A 2D displacement sensor is used to measure displacement in three dimensions. For example, the sensor can be used in conjunction with a pulse-modulated or frequency-modulated laser beam to measure displacement caused by deformation of an antenna on which the sensor is mounted.
FIG. 6A

1. Receive signal from reference detector
2. Start timer
3. Receive signal from detector of interest
4. Stop timer
5. Store timer value as reference delay ($T_{REF}$)

FIG. 6B

1. Receive signal from reference detector
2. Start timer
3. Receive signal from detector of interest
4. Stop timer
5. Store timer value as current delay ($T$)
6. Clear timer
7. Calculate difference between $T$ and $T_{REF}$
8. Calculate deformation
FIG. 7
1 **USING A 2D DISPLACEMENT SENSOR TO DERIVE 3D DISPLACEMENT INFORMATION**

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application No. 60/102,158, filed on Sep. 28, 1998, which is incorporated herein by reference.

STATEMENT AS TO FEDERALLY SPONSORED RESEARCH

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 U.S.C. 202) in which the Contractor has elected to retain title.

TECHNOLOGICAL FIELD

This application relates to the use of displacement sensors in detecting mechanical motion.

BACKGROUND

In many signal acquisition systems, such as optical signal and RF signal acquisition systems, signal stabilization is critical for error-free data recovery. Signal stabilization is difficult to achieve when atmospheric or mechanical jitter exists in the acquisition system. Jitter can result from movement of the signal source and movement of the signal reception system. For example, movement by a human operator is a common source of mechanical jitter in a video recording system, such as a handheld camcorder.

Signal reception systems used in interplanetary communication receive signals from distant sources at very high data rates. These signals are often in the form of plane waves. The rates at which these systems can recover data accurately is limited by signal distortions that result from mechanical deformation and vibration of the reception systems. For earth-bound reception systems, common causes of mechanical deformation and vibration include gravitational weight redistribution during tracking and pointing, deflection caused by wind, thermal effects and gradients arising from solar heating and cooling, and stray mechanical resonance. The antennas in the U.S. deep space network, for example, include 34-meter and 70-meter mirrors that vibrate characteristically at a frequency of approximately 5-10 Hz with a deformation amplitude of approximately 1-2 cm.

SUMMARY

Recognition of the above led the inventor to develop a signal acquisition system capable of detecting displacement in three dimensions and correcting received signals to compensate for this displacement. The system is useful in a wide variety of applications, including interplanetary communication with very large antenna systems that are subject to a wide variety of sources of mechanical deformation and vibration. In these systems, incoming signals can be corrected to compensate for distortions introduced by deformation and vibration of the antennas. This in turn improves data transmission and recovery, in part, by reducing link noise temperatures and increasing bit transmission rates.

In one aspect, the invention involves measuring physical displacement in three dimensions with a displacement sensor. An optical signal source produces an optical signal, such as a pulse-modulated or frequency-modulated laser beam, having a characteristic feature that varies with linear distance traveled by the optical signal. The displacement sensor is positioned to receive at least a portion of the optical signal. The sensor produces an output signal indicating a position at which the optical signal strikes the sensor in each of two orthogonal dimensions. The sensor itself is subject to displacement in a third orthogonal dimension, such as the displacement caused by deformation of an antenna on which the sensor is mounted.

Processing circuitry is coupled to the sensor to derive information about the characteristic feature of the optical signal at the target sensor. The processing circuitry applies this information in calculating a linear distance traveled by the optical signal in the third orthogonal dimension and then derives from the linear distance an amount by which the target sensor has been displaced in the third orthogonal dimension.

Other embodiments and advantages will become apparent from the following description and from the claims.

DESCRIPTION OF THE DRAWINGS

These and other aspects will now be described in detail with respect to the accompanying drawings, wherein:

FIG. 1 shows a signal reception system, such as an antenna in the U.S. deep space network.

FIG. 2 is a schematic diagram of a signal reception system with components for correcting distortions caused by mechanical deformation in the reception system.

FIG. 3 is a perspective view of a 2D displacement sensor.

FIGS. 4A and 4B are graphs showing the relationship between the position of an optical signal on a 2D displacement sensor and the current out of the sensor.

FIG. 5 is a schematic diagram of a system for use in deriving 3D displacement information from a 2D displacement sensor.

FIGS. 6A and 6B are flow charts of a process for deriving 3D displacement information from a 2D displacement sensor.

FIG. 7 is a schematic diagram of another technique for use in deriving 3D displacement information from a 2D displacement sensor.

FIG. 8 is a schematic diagram of another system for use in deriving 3D displacement information from a 2D displacement sensor.

FIG. 9 shows an array of displacement sensors mounted to a parabolic antenna.

DETAILED DESCRIPTION

FIG. 1 shows a signal acquisition system 10 that is used in the U.S. deep space network. In general, the antenna 10 receives signals from space-based transmitters and recovers digital data from these signals. The antenna 10 includes a primary mirror 15 that captures and focuses the incoming signals. A secondary mirror 20 placed near the focal point of the primary mirror 15 redirects the signals toward a radio frequency (RF) receiver circuit that converts the incoming RF signals into intermediate frequency (IF) signals. A backing structure 25 supports the antenna 10 and prevents minor deformation of the primary mirror 15. Various motors, bearings, and gear assemblies allow elevation and rotation of the antenna 10.

As described above, the antenna’s primary mirror 15 is subject to mechanical deformation and vibration from a variety of sources, including redistribution of gravitational
FIG. 2 illustrates a technique for automatically detecting and compensating for deformation and vibration of the antenna. A laser source is placed at or near the focal point of the primary mirror. At least one optical sensor is placed on the primary mirror to receive a portion of the beam generated by the laser source. As described below, the optical sensor produces signals that are used by a signal processing circuit in measuring the sensor’s displacement with respect to the laser source in three dimensions. These changes are usually caused by the deformation of the primary mirror. In some embodiments, one or more optical sensors, or “reference” sensor placed at or near the laser source generates signals that assist in measuring deformation in the antenna. An optical head, which typically includes one or more beam splitters, directs portions of the laser beam to the sensors.

As signal correction device, such as a deformable mirror or a wave front correcting device, is placed in the path between the antenna’s secondary mirror and the RF receiving circuitry. The correction device compensates for deformation in the antenna by changing the shape of the incoming wave front in response to this deformation. An electronic controller, such as a programmable controller, generates a control signal that alters the characteristics of the correction device as the deformation in the antenna varies.

FIG. 3 shows one type of photo sensor that is suited for use in deriving 3D displacement information. This photo sensor is a conventional high-resolution, 2D displacement-type or position-type photo sensor having two pairs of Schottky-barrier contacts comprising Schottky photodiodes. The contacts enclose a two-dimensional photosensitive area exposing a semiconductor surface.

An optical signal impinges on the semiconductor surface, the contact pairs in each pair enclose a twodimensional secondary mirror as long as the mirror is formed from a material. As the deformation increases, the signals from the photo sensor are used to derive information about the surface-of-interest, such as the primary mirror of an earth-bound antenna, for which displacement information is needed. Another displacement sensor, or “reference” sensor mounted near the reference sensor before it reaches the other sensor.

FIGS. 6A and 6B illustrate one technique for using the hardware configuration for use in deriving displacement from a 2D displacement sensor. The displacement sensor is mounted near the reference sensor at a position that is fixed with respect to the reference sensor. In an earth-bound application, the reference mirror is usually very near the antenna’s secondary mirror. A laser source mounted near the reference sensor at a position that is fixed with respect to the reference sensor.

The beam emitted by the laser source passes through a beam splitter that directs a portion of the beam toward the reference sensor and a portion toward the sensor. The laser source emits a stream of pulses, instead of a continuous beam. This causes the two sensors to produce pulsed output signals. Because the laser source is closer to the reference sensor than it is to the sensor, the laser pulse reaches the reference sensor before it reaches the other sensor. This causes a delay between the signal pulses produced by the two sensors. A signal processing circuit is connected to receive the pulsed output signals from the sensors and measures displacement of the surface-of-interest in the z-direction by calculating changes in this delay. An electronic controller controls the pulse modulation of the laser beam.
when the deformation of the surface is at a minimum. In doing so, the processing circuit receives a signal pulse from the reference sensor 160 in response to a laser pulse generated by the laser source (step 200). Upon receiving the signal pulse, the processing circuit starts a timer (205). A short time later, the processing circuit receives a corresponding signal pulse from the sensor 150 mounted to the surface-of-interest (step 210). The processing circuit stops the timer upon receiving this signal pulse (step 215) and then stores the timer value as the reference time delay \( T_{REF} \) (step 220).

In detecting and measuring subsequent displacement of the surface-of-interest with respect to the reference surface, the processing circuit receives a series of signal pulses generated by the reference sensor 160 in response to a series of laser pulses from the laser source (step 225). The processing circuit starts the timer upon receiving each of these signal pulses (step 230). For each signal pulse received from the reference sensor 160, the processing circuit receives a corresponding signal pulse from the sensor 150 mounted to the surface-of-interest (step 235). The processing circuit stops the timer upon receiving each of these signal pulses (step 240) and, upon stopping the timer, stores the timer value as the current time delay \( T \) between signal pulses (step 245). The processing circuit clears the timer after each of these signal pulses (step 250).

For each pair of corresponding pulses from the two sensors, the processing circuit calculates the difference \( T_{A} \), between the time delay \( T \) for those pulses and the reference time delay \( T_{REF} \) (step 255). The processing circuit uses this difference \( T_{A} \) to calculate the displacement \( D \) of the surface-of-interest in the z-direction (step 260), applying the following equation:

\[
D = C_{av} \cdot \Delta T,
\]

where \( C_{av} \) represents the velocity of light in air.

FIG. 7 shows an alternative technique for measuring displacement along the z-axis. Instead of using a timer to measure delay between the signal pulses from the reference sensor 160 and the target sensor 150, this technique applies a correlation algorithm to detect misalignment between the signal pulses. In this embodiment, the system includes a correlation element 162 connected to receive the signal pulses from the sensors 150, 160. A delay element 164 is placed between the reference sensor 160 and the correlation element 162.

The delay element 164 applies a time delay that, when the surface-of-interest is experiencing no deformation, causes each signal pulse from the reference sensor 160 to reach the correlation element 162 at the same time as the corresponding signal pulse from the target sensor 150. When no deformation exists, the correlation element 162 produces an output signal having a value indicating that the two signal pulses are aligned. When deformation does exist, the signal pulses do not align, and the value of the output signal from the correlation element 162 indicates the amount of decorrelation between the two signal pulses. This decorrelation value provides a direct indication of the deformation of the surface-of-interest. Common technologies for implementing the correlation element 162 include digital electronic circuitry and program code executed by a programmable processor.

FIG. 8 shows another hardware configuration for use in deriving 3D displacement information from a 2D displacement sensor 300. In this configuration, the displacement sensor 300 is mounted to the surface-of-interest 305, and a laser source 310 is mounted to a reference surface 315. The laser source 310 emits a frequency-modulated beam.
A method for use in measuring physical displacement in three dimensions comprising:

1. A system for use in measuring physical displacement in three dimensions comprising:

   - an optical signal source configured to produce an optical signal having a characteristic feature that varies with distance traveled by the optical signal;
   - a target optical sensor positioned to receive at least a portion of the optical signal and configured to produce an output signal indicating a position at which the optical signal strikes the sensor in each of the third orthogonal dimensions, indicate a position at which the optical signal strikes the sensor in each of two orthogonal dimensions, where the target sensor is subject to displacement in a third orthogonal dimension; and
   - circuitry connected to receive the output signal and configured to:
     - derive information about the characteristic feature of the optical signal at the target sensor;
     - apply the information in calculating a linear distance traveled by the optical signal in the third orthogonal dimension; and
     - derive from the linear distance an amount by which the target sensor has been displaced in the third orthogonal dimension.

2. The system of claim 1, wherein the characteristic feature that varies with linear distance traveled is phase.

3. The system of claim 2, further comprising a storage device containing information that indicates a nominal time elapsed when no displacement of the target sensor has occurred.

4. The system of claim 2, further comprising a reference sensor positioned a predetermined linear distance from the optical signal source and configured to produce an output signal upon receiving a portion of the optical signal.

5. The system of claim 4, wherein the circuitry is configured to calculate time elapsed between creation of an output signal by the reference sensor and creation of an output signal by the target sensor.

6. The system of claim 1, wherein the characteristic feature that varies with linear distance traveled is phase.

7. The system of claim 6, wherein the circuitry includes a component configured to calculate phase of the optical signal at the target sensor with respect to a reference phase.

8. The system of claim 7, wherein the circuitry includes a component configured to measure phase of the optical signal at a reference position that is separated from the optical signal source by a predetermined linear distance.

9. The system of claim 1, wherein the circuitry includes a correlation element configured to produce an output signal indicating an amount of correlation between the characteristic feature of the optical signal at the target sensor and the characteristic feature of the optical signal at a reference point.

10. A method for use in measuring physical displacement in three dimensions comprising:

    - producing an optical signal having a characteristic feature that varies with distance traveled by the optical signal;
    - directing at least a portion of the optical signal toward a target optical sensor, where the target sensor has a photosensitive surface that is subject to displacement in a direction orthogonal to the photosensitive surface, and where the target sensor generates an output signal indicating a position at which the optical signal strikes the photosensitive surface;
    - receiving the output signal from the target sensor;
    - deriving information from the output signal about the characteristic feature of the optical signal at the target sensor;
    - using the information in calculating the distance traveled by the optical signal; and
    - deriving from the linear distance an amount by which the target sensor has been displaced in the direction orthogonal to the photosensitive surface of the target sensor.

11. The method of claim 10, wherein the characteristic feature that varies with linear distance traveled is actual time elapsed between a selected reference time and a time at which the optical signal strikes the target sensor.

12. The method of claim 11, further comprising receiving a signal indicating an amount of time over which the optical signal travels between the optical signal source and a reference sensor and applying the amount of time as the selected reference time.

13. The method of claim 12, further comprising calculating time elapsed between creation of an output signal by the reference sensor and creation of an output signal by the target sensor.

14. The method of claim 10, wherein the characteristic feature that varies with linear distance traveled is phase.

15. The method of claim 14, further comprising calculating phase of the optical signal at the target sensor with respect to a reference phase.

16. The method of claim 15, further comprising measuring phase of the optical signal at a reference position that is separated from the optical signal source by a predetermined linear distance.

17. The method of claim 10, further comprising producing an output signal indicating an amount of correlation between the characteristic feature of the optical signal at the target sensor and the characteristic feature of the optical signal at a reference point.
It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1,
Lines 11-17, please delete “STATEMENT AS TO .....elected to retain title.”

Signed and Sealed this
Eighteenth Day of February, 2003

JAMES E. ROGAN
Director of the United States Patent and Trademark Office