United States Patent Application Publication	20250259324
Kind Code	A1
Publication Date	August 14, 2025
Inventor(s)	Klug; Michael et al.

SPACECRAFT SYSTEM FOR GENERATING A 3-D MAP OF AN OBJECT IN NEAR REAL-TIME UNDER NON-IDEAL LIGHTING CONDITITONS

Abstract

An apparatus for generating a 3D image map comprises a camera, mounted to a spacecraft, configured to capture plurality of images of an object from a plurality of positions about the object. An unstructured light source for illuminating the object to capture the plurality of images of the object. A gimbal mechanism for mounting the camera and the unstructured light source and moving the camera to a plurality of positions. Image processing circuitry configured to process the plurality of images of the object and generate a 3D image map of the of the object responsive to the plurality of image of the object. The image processing circuitry further having a processor configured to implement a shape-from-motion algorithm for generating the 3D image map responsive to the plurality of images of the object.

Inventors: **Klug; Michael (Redondo Beach, CA), Vermeersch; Joseph (Hermosa Beach, CA), Pank; Justin (El Segundo, CA), Plantenga; Scott (El Segundo, CA), Lopez; Brayamh (El Segundo, CA), Dow; Scott (El Segundo, CA), Bustamante; Adriel (Jurupa Valley, CA)**

Applicant: **Falcon Exodynamics, Inc.** (El Segundo, CA)

Family ID: **96661236**

Appl. No.: **19/040133**

Filed: **January 29, 2025**

Related U.S. Application Data

us-provisional-application US 63551358 20240208

Publication Classification

Int. Cl.: **G06T7/579** (20170101); **B64G1/66** (20060101); **H04N23/20** (20230101); **H04N23/695** (20230101); **H04N23/74** (20230101)

U.S. Cl.:

CPC **G06T7/579** (20170101); **B64G1/66** (20130101); **H04N23/20** (20230101); **H04N23/695** (20230101); **H04N23/74** (20230101); G06T2207/10032 (20130101)

Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application claims benefit of U.S. Provisional Application No. 63/551,358, filed Feb. 8, 2024, entitled SPACECRAFT SYSTEM FOR GENERATING 3-D MAP OF AN OBJECT IN NEAR REAL-TIME UNDER NON-IDEAL LIGHTING CONDITIONS (Atty. Dkt. No. FALC90-00004), the specifications of which is incorporated by reference herein in their entirety.

TECHNICAL FIELD
[0002] The present invention relates to 3D image mapping of an object, and more particularly, to a system for generating a 3D map of an object in real-time under nonideal lighting conditions.
BACKGROUND
[0003] Spacecraft operations often require supporting rendezvous of the spacecraft with other spacecraft, proximity operations with other spacecraft or other objects in space, docking with other spacecraft and landing the spacecraft on objects. In order to accomplish docking, repair or characterization of an object in space, 3D knowledge of the object is required to safely navigate around and potentially interact with the space object. For these operations to be automatically controlled, it is necessary to provide a 3D rendering and mapping the surface of an unknown space object or perform terrain elevation mapping of a planetary surface.
[0004] Existing solutions use active ranging techniques to perform a mapping of space objects or planetary terrain. Existing approaches for performing 3D mapping of objects under nonideal lighting conditions include the use of RF ranging techniques such as radar to measure the distance from a radar source to various points on a target object and generating a map of the radar pulse/distance returns. Other solutions involving the use of optical ranging such as LiDAR measure the distance from a LiDAR source to various points on the target and then generating a map of the LiDAR/pulse distance returns.
[0005] Structured light approaches using a projected pattern of light onto the surface of an object of interest to measure the difference between the distortion of the resulting projection on the object and the original light pattern transmitted to the object and determine the difference in height of areas across the target surface. All of these methods typically require expensive, complex and well calibrated hardware setups in order to perform the 3D mapping processes. A system enabling the creation of 3D images of objects having smaller size, weight, power and cost than those associated with traditional approaches would be greatly beneficial. This solution would especially help with low cost missions such as capturing and removing space junk.
SUMMARY
[0006] The present invention, as disclosed and described herein, in one embodiment thereof, comprises an apparatus for generating a 3D image map comprising a camera, mounted to a spacecraft, configured to capture a plurality of images of an object from a plurality of positions about the object. An unstructured light source for illuminating the object captures the plurality of images of the object. A gimbal mechanism for mounting the camera and the unstructured light source and moving the camera and unstructured light source to a plurality of positions. Image

processing circuitry processes the plurality of images of the object and generates a 3D image map of the of the object responsive to the plurality of images of the object. The image processing circuitry further has a processor configured to implement a shape-from-motion algorithm for generating the 3D image map responsive to the plurality of images of the object.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] For a more complete understanding, reference is now made to the following description taken in conjunction with the accompanying Drawings in which:

[0008] FIG. **1** illustrates a manner in which a spacecraft may take multiple images of an object to enable these images to create a 3D map of the object;

[0009] FIG. **2** illustrates a block diagram of a system for generating a 3D map of an object;

[0010] FIG. **3** illustrates a block diagram of a system for generating a 3D map of an object including the image processing components;

[0011] FIG. **4** illustrates a flow diagram of the process for generating a 3D map of an object;

[0012] FIG. **5** illustrates a further embodiment of the system for generating a 3D map of an object implemented with respect to a spacecraft;

[0013] FIG. **6** illustrates the control processes of a system for generating a 3D map of an object;

[0014] FIG. **7** illustrates a perspective view of one embodiment of a first side of the system for generating a 3D map of an object;

[0015] FIG. **8** illustrates a perspective view of one embodiment of a second side of the system for generating a 3D map of an object;

[0016] FIG. **9** illustrates a block diagram of one embodiment of the system controllers for the system for 3D mapping of an object; and

[0017] FIG. **10** illustrates the generation of an image using the system described herein.

DETAILED DESCRIPTION

[0018] Referring now to the drawings, wherein like reference numbers are used herein to designate like elements throughout, the various views and embodiments of a spacecraft system for generating a 3D map of an object in near real-time under nonideal lighting conditions are illustrated and described, and other possible embodiments are described. The figures are not necessarily drawn to scale, and in some instances the drawings have been exaggerated and/or simplified in places for illustrative purposes only. One of ordinary skill in the art will appreciate the many possible applications and variations based on the following examples of possible embodiments.

[0019] Referring now to FIG. **1**, there is illustrated the manner in which an object **102** may be surveyed (3D mapped) by a spacecraft **104**. The object **102** may comprise any celestial body moving through outer space on which the spacecraft **104** may desire to land or may comprise a man-made object such as a spacecraft, satellite, space junk, etc. with which the spacecraft **104** may desire to dock, contact or rendezvous. The object **102** when located within nonideal lighting conditions may make generating a 3D map of the surface of the object very difficult. In order to generate a 3D map of the surface of the object **102**, the spacecraft **104** moves in a path **106** about the area of interest upon the object **102**. The area of interest can be the entire surface of the object **102** or may comprise only certain areas of the object. In each of multiple positions, the spacecraft would take an image as indicated generally at **108** of the object **102**. In practice, these images **108** would overlap and the combined images **108** can be processed in order to generate the 3D map of the area of interest of the object **102** using various image processing techniques.

[0020] Referring now to FIG. **2**, there is illustrated a block diagram of a general version of the 3D mapping system **202** for generating a 3D map of an object. The 3D mapping system **202** comprises an integrated hardware and software system hosted on a moving platform such as a spacecraft. The

3D mapping system **202** includes a high-resolution camera **204** and an unstructured light source **206**. In other implementations, an infrared or other camera is used when use can be made of the object's self-illumination in which case the unstructured light source **206** is optional. Each of the high-resolution camera **204** and the unstructured light source **206** are mounted upon a gimbal **208** enabling the camera **204** and light source **206** to be adjusted to various positions. An unstructured light source **206** comprises a light source that emits light without a specific pattern or arrangement. The unstructured light waves from the unstructured light source **206** are not organized in a predictable way, unlike a structured light source which might project a specific pattern or grid of light to capture 3D information about an object. An unstructured light source **206** provides a diffused, non-directional light like a regular light bulb or sunlight.

[0021] The high-resolution camera **204** is sensitive in the same spectrum as the unstructured light source **206**. In alternative embodiments, the high-resolution camera **204** may take advantage of an object's self-illumination using for example an infrared camera. The gimbal **208** is an optional structure that enables pointing of the camera **204** and light source **206** in a desired direction. An image processing system **210** comprises hardware and software for receiving multiple images taken by the high-resolution camera **204** and processing these multiple images to generate a 3D map of the object **102**. The 3D mapping system **202** may include an onboard computer that utilizes structure/shape-from-motion algorithms in order to generate the 3D map from the multiple images taken by the camera. The 3D mapping system **202** enables the generation of 3D maps of an object **102** from the multiple images.

[0022] Referring now to FIG. **3**, there is more particularly illustrated the image processing components of the 3D mapping system **202** of FIG. **2**. The system is useful in any spacecraft and may be used to perform 3D mapping, proximity operations, rendezvous, docking or landing operations. As described previously, the 3D mapping system **202** includes a camera **302** that may be positioned in a variety of direction. As noted previously, the camera **302** could be in a fixed position rather than a gimbaled camera. The gimbaled camera **302** captures resolved images of a subject object at a programmable rate as the spacecraft moves around the object. Illumination source **304**, if present, shines non-structured light onto the surface of the object which is being 3D mapped. The illumination source **304** is powered by the power unit **314** when nonideal lighting conditions are detected. However, a lighting source may not be utilized in a situation where another type of camera such as an infrared camera is utilized that does not require illumination of the object by the lighting source or if sufficient light is present.

[0023] A positioning and measurement unit **306** may optionally be included to determine a position of the 3D mapping system **202** and a location of the images that are taken by the 3D mapping system. This position information may be used to assist in the 3D image mapping from the multiple individual images taken of a particular object. A general purpose graphics processor **308** may be included with the camera **302** in order to process the multiple images being taken by the camera **302**. The 3D mapping is carried out by a shape-from-motion algorithm **310** implemented in conjunction with a processor **312**. The shape-from-motion algorithm **310** receives the individual images from the camera **302** and the associated graphics processor **308** generates the 3D image map. The 3D mapping system **202** may be self-contained such that it does not rely upon power or data from the spacecraft on which the system is implemented. In this case, the 3D mapping system **202** would include a power unit **314** enabling powering the various components of the 3D mapping system for generating the 3D maps.

[0024] Referring now to FIG. **4**, there is illustrated of the process for generating a 3D map from a plurality of images taken by the 3D mapping system **202** described herein above. The camera **302** initially captures multiple images at step **402** from the surface of the object being mapped. At least two images are required. However, in most cases, a much greater number of images will be captured. The images are time tagged and optionally tagged with position measurement information from the position and measurement unit **306** at the time of capture. Once the images have been captured, the image processing software determines the shape from motion algorithm **310** which will detect at step **404** features within the multiple images. Next, the shape from motion algorithm **310** will align and match the detected features between the various images at step **406**. The aligned and matched features will be used to create tracks of the features at step **408** within physical space. The shape from motion algorithm **310** will then reconstruct the physical motion of the camera **302** and determine feature tracks between images at step **410**. The reconstruction will be undistorted at step **412**. From the undistorted reconstruction at step **412**, a depth map is generated at step **414** which may be merged into a 3D point cloud at step **416**.

[0025] Referring now to FIG. **5**, there is illustrated the interconnection of the various system components illustrated with respect to FIG. **3**. The camera **302** and illumination source **304** are each positioned on a one or two axis gimbal mount plate **502**. The gimbal mount plate **502** is controlled by gimbal control electronics **504** over a control line **507**. The gimbal control electronics **504** position the camera **302** and illumination source **304** in a desired position in order to capture images of the object being 3D mapped. The control line **507** provides both control and power signals from the gimbal control electronics **504** to the gimbal mount plate **502**.

[0026] Processing circuitry **506** is connected to the camera **302** via a control line **508** and to the illumination source **304** via a control line **510**. The processing circuitry **506** may comprise a CPU, GPU or FPGA processor for controlling capture of multiple images by the camera **302**. The control signals provided via control line **508** instructs the camera **302** when to take the multiple images of the surface of the object which is being 3D mapped by the 3D mapping system **202**. The control signals received over the control line **510** instruct the illumination source **304** when to illuminate the surface of the object such that the camera **302** may capture images of an illuminated object. The processing circuitry **506** will process each of the multiple images that are captured by the camera **302** in the manner described with respect to the flow diagram of FIG. **3** in order to generate the 3D map of the object. A spacecraft **104** receives from the processing circuitry **506** camera and floodlight status information, control information and image data.

[0027] The power management unit **314** controls the flow of power from a battery pack **512** to the camera **302** and illumination source **304** via power lines **514**. Position and inertial sensor circuitry **306** are associated with the camera **302** and the processing circuitry **506** in order to enable position and timestamp information to be associated with each of the images captured by the camera **302**.

[0028] Referring now to FIG. **6**, there is illustrated the software processing associated with generation of a 3D map of the surface of an object from multiple images of the object taken by a camera **302**. Once the system is powered on at **602**, power is provided from the battery pack **512** to control the camera at **604**, to process hosts position and attitude data at **606**, to control the gimbal at **602**, to control the illumination source at **610** and to process internal position and attitude data at **612**. The camera is controlled at **604** responses to the power and exposure settings received from the process image set at **614** and the illuminator control **610**. The camera **302** will capture images responsive to the provided exposure settings and provide images **616** for processing at the process image sets **614**. The image sets **616** received from the camera control **604** are processed at **614** responsive to the received images **616** and the time, position, velocity and attitude data **618** provided from the process host position and attitude data **606** and the process internal position and attitude data **612**. The process host position and attitude data **606** also provides position and movement information **620** to control the gimbal at **608**. The illumination sources are controlled at illuminator control **610** responsive to mode on/off commands **622** from the process hosts position and attitude data and brightness commands **624** from the camera control **604**. This enables the establishment of the exposure settings **613** for the camera control **604**. The process image sets **614** provide point clouds and intermediate data **626** responsive to the multiple received image sets **616**. All of the images received from the camera **302** are combined into point cloud data and the images processed.

[0029] Referring now to FIG. **7**, there is provided perspective view of one embodiment of the of the 3D mapping system **702**. As noted before, a camera **704** is mounted on a gimbal plate **706** along with a pair of unstructured light sources **708**. The use of the gimbal camera **704** reduces dependency on host spacecraft pointing. The camera **704** is held in place by a camera bracket **710** while the unstructured illumination sources **708** are secured to the gimbal plate **706** via light brackets **712**. Other configurations of the system may also be used.

[0030] Referring now to FIG. **8**, there is illustrated one embodiment of the backside of the 3D mapping system **702** by which the gimbal plate **706** and associated camera **704** and unstructured illumination sources **708** are mounted to a structure such as a spacecraft using a harness bracket **802**. Harness bracket **802** comprises an external harness bracket that mounts to angle brackets and supports of, for example, a spacecraft. Other configurations of the system may also be used.

[0031] Referring now to FIG. **9**, there is illustrated one embodiment of the controller architecture for the 3D mapping system **702**. The 3D mapping system **702** interconnects with the spacecraft through data connection **902**. The connection **902** provides signals to and from a host interface **904**. The host interface **904** enables the provision of control signals to each of a camera controller **906** that controls the camera, an illumination controller **908** that controls the unstructured illumination source/sources and the gimbal controller **910** that controls the positioning of the camera and the illumination source via the gimbal. The gimbal controller **910** provides gimbal telemetry control signals to the camera controller **906** in order to position the camera in a desired position. The camera controller **906** upon receiving the recorded images from the camera stores the images **914** on a storage system **916**. The raw image data **918** is also provided from the camera controller **906** to an image processor **920**. The image processor **920** creates the point cloud file **922** comprising the 3D image mapping that may be stored on the storage system **916** or output via an output **924**. The image processor **920** in addition to the raw image data **918** from the camera controller **906** may utilize the image file **914** stored within the storage system **916**.

[0032] Referring now to FIG. **10**, there is illustrated one manner for generating a 3D image map from the multiple sets of image data taken by the camera. Initially, the actual image data **1002** is first processed into a raw point cloud image **1004**. The raw point cloud image **1004** has outliers removed as shown at **1006** and then a Poisson surface reconstruction may be made of the image as shown at step **1008**. The example of 3D mapping processing illustrated in FIG. **10** comprises merely one example thereof. It will be appreciated that other 3D image processing techniques using the 3D mapping system described herein above may be utilized.

[0033] It will be appreciated by those skilled in the art having the benefit of this disclosure that this spacecraft system for generating a 3D map of an object in near real-time under nonideal lighting conditions provides an improved manner of generating 3D maps in low light environments. It should be understood that the drawings and detailed description herein are to be regarded in an illustrative rather than a restrictive manner, and are not intended to be limiting to the particular forms and examples disclosed. On the contrary, included are any further modifications, changes, rearrangements, substitutions, alternatives, design choices, and embodiments apparent to those of ordinary skill in the art, without departing from the spirit and scope hereof, as defined by the following claims. Thus, it is intended that the following claims be interpreted to embrace all such further modifications, changes, rearrangements, substitutions, alternatives, design choices, and embodiments.

Claims

1. An apparatus for generating a 3D image map of an object, comprising: a high-resolution camera within a spacecraft configured to capture plurality of overlapping images of the object from a plurality of positions about the object; an unstructured light source within the spacecraft for illuminating the object with light not having a specific pattern or arrangement to capture the plurality of overlapping images of the object; image processing circuitry within the spacecraft configured to process the plurality of overlapping images of the object and generate a 3D image map of the of the object responsive to the plurality of overlapping images of the object.

2. (canceled)

3. The apparatus of claim 1, further comprising an infrared camera configured to capture the plurality of overlapping images of the object.

4. The apparatus of claim 1 further comprising a gimble mechanism for mounting the high-resolution camera and the unstructured light source, the gimble mechanism enabling the high-resolution camera and the unstructured light source to be moved to a plurality of positions.

5. The apparatus of claim 4 further comprising a gimbal controller configured to control movement of the gimbal mechanism to move the high-resolution camera and the unstructured light source to the plurality of positions.

6. The apparatus of claim 1 further comprising position measurement circuitry configured to determine a position and associated data indicating the position with each of the plurality of overlapping images of the object.

7. The apparatus of claim 1, wherein the image processing circuitry further comprises a graphics processor configured to process the plurality of overlapping images of the object.

8. The apparatus of claim 1, wherein the image processing circuitry further comprises a processor configured to implement a shape-from-motion algorithm for generating the 3D image map responsive to the plurality of overlapping images of the object.

9. An apparatus for generating a 3D image map, comprising: a high-resolution camera, mounted to a spacecraft, configured to capture a plurality of overlapping images of an object from a plurality of positions about the object; an unstructured light source, mounted to the spacecraft, for illuminating the object with light not having a specific pattern or arrangement to capture the plurality of overlapping images of the object; a gimbal mechanism, mounted to the spacecraft, for mounting the high-resolution camera and the unstructured light source, the gimbal mechanism enabling movement of the camera and the unstructured light source to a plurality of positions; and image processing circuitry associated with the spacecraft configured to process the plurality of overlapping images of the object and generate a 3D image map of the of the object responsive to the plurality of overlapping image of the object, wherein the image processing circuitry further comprises a processor configured to implement a shape-from-motion algorithm for generating the 3D image map responsive to the plurality of overlapping images of the object.

10. The apparatus of claim 9 further comprising an infrared camera configured to capture the plurality of overlapping images of the object.

11. The apparatus of claim 9 further comprising a gimbal controller configured to control movement of the gimbal mechanism to move the high-resolution camera and the unstructured light source to the plurality of positions.

12. The apparatus of claim 9 further comprising a position measurement circuitry configured to determine a position and associated data indicating the position with each of the plurality of overlapping images of the object.

13. The apparatus of claim 9, wherein the image processing circuitry further comprises a graphics processor configured to process the plurality of overlapping images of the object.

14. A method for generating a 3D image map for a 3D mapping system mounted to a spacecraft, comprising: capturing at the spacecraft a plurality of overlapping images of an object from a plurality of positions about the object using a high-resolution camera mounted to the spacecraft; generating light not having a specific pattern or arrangement from an unstructured light source at the spacecraft; illuminating the object with the light not having the specific pattern or arrangement to capture the plurality of overlapping images of the object with the unstructured light source; and processing at the spacecraft the plurality of images of the object to generate a 3D image map of the of the object responsive to the plurality of overlapping image of the object using image processing circuitry.

15. The method of claim 14 further comprising capturing further comprises capturing the plurality of images of the object using an infrared camera.

16. The method of claim 14 further comprising: mounting the high-resolution camera and the unstructured light source to a gimbal mechanism; and moving the high-resolution camera and the unstructured light source between a plurality of positions using the gimbal mechanism.

17. The method of claim 16 further comprising controlling movement of the gimbal mechanism to move the high-resolution camera and the unstructured light source to the plurality of positions using a gimbal controller.

18. The method of claim 14 further comprising a position measurement circuitry configured to determine a position and associated data indicating the position with each of the plurality of overlapping images of the object.

19. The method of claim 14, wherein the step of processing further comprises processing the plurality of overlapping images of the object using a graphics processor.

20. The method of claim 14, wherein the step of processing further comprises generating the 3D image map responsive to the plurality of overlapping images of the object using a processor configured to implement a shape-from-motion algorithm.

21. The apparatus of claim 1, wherein the high resolution camera, the unstructured light source and the image processing circuitry are self-contained and do not rely upon data from the spacecraft on which the apparatus is implemented.