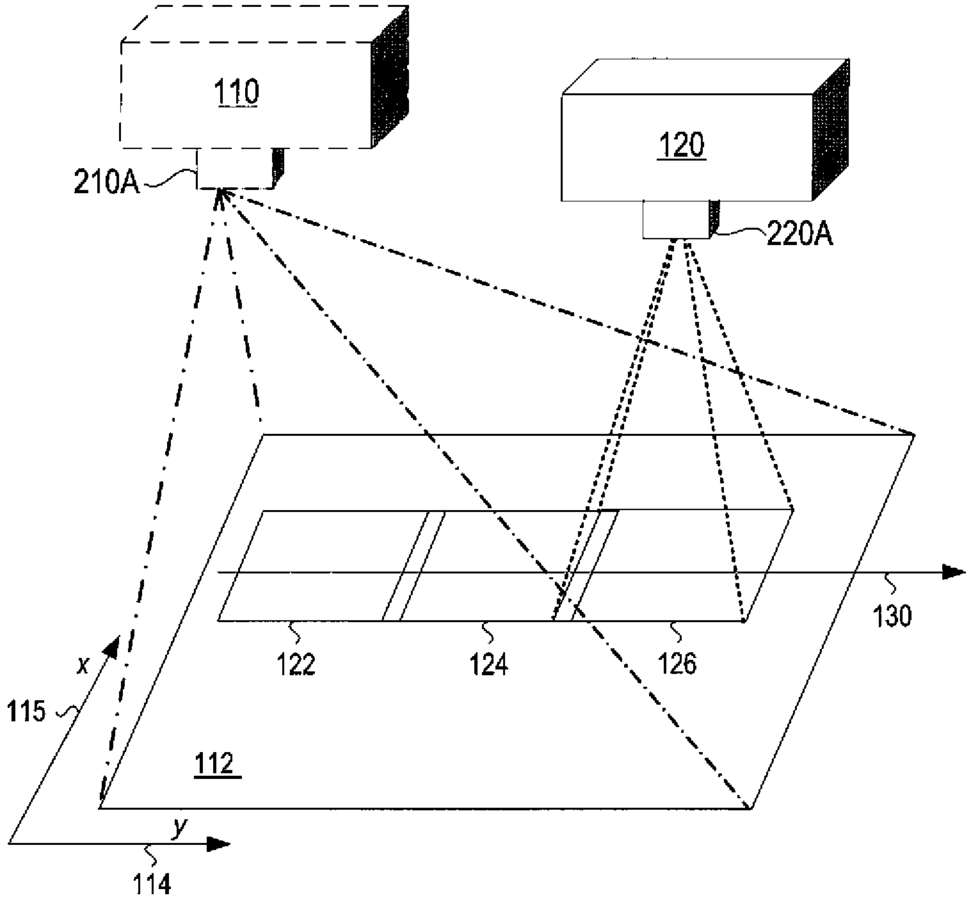


Fig. 2B

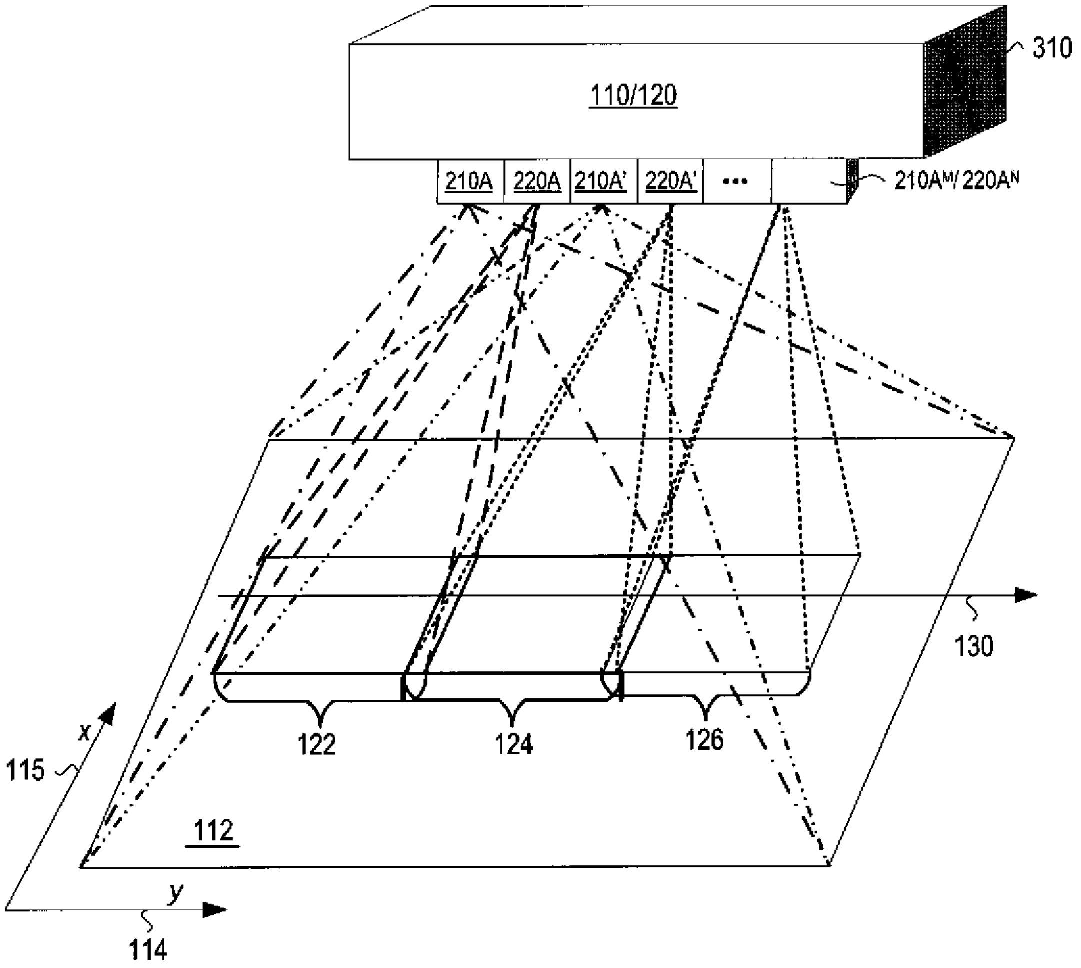
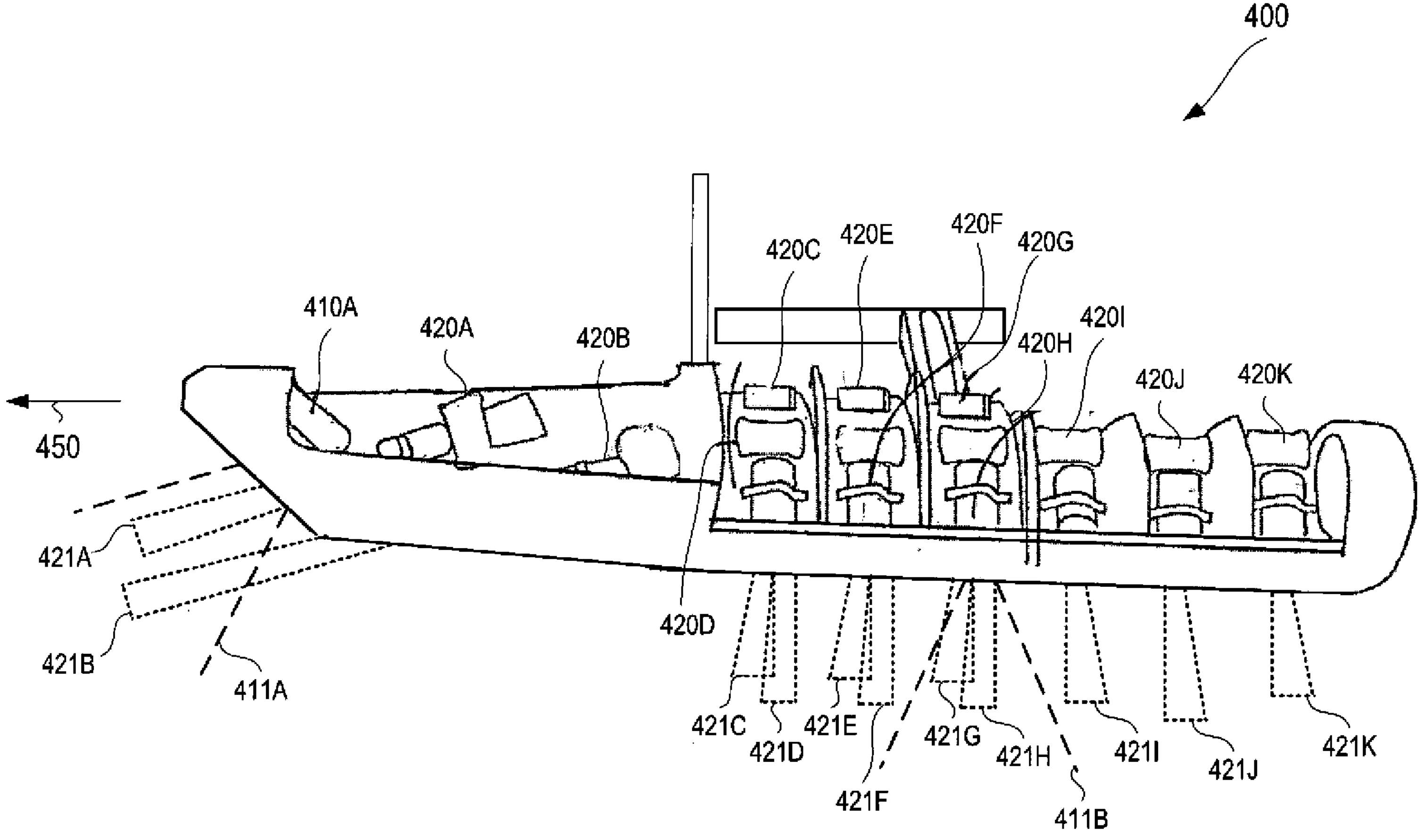

310
110/120
210A
220A
210A'
220A'
•••
210A^{M}/220A^{N}
130
122
124
126
115
x
112
y
114

Fig. 3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410A
420A
420B
420C
420E
420F
420G
420H
420I
420J
420K
450
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421B
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421J
421K
411B

Fig. 4

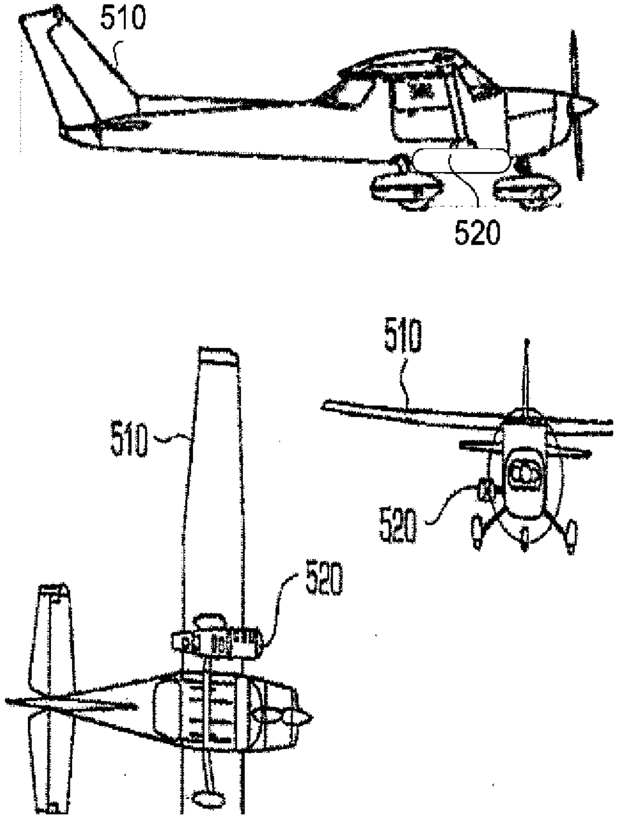


Fig. 5A

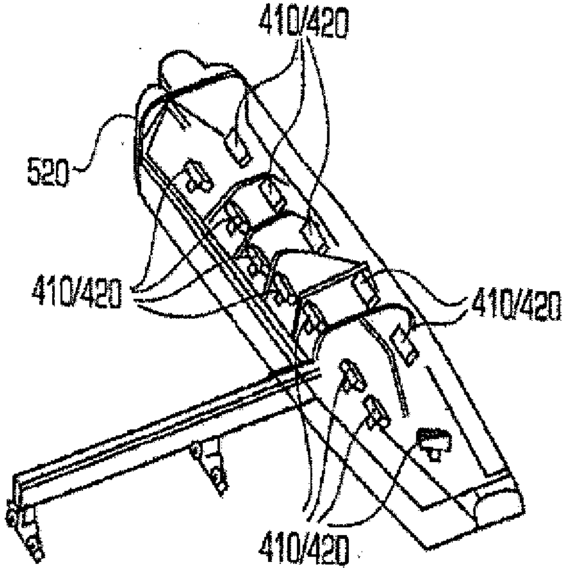
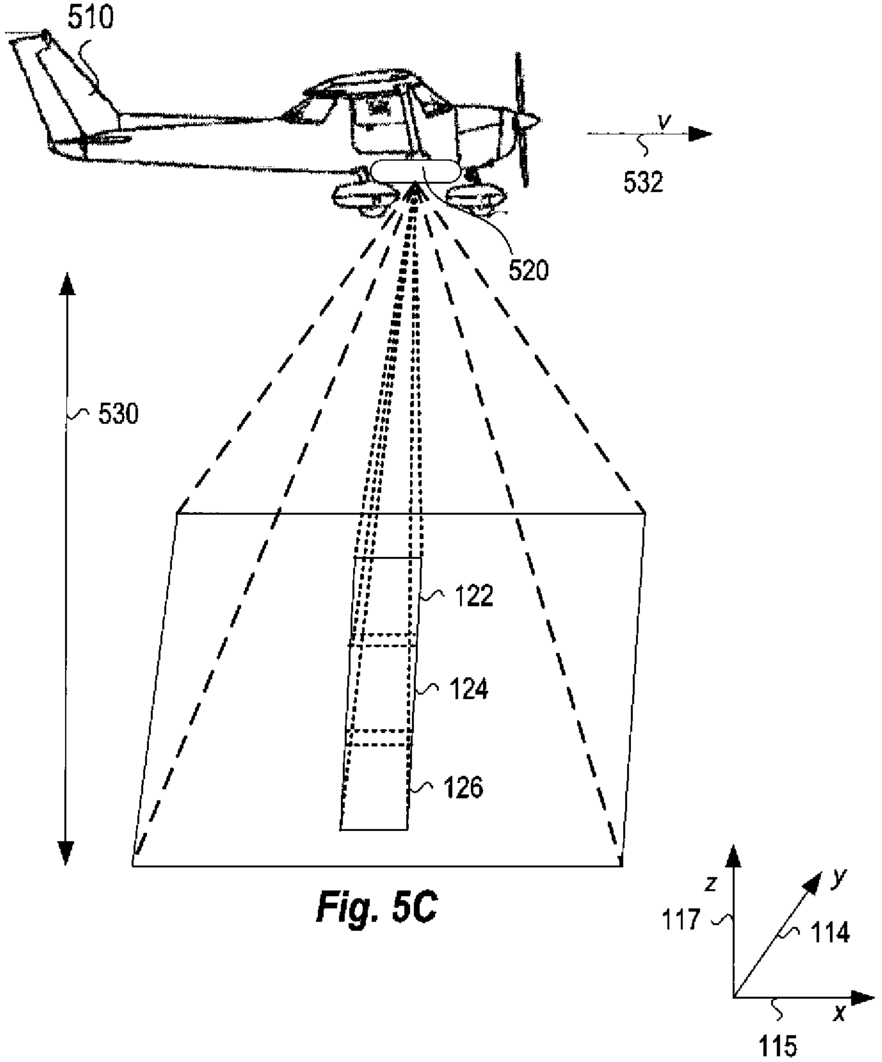


Fig. 5B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v
532
520
530
122
124
126
z
117
y
114
x
115

Fig. 5C

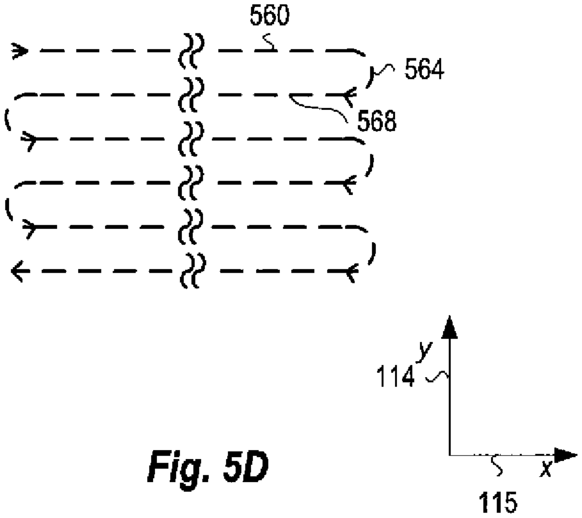
560
564
568
y
114
x
115

Fig. 5D

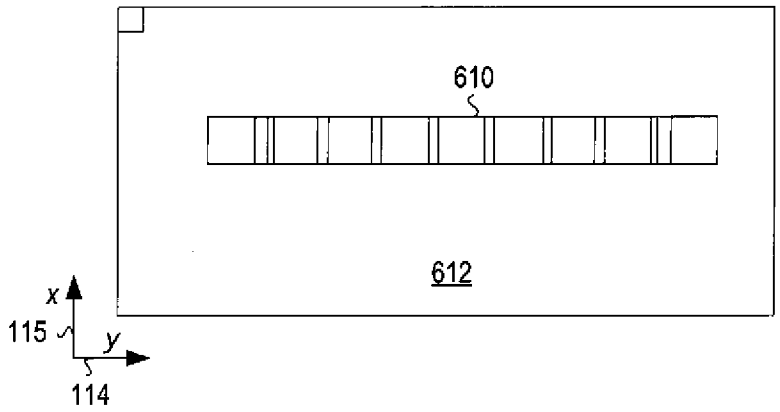

Fig. 6A1

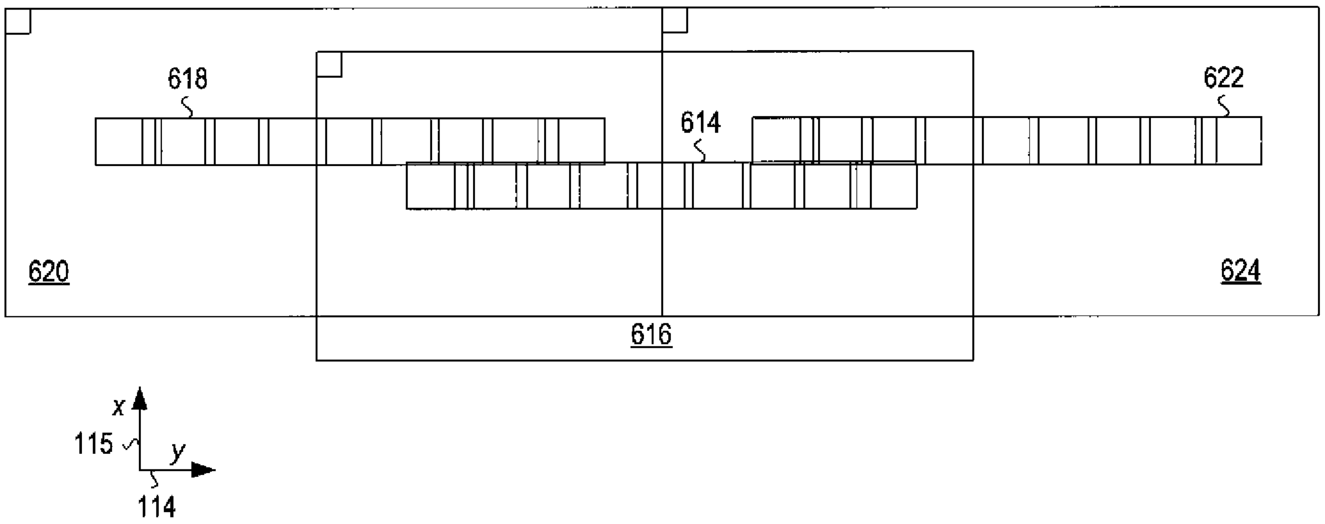

Fig. 6B1

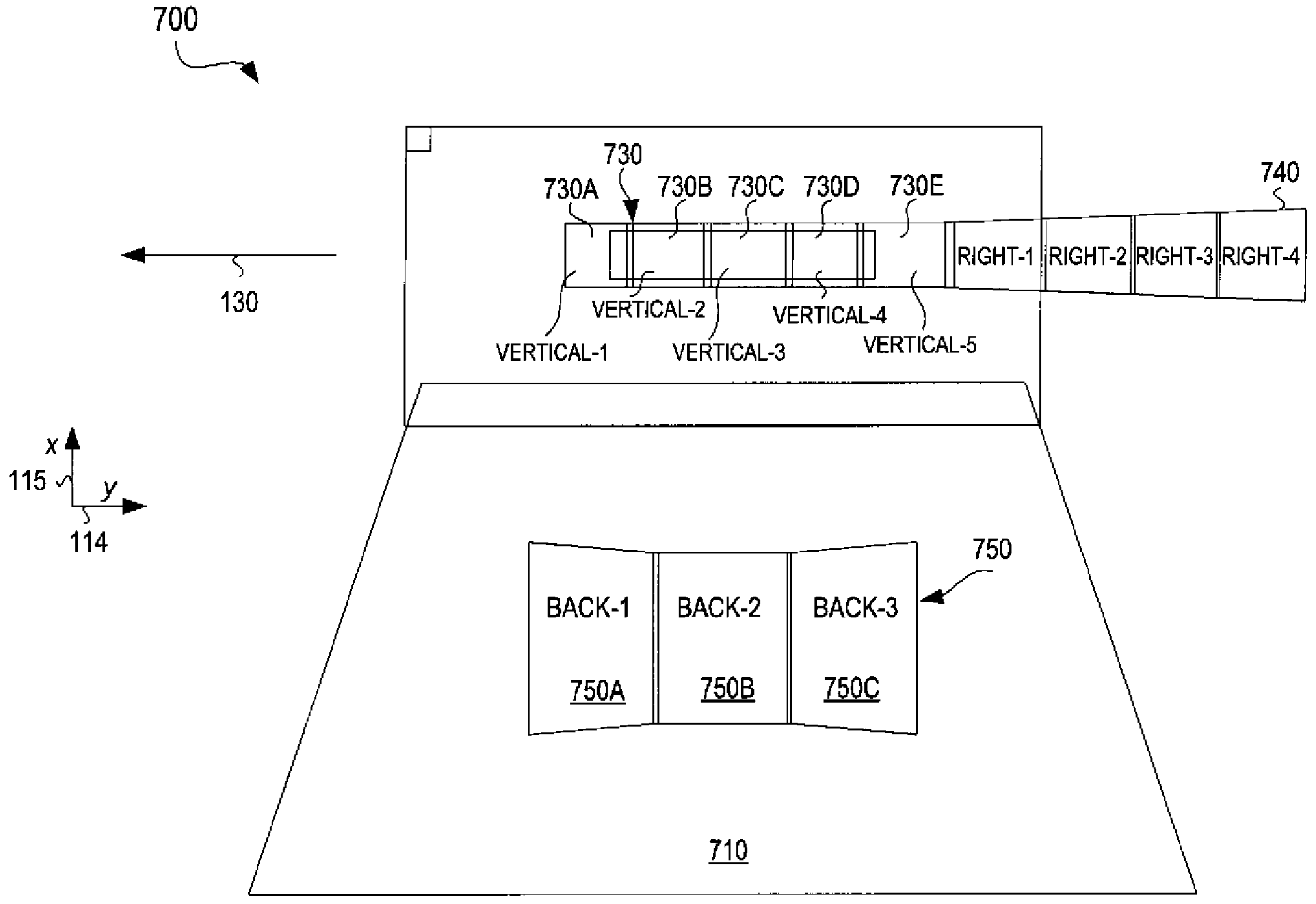
700
730
730A
730B
730C
730D
730E
740
RIGHT-1
RIGHT-2
RIGHT-3
RIGHT-4
130
VERTICAL-1
VERTICAL-2
VERTICAL-3
VERTICAL-4
VERTICAL-5
x
115
y
114
750
BACK-1
BACK-2
BACK-3
750A
750B
750C
710

Fig. 7A1

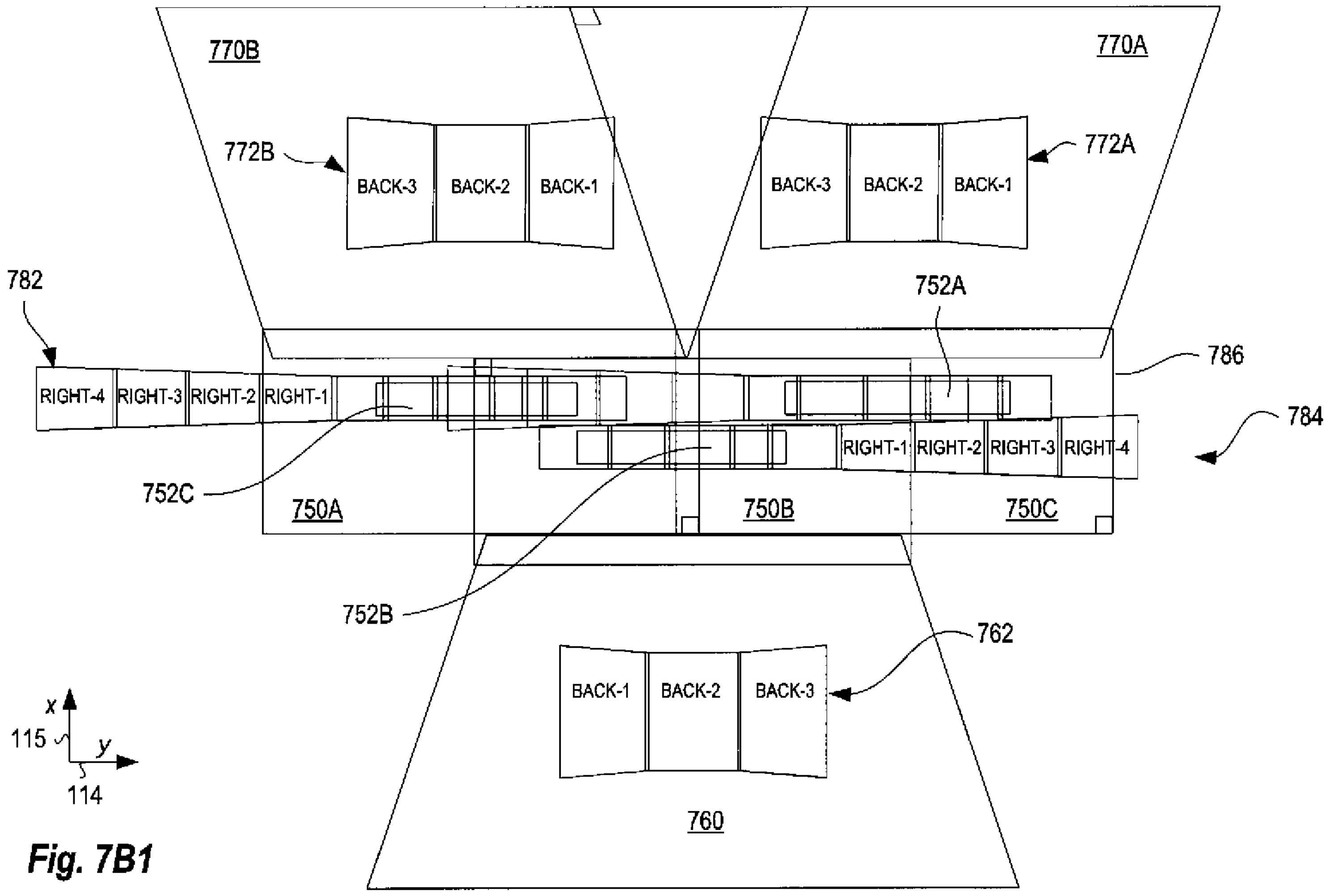
770B
770A
772B
BACK-3
BACK-2
BACK-1
BACK-3
BACK-2
BACK-1
772A
782
752A
786
RIGHT-4
RIGHT-3
RIGHT-2
RIGHT-1
784
RIGHT-1
RIGHT-2
RIGHT-3
RIGHT-4
752C
750A
750B
750C
752B
762
BACK-1
BACK-2
BACK-3
760
x
115
y
114

Fig. 7B1

TABLE I: CAMERA BODY DETAILS

CAMERA BODY DETAILS	Canon 1Ds MkII	Canon 1Ds MkIII	Nikon D3X	Nikon D3X
Resolution (megapixels)	16.6	23.0	12.0	24.0

TABLE II: VERTICAL OVERVIEW

VERTICAL OVERVIEW	Canon 1Ds MkII	Canon 1Ds MkIII	Nikon D3	Nikon D3X
Focal Length (mm)	28.0	28.0	28.0	28.0
Number of Cameras	1	1	1	1
Lens FOV Wide (degrees/lens)	65.4	65.4	65.4	65.4
Lens FOV High (degrees/lens)	46.3	46.3	46.3	46.3
Across Center Angle (degrees from vertical)	0	0	0	0
Along Center Angle (degrees from vertical)	0	0	0	0
Filter Diameter (mm)	52	52		
Installation Angle Spacing (degrees)	*n/a*	*n/a*	*n/a*	*n/a*

TABLE III: REAR OVERVIEW

REAR OVERVIEW	Canon 1Ds MkII	Canon 1Ds MkIII	Nikon D3	Nikon D3X
Focal Length (mm)	28.0	28.0	28.0	28.0
Number of Cameras	1	1	1	1
Lens FOV Wide (degrees/lens)	65.4	65.4	65.4	65.4
Lens FOV High (degrees/lens)	46.3	46.3	46.3	46.3
Across Center Angle (degrees from vertical)	0	0	0	0
Along Center Angle (degrees from vertical)	35	35	35	35
Filter Diameter (mm)	52	52		
Installation Angle Spacing (degrees)	*n/a*	*n/a*	*n/a*	*n/a*

Fig. 8A

TABLE IV: VERTICAL HIGH RESOLUTION

VERTICAL HIGH RESOLUTION	Canon 1Ds MkII	Canon 1Ds MkIII	Nikon D3	Nikon D3X
Focal Length (mm)	200.0	200.0	180.0	180.0
Number of Cameras	5	5	5	5
Lens FOV Wide (degrees/lens)	10.3	10.3	11.4	11.4
Lens FOV High (degrees/lens)	6.9	6.9	7.6	7.6
Across Center Angle (degrees from vertical)	0	0	0	0
Along Center Angle (degrees from vertical)	0	0	0	0
Filter Diameter (mm)	72	72		
Installation Angle Spacing (degrees)	*9.5*	*9.5*	*10.5*	*10.5*

TABLE V: RIGHT OBLIQUE

RIGHT OBLIQUE	Canon 1Ds MkII	Canon 1Ds MkIII	Nikon D3	Nikon D3X
Focal Length (mm)	200.0	200.0	180.0	180.0
Number of Cameras	3	3	3	3
Lens FOV Wide (degrees/lens)	10.3	10.3	11.4	11.4
Lens FOV High (degrees/lens)	6.9	6.9	7.6	7.6
Across Center Angle (degrees from vertical)	45	45	45	45
Along Center Angle (degrees from vertical)	0	0	0	0
Installation Angle Spacing (degrees)	*9.5*	*9.5*	*10.5*	*10.5*

TABLE VI: REAR OBLIQUE

REAR OBLIQUE	Canon 1Ds MkII	Canon 1Ds MkIII	Nikon D3	Nikon D3X
Focal Length (mm)	135.0	135.0	135.0	135.0
Number of Cameras	3	3	3	3
Lens FOV Wide (degrees/lens)	15.2	15.2	15.2	15.2
Lens FOV High (degrees/lens)	10.1	10.1	10.1	10.0
Across Center Angle (degrees from vertical)	0	0	0	0
Along Center Angle (degrees from vertical)	50	50	50	50
Installation Angle Spacing (degrees)	*14.5*	*14.5*	*14.5*	*14.5*

Fig. 8B

TABLE VII: CAMERA BODY DETAILS

CAMERA BODY DETAILS	Canon 1Ds MkII	Canon 1Ds MkIII	Nikon D3X	Nikon D3X
Resolution (megapixels)	16.6	23.0	12.0	24.0

TABLE VIII: VERTICAL OVERVIEW

VERTICAL OVERVIEW	Canon 1Ds MkII	Canon 1Ds MkIII	Nikon D3	Nikon D3X
Focal Length (mm)	28.0	28.0	28.0	28.0
Number of Cameras	1	1	1	1
Lens FOV Wide (degrees/lens)	65.4	65.4	65.4	65.4
Lens FOV High (degrees/lens)	46.3	46.3	46.3	46.3
Across Center Angle (degrees from vertical)	0	0	0	0
Along Center Angle (degrees from vertical)	0	0	0	0
Filter Diameter (mm)	52	52		
Installation Angle Spacing (degrees)	*n/a*	*n/a*	*n/a*	*n/a*

TABLE IX: VERTICAL HIGH RESOLUTION

VERTICAL HIGH RESOLUTION	Canon 1Ds MkII	Canon 1Ds MkIII	Nikon D3	Nikon D3X
Focal Length (mm)	300	300	300	300
Number of Cameras	9	9	9	9
Lens FOV Wide (degrees/lens)	6.87	6.87	6.87	6.87
Lens FOV High (degrees/lens)	4.58	4.58	4.58	4.58
Across Center Angle (degrees from vertical)	0	0	0	0
Along Center Angle (degrees from vertical)	0	0	0	0
Filter Diameter (mm)	72	72		
Installation Angle Spacing (degrees)	*9.5*	*9.5*	*10.5*	*10.5*

Fig. 8C

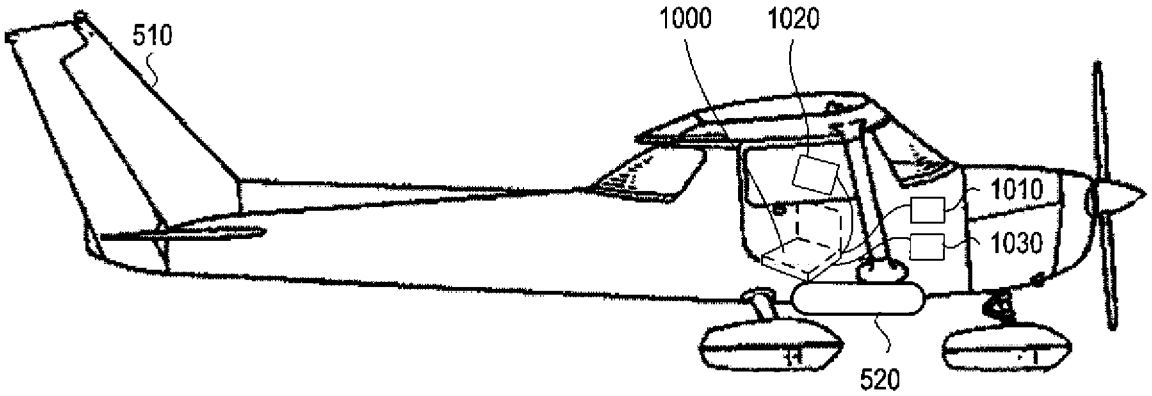

Fig. 9

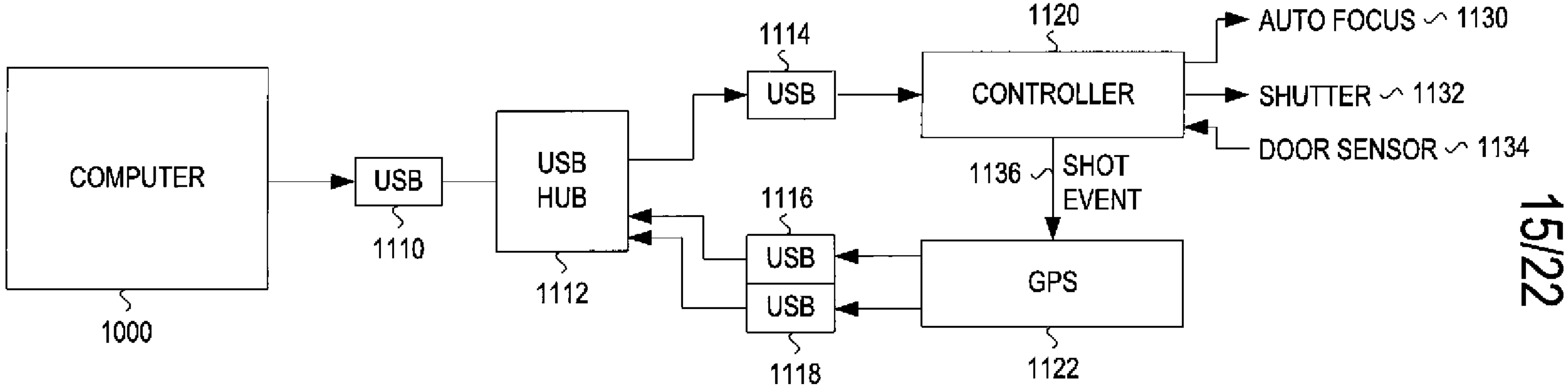
COMPUTER
1000
USB
1110
USB
HUB
1112
1114
USB
1116
USB
USB
1118
1120
CONTROLLER
1136
SHOT
EVENT
GPS
1122
AUTO FOCUS
1130
SHUTTER
1132
DOOR SENSOR
1134

Fig. 10

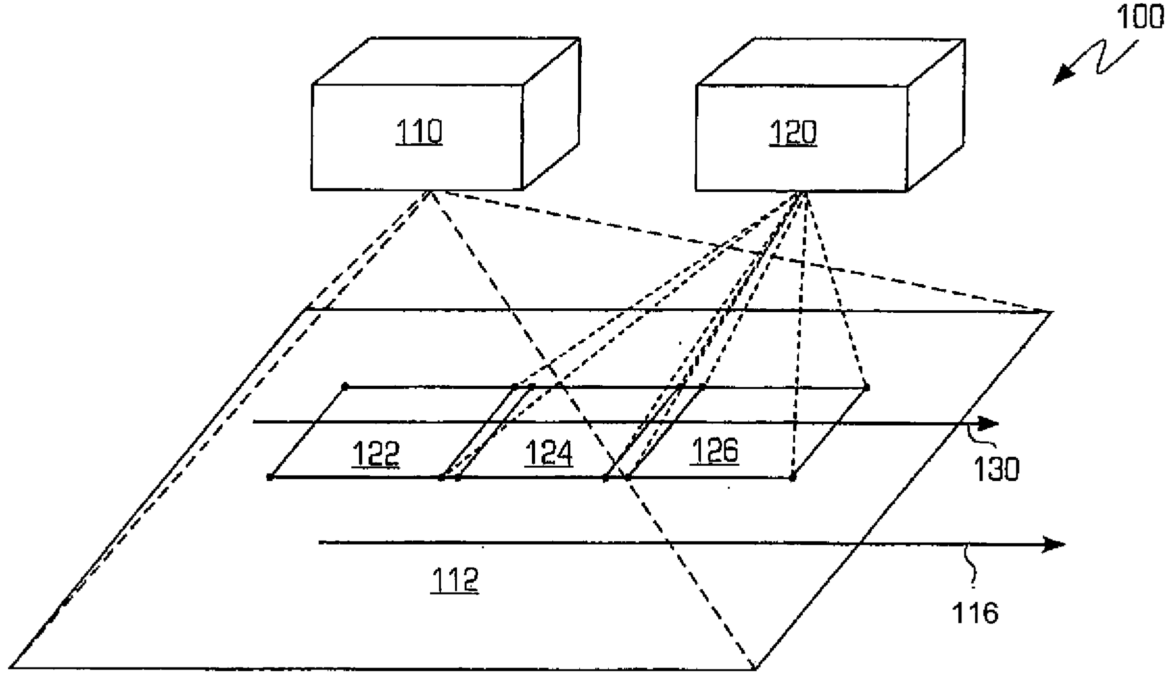

FIG. 11

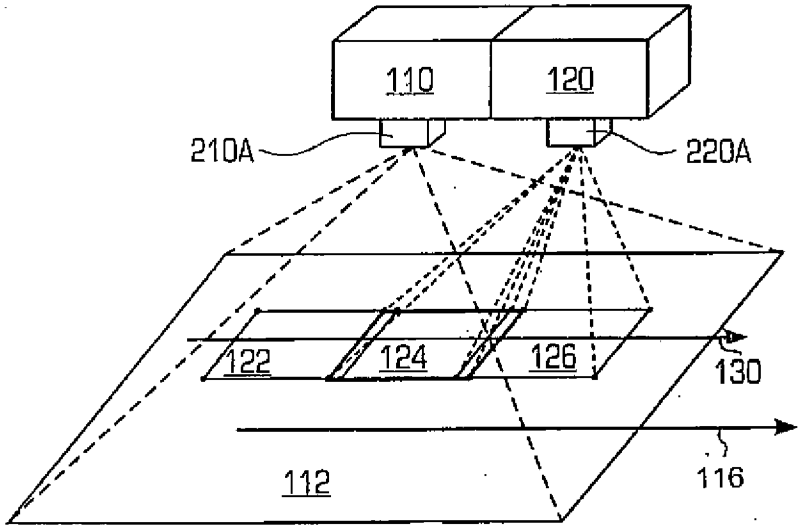

FIG. 12A

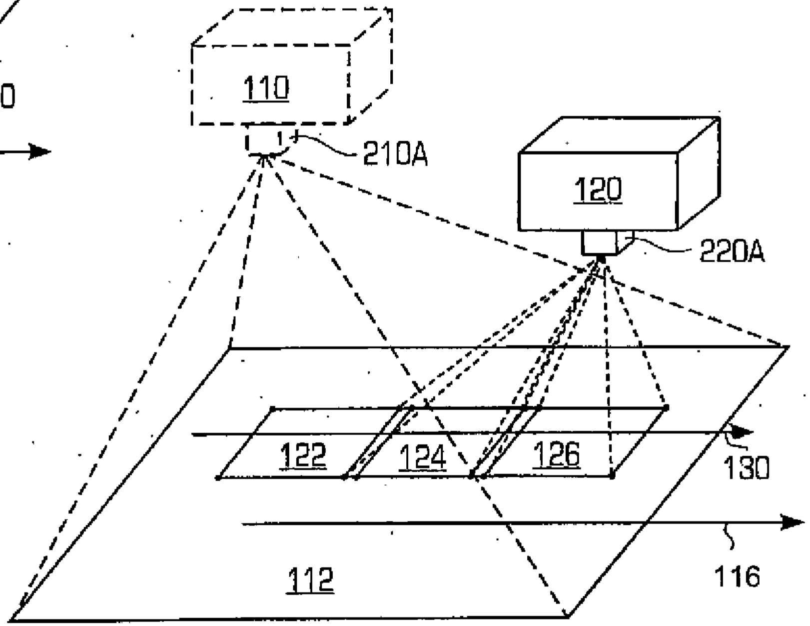

FIG. 12B

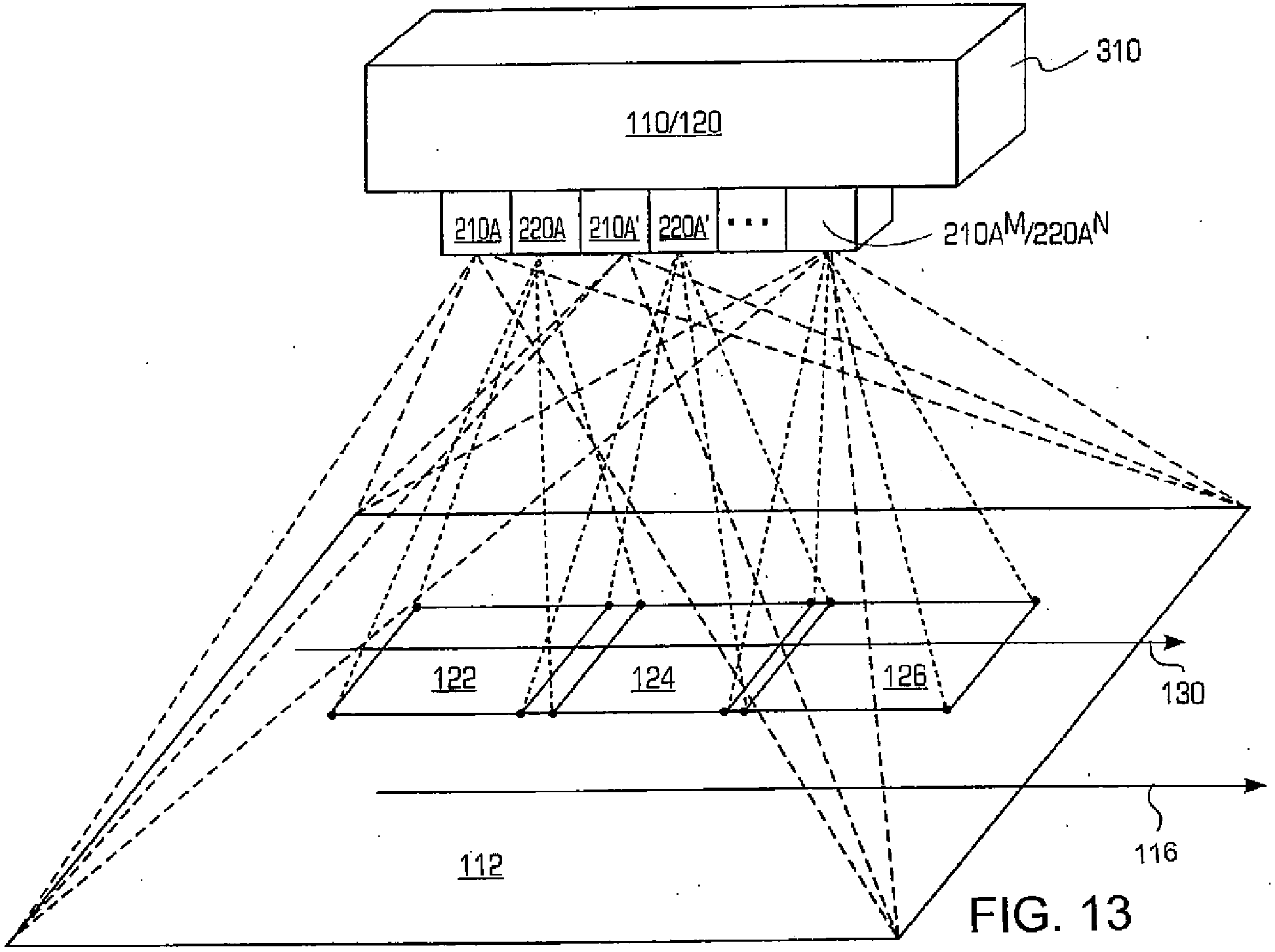
310
110/120
210A
220A
210A'
220A'
. . .
210A^M/220A^N
122
124
126
130
116
112

FIG. 13

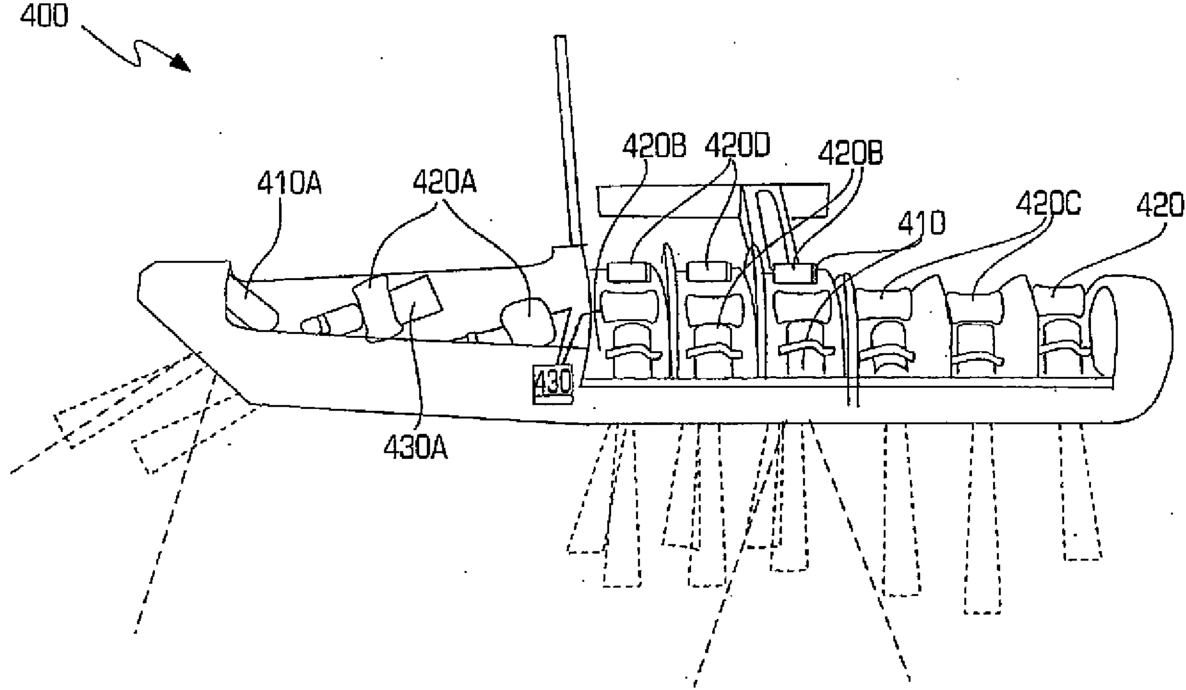

FIG. 14

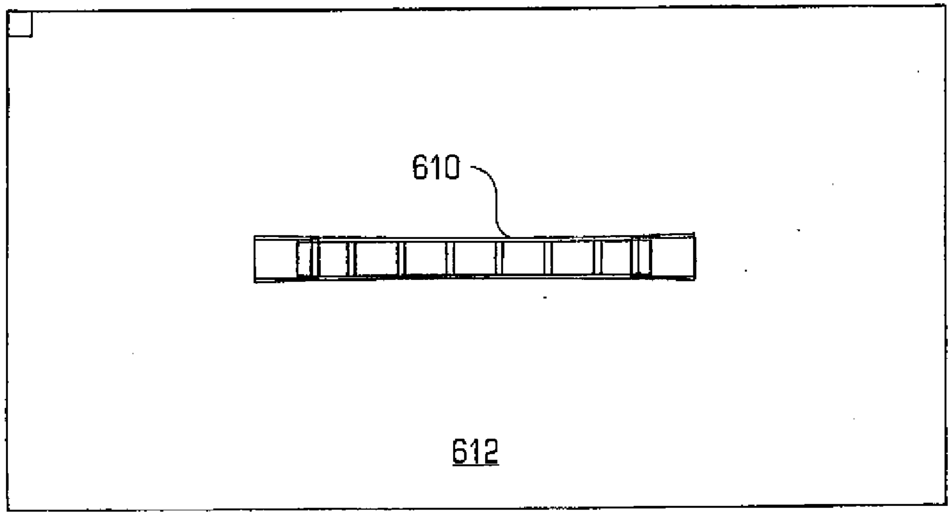

FIG. 6A2

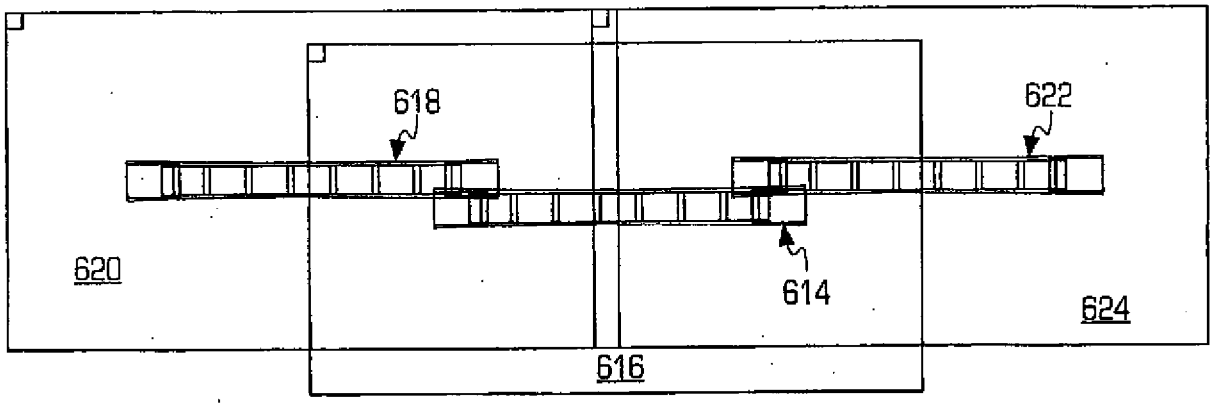

FIG. 6B2

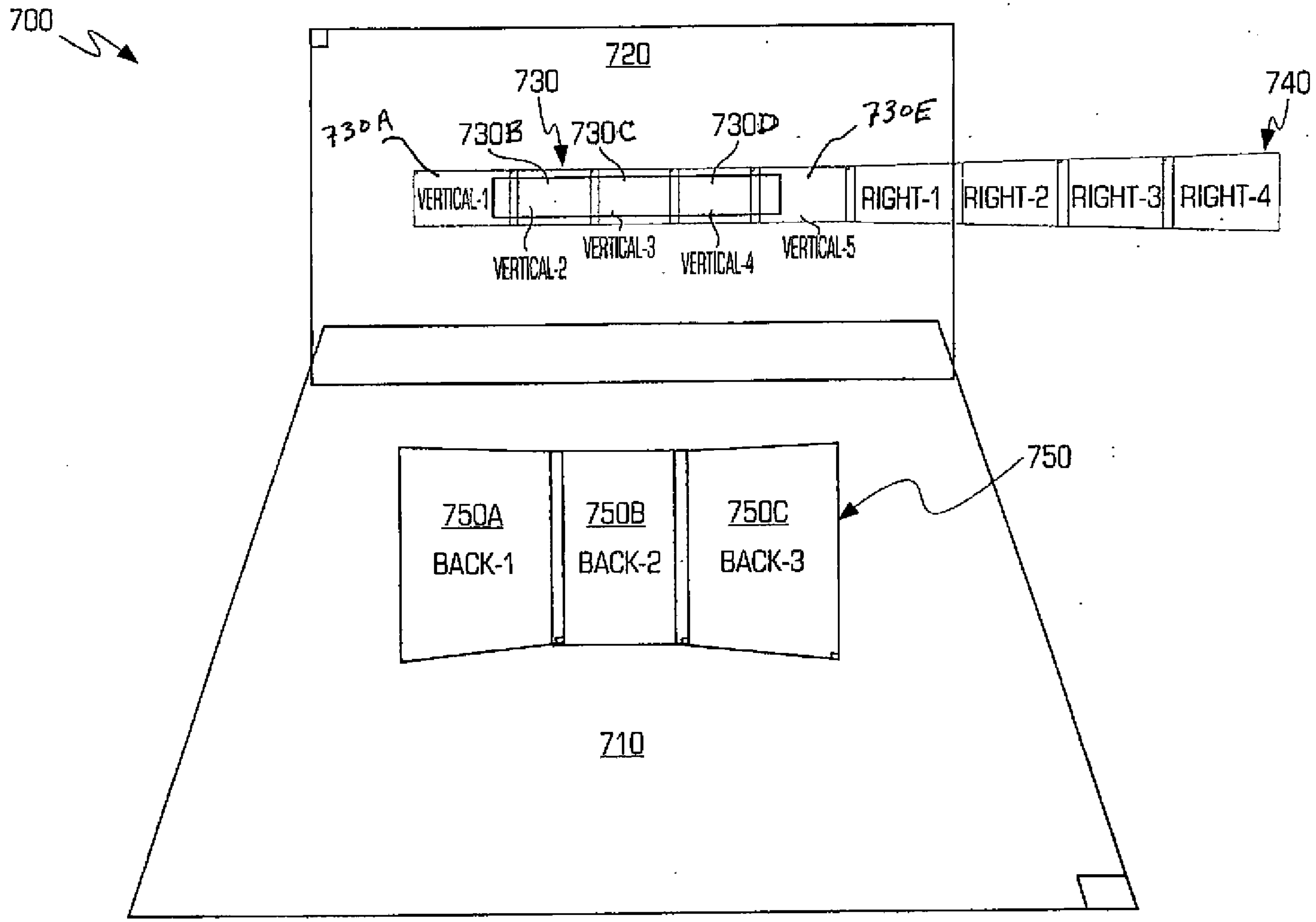
700
720
730
730A
730B
730C
730D
730E
740
VERTICAL-1
VERTICAL-2
VERTICAL-3
VERTICAL-4
VERTICAL-5
RIGHT-1
RIGHT-2
RIGHT-3
RIGHT-4
750
750A
BACK-1
750B
BACK-2
750C
BACK-3
710

FIG. 7A2

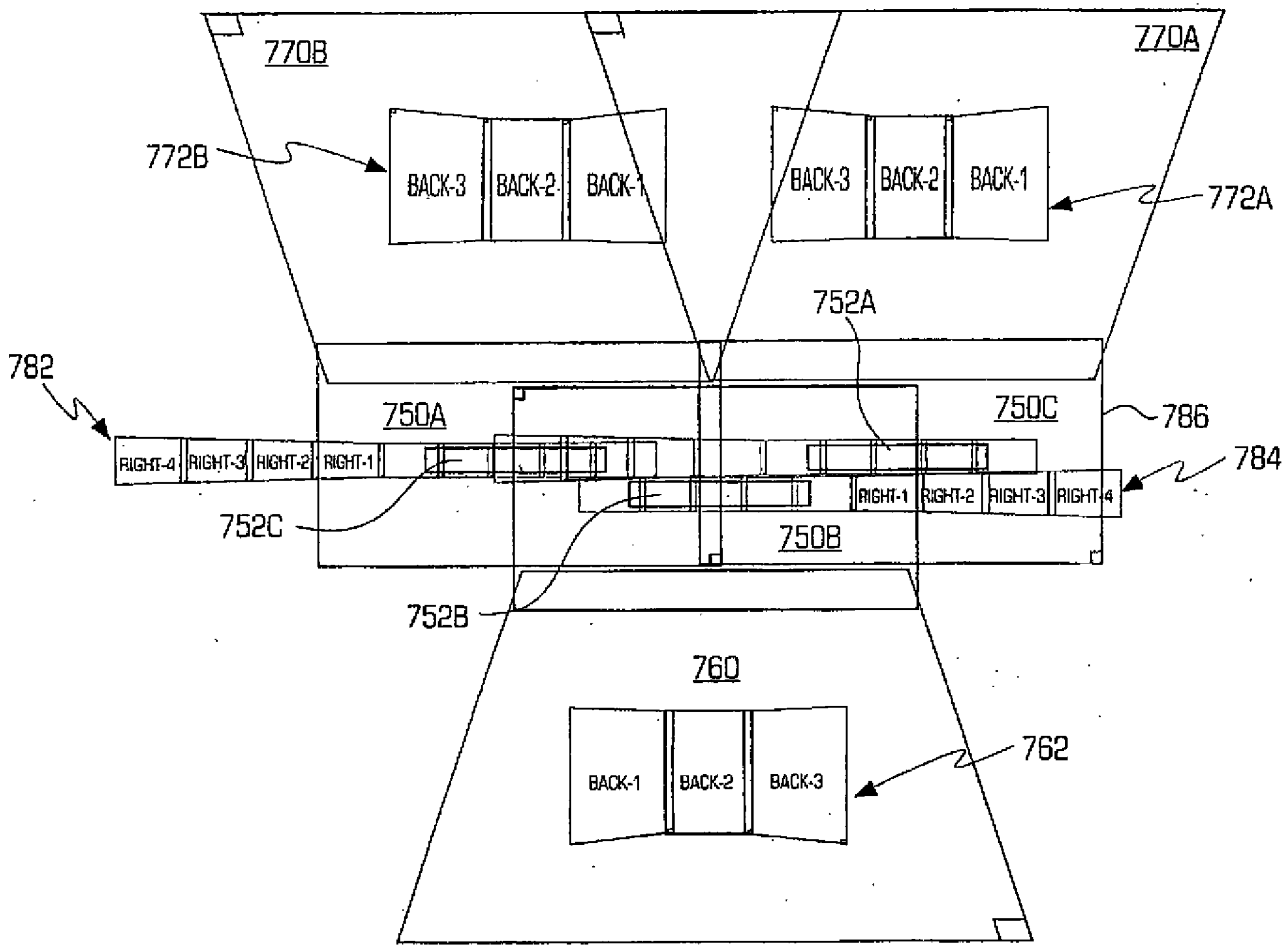
770B
770A
772B
BACK-3
BACK-2
BACK-1
BACK-3
BACK-2
BACK-1
772A
752A
782
750A
750C
786
RIGHT-4
RIGHT-3
RIGHT-2
RIGHT-1
784
RIGHT-1
RIGHT-2
RIGHT-3
RIGHT-4
752C
750B
752B
760
BACK-1
BACK-2
BACK-3
762

FIG. 7B2