NASA/TM—2005–214186

Advanced Sensor Concepts
(MSFC Center Director's Discretionary Fund Final Report, Project No. 03–11)

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September 2005

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National Aeronautics and
Space Administration

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ACRONYMS

ac	alternating current
ALS	absolute limit sensor
ASC	advanced sensor concepts
CDDF	Center Director's Discretionary Fund
DMM	digital multimeter
GapSyn	gap sensor/synchronization
g-LIMIT	Glovebox Integrated Microgravity Isolation Technology
MEMS	microelectromechanical systems
mSCAPS	metal single-coil absolute position sensor
MSFC	Marshall Space Flight Center
PWB	printed wiring board
RPS	rotary position sensor
SCAPS	single-coil absolute position sensor
SRA	short range antenna

TECHNICAL MEMORANDUM

ADVANCED SENSOR CONCEPTS
(MSFC Center Director's Discretionary Fund Final Report, Project No. 03–11)

1. INTRODUCTION

The purpose of this Technical Memorandum is to fulfill the requirements of the Center Director's Discretionary Fund (CDDF) project and document the success of this effort. The original effort that started this project is the development of a position sensor technology for the Glovebox Integrated Microgravity Isolation Technology (g-LIMIT) project. The dual axis position sensor developed for the g-LIMIT project was patented under U.S. Patent No. 6,246,228.[1] This patented position sensor is used in the g-LIMIT flight project for position sensing. The other sensor concepts developed in this CDDF stem from that original patent. Another patent being studied under this CDDF project is the rotary position sensor (RPS), U.S. Patent No. 6,313,624.[2] These technologies have been demonstrated at several sensor tradeshows during the past few years, and partners for commercialization are currently being sought. Copies of the first page of these patents are included in appendices A and B, respectively.

The CDDF was solicited to continue development of the sensor concepts. The base objective of the advanced sensor concepts (ASC) CDDF was to develop two novel sensor concepts based on the aforementioned patents and refine the capabilities of the RPS: (1) A low-cost, rugged, absolute linear position sensor, and (2) an absolute limit switch for general-purpose applications. Due to the patent process, the technologies developed with this CDDF cannot be fully detailed. In addition, test data and specific design information that would normally be included in appendices to this report are intentionally omitted. This information is available with appropriate authorization. To date, the investigators have developed and submitted seven technology disclosures based on the original patents. These technologies are currently in the patent process at the Marshall Space Flight Center (MSFC).

2. DESCRIPTION

2.1 Basic Sensor and Testing

All the technologies developed with this effort utilize a sensor unit that consists of only two active components: (1) A sensor coil and (2) an excitation coil. To allow multiple iterations for a single sensor concept, the sensor coil printed wiring board (PWB) was designed with multiple coils. The prototype sensor coils were fabricated on a PWB that was manufactured with Kapton® foil as the base material. Although a fully developed sensor would have multiple layers to provide more access to the individual sensor signals, single-layer coils were produced. These PWBs would be mounted on a rigid material to permit sensor configuration switching during testing. Figure 1 is a picture of the active sensor components, and figure 2 shows the sensor coil PWB mounted to a rigid base board. Figure 3 is a picture of the test fixture for testing the linear sensor. The linear test setup has the ability to move in 0.1-µm steps. This resolution provides the basis for specifying the overall accuracy of the sensor technology.

Figure 1. Sensor active components.

The prototype sensors were using an automated test system that moves the excitation coil, records the position, and then moves to the next position. This automated tester allows multiple runs to be analyzed together without having to recalibrate the system. Various sensor configurations were

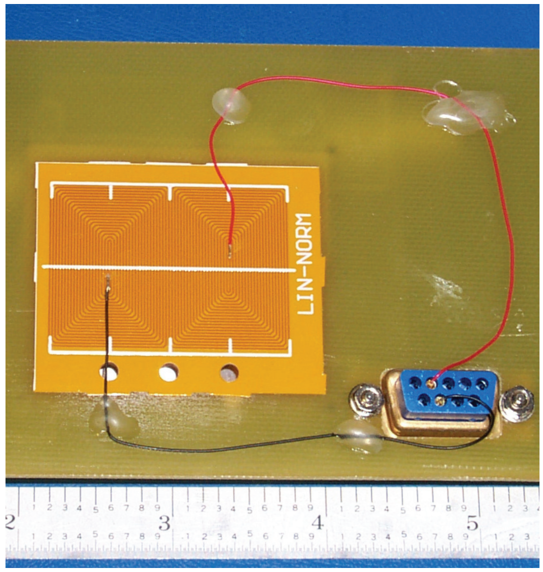

Figure 2. Sensor coil mounted to rigid base board.

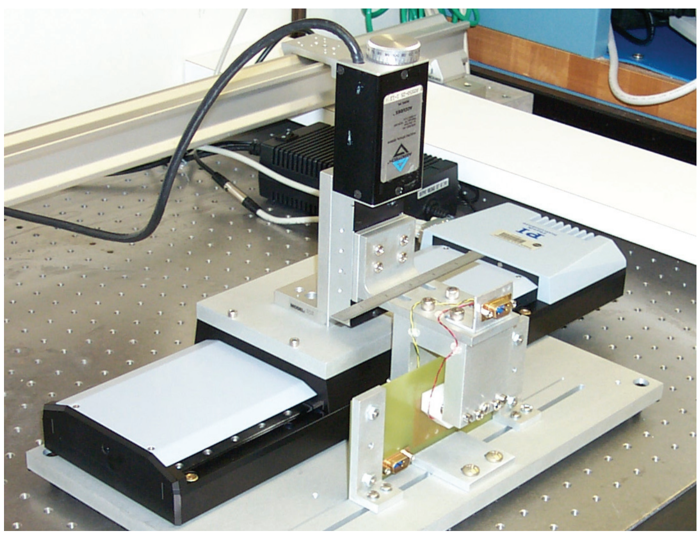

Figure 3. Test fixture setup.

tested, and these data were used to determine the best sensor coil configuration. The plot shown in figure 4 presents several data runs for a specific sensor prototype. In the plots, note that data from each run follow the same trend and that the difference between a straight line and the data is the sensor error and, thus, the accuracy of the sensor.

Analyzed data from those tests are discussed in this paragraph. Table 1 lists the test results for a specific sensor. These data present the accuracy of the sensor by stating the maximum, average, and standard deviation errors with respect to a straight line. In addition, these data are analyzed for

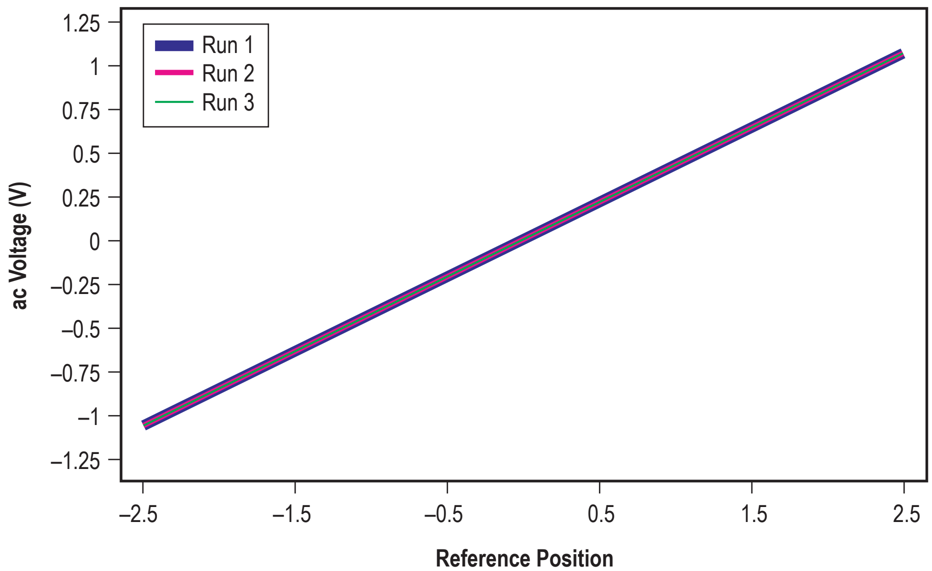

Figure 4. Typical multirun sensor data plot.

Table 1. Sensor capabilities.

	Run/Run	Accuracy
Correlation	0.9999999	N/A
Max error	1.72 μm	3.7 μm
Average error	0.59 μm	0.86 μm
Standard deviation	0.41 μm	0.67 μm

run-to-run correlation. Correlation of data from run to run is important for sensor repeatability. If a sensor has a high correlation from run to run, then it is possible to improve the accuracy by calibrating the sensor to a nominal calibration curve. An explanation of correlation significance is necessary. When analyzing data sets for correlation, changing only one data point from one data set reduces the correlation from 0.9999999 to 0.99995. The second value, 0.99995, is still a good correlation, but the closer to 1—from run to run—the better the ability to produce accurate results from sensor calibration.

During the testing phase of this CDDF, an unusual anomaly was detected with the data. Figure 5 shows a magnified example of the anomaly. Several configurations were tested, and every sensor produced the anomaly. When the test equipment parameters were changed, the anomaly changed scale. After much analysis, it was determined that the anomaly was due to the capabilities of the digital multimeter. (DMM) The DMM was used as a voltmeter in the alternating current (ac) range. The minimum voltage in this frequency range that can be accurately measured is around 0.1 μV. Below this value, the DMM loses gain, and therefore, the sensor appears to have a significant problem around null. To correct for this anomaly, data around null has been numerically corrected for the accuracy analyses. The analysis of correlation utilizes the raw uncorrected data, and thus, the repeatability of the sensor is as stated in table 1.

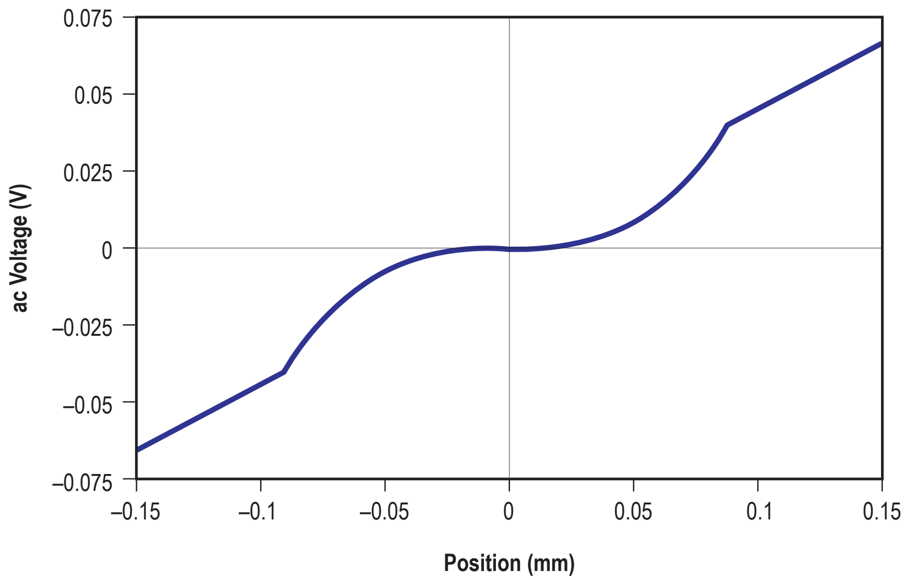

Figure 5. Anomaly caused by DMM.

2.2 Sensor Derivatives

The first sensor developed in this CDDF is a low cost, rugged, absolute linear position sensor. The base sensor concept is known as the single-coil absolute position sensor (SCAPS). This basic sensor component can be utilized in many different configurations. Each of the other technologies developed during this project will be briefly discussed, but due to patent filing restrictions, full technological disclosure is limited.

2.2.1 Gap Sensor/Synchronization Winding Technology

The SCAPS sensor has the ability to measure linear position, but by adding the gap sensor/synchronization (GapSyn) winding to the base sensor, other axes of measurement can be detected. This second winding can be used to not only measure the gap between the base sensor and excitation source but also act as a method for transferring the base frequency to the signal conditioning electronics. This GapSyn winding does not have to be present for the base sensor concept to operate, but by combining the two technologies, the excitation or reference signal is wirelessly transmitted to the sensor coil side of the device.

2.2.2 Metal Single Coil Absolute Position Sensor

During the testing phase of the SCAPS sensor concept, it was theorized that there might be a method of shielding the unused portion of the winding from the excitation source. This proved to be unsuccessful, but during this testing, it was discovered that the shield acts as a method of enhancing the base sensor's accuracy. This modified sensor was termed the metal SCAPS (mSCAPS). The mSCAPS innovation improved the sensor's linearity and significantly increased the signal-to-noise ratio. This technology innovation could be used to make similar improvements to the already patented RPS technology.

Addition of metal to the base sensor does not change the ability of the original sensor to function. There may be applications where addition of the metal is undesirable and the original sensor will function, albeit less accurately.

2.2.3 Short Range Antenna

While testing the sensor, it was theorized that the components that make up the sensor can be utilized to transmit data across the gap. This makes the sensor windings function as a short range antenna (SRA). The SRA function can be used in parallel to transfer data while the base sensor is operating, or the SRA function can be multiplexed with the position sensor function.

2.2.4 Absolute Limit Sensor

The absolute limit sensor (ALS) is a combination of the base sensor technology with a limit switch. This combination provides the functions of a noncontact limit switch with the position information from the sensor. This combination is very useful when comparing to current limit switch technology. Limit switches are generally used to define end-of-travel and home locations. Generally, limit switch technology is not precise enough to determine the exact location of the system when the switch is activated. This ALS combination provides an inexpensive method for determining the precise position on the limit switch being operated without the need for another position sensor in the system. Since the ALS provides absolute position information, is not necessary on startup to send the system to a predefined home location. The sensor would provide accurate position information on restart even if the system has moved during down periods.

2.2.5 Single Coil Absolute Position Sensor Digital Signal Conditioning Electronics

The SCAPS digital signal conditioning electronics are a novel electronic circuit. This circuit is used to signal condition the output of any of the previous technologies. This technology innovation affords more flexibility and accuracy than any prior signal conditioning technology. These electronics enable the system to include look-up tables with calibration curves. This allows the manufacturer to calibrate the unit prior to delivery, and increase accuracy. Also, it provides the capability of recalibrating the system post assembly.

2.3 Rotary Position Sensor

In this CDDF, the advances to RPS technology were mainly focused on achieving a brushless design. For a complete discourse of the RPS technology, reference is made to U.S. Patent No. 6,313,624. Several different rotary transformers were acquired and subsequently tested. The intended use of the rotary transformer was to transfer the excitation to the rotor of a shaft. The resultant use is to return the sensor coil data from the rotor. In the original design of the RPS unit, the excitation signal was transferred to the rotor via a slip ring.

Rotary transformer testing indicated that the load from the excitation inductor was too great for transmitting significant signal strength. This is important since signal magnitude is the means by which the sensor coil operates. The greater input signal, the more output signal is developed and thus, greater the ability to measure absolute position developed from the output signal. Due to this, several rotary transformers were designed and tested to achieve an optimal transformer design/winding ratio that would be able to transfer the excitation signal to the rotor. Figure 6 is a picture of the rotary transformers during testing. Unfortunately, these efforts were also unsuccessful in generating sufficient output signal.

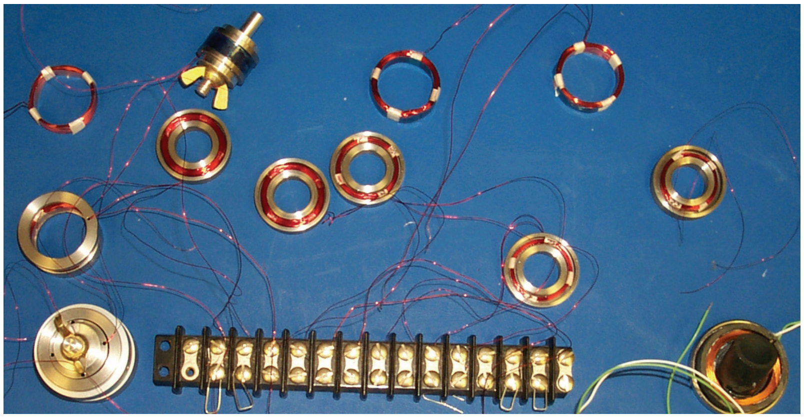

Figure 6. Rotary transformers.

Therefore, it became necessary to redesign the RPS in order to place the sensor coil on the rotary shaft. This design effort is dependent on a multicoil rotary transformer. These multicoil rotary transformers are common in video cassette recorders and digital audio/video tapes. The manufacturers of these units are overseas, and through much effort, several units were acquired. Figure 7 is a picture of the multicoil rotary transformers. These transformers have two or four channels for transmitting data across the rotary interface. The redesign of the brushless RPS unit is still in process.

Figure 7. Multicoil rotary transformers.

During the CDDF, a third rotary sensor based on the basic sensor coil was developed. This design was developed for an army prototype missile program. Details about the design are confidential, and therefore, any specific detail is not included. This rotary sensor design is a limited angle sensor, ±90°. Originally this sensor design was to utilize a rotary transformer. Due to the rotary transformer design problems, the decision to utilize a miniature pancake slip ring was made. This sensor configuration has been tested in the laboratory at MSFC. The accuracy of this sensor is 10–12 bits over ±90°. Similar to the basic sensor, this configuration also has a high degree of correlation from run to run. The correlation valve for this rotary sensor design is 0.9999996. Figure 8 is a picture of the rotary sensor testing.

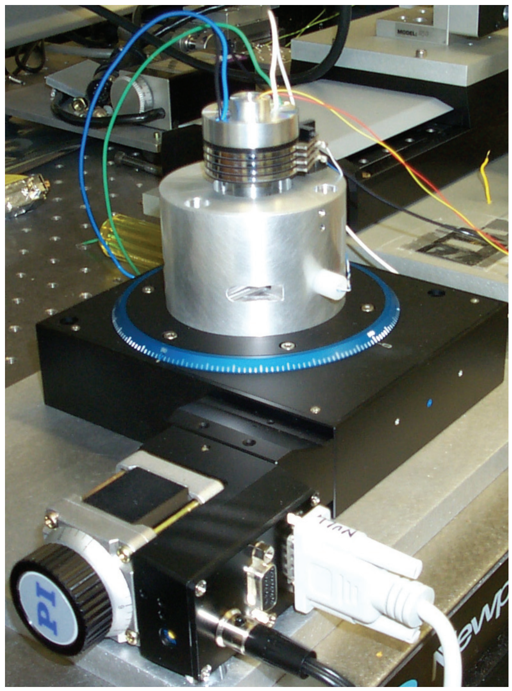

Figure 8. Rotary sensor testing.

2.4 Sensor Applications

Applications of this novel sensor technology have just started to materialize. The sensor components can be utilized as a microposition sensor with the technology as originally developed. If the sensor components were buried in layers of carbon composite, component movement may detect interlayer separation. This concept can be used as a nondestructive test to determine the carbon composite lattice structure integrity. Similarly, the components could be buried inside a structure to provide measurements of internal component motion. The sensor components can be activated, and the information can be transmitted to a remote monitoring location.

This sensor concept was also the basis for a proposal that used the sensor to measure the gap between beams or panels during automated assembly. Multiple sensors would provide the means for determining the position and orientation between two major structural components. If the components were not in the proper alignment or were attempted to be incorrectly assembled, the sensor technology would inhibit improper assembly. Post assembly, the sensor would provide position measurement of the joint and would provide the ability to detect if structural integrity was being compromised. The SRA function provides the ability to transfer data between the major components without the need for direct connections. The SRA function would also be utilized during initial assembly to transfer other assembly information as required. This sensor application was presented in a conference paper for the Space Technology Applications International Forum in February 2005.[3] Figure 9 is an illustration of the concept for space- and moon-based operations.

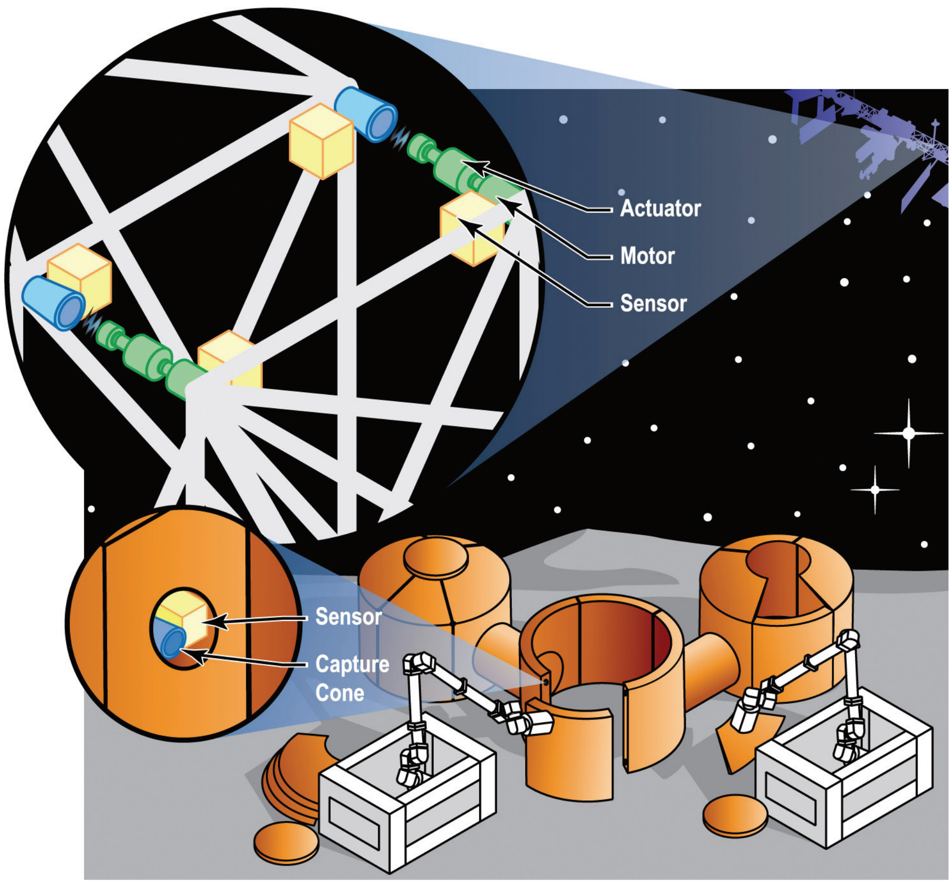

Figure 9. Autonomous assembly concept.

3. CONCLUSIONS AND RECOMMENDATIONS

The ASC project has been a remarkable success. Using the CDDF to develop these concepts into reality has contributed to the potential migration of these sensors into several useful products. The investigators have developed a new absolute linear sensor technology that has great promise to be utilized in a wide range of applications. This sensor technology has only two active components and can be reconfigured as the application warrants. In addition, the investigators have developed five other novel sensor related technologies plus one other signal conditioning electronics technology. These innovations have been submitted for patent application. The RPS is currently under redesign in order to incorporate a brushless transformer and mSCAPS technology. The inclusion of the rotary transformer will increase the market for this sensor configuration, and it is expected that the inclusion of the concepts used in mSCAPS technology will significantly improve the linearity and signal-to-noise ratio of the RPS. Finally, another rotary sensor design has been identified and is currently being developed for an army missile program. This sensor technology is the basis for a proposed autonomous assembly of a modular structures concept that will enable the realization of building large structures in space, on the Moon, or on Mars.

The SCAPS sensor combines several functions into a single sensor unit. This simplifies the number of active components in the system and, thus, increases reliability. The basic sensor is a simple two-component device that can be reconfigured as the user requires. Because of its simplicity, the SCAPS technology is inherently inexpensive to manufacture and can, therefore, be widely utilized without significant cost. Also, the simplicity allows multiple units to work in the same location. This configuration provides redundancy and increases reliability even more. All this simplicity belies the sensor's accuracy. This sensor technology can provide absolute repeatable measurements accurate to 1 µm and can be configured as a two- or three-dimensional sensor along with additional capabilities, such as the SRA. This technology has the potential to be microminiaturized for use in microelectromechanical systems (MEMS). This will provide the capability to measure motion inside a MEMS device.

It is the investigator's belief that the CDDF process has provided the initial impetus to bring about the realization of this sensor technology. It is recommended that continued development of this sensor technology and related applications of the technology be pursued. This sensor technology has the potential to become a new class of linear and rotary sensors, which would compete well in current linear and rotary sensor markets. In addition, this sensor technology is unique with its low cost, light weight, and relatively unobtrusive implementation. The sensors have the ability to be incorporated into locations where current linear sensors cannot be utilized or are impractical for cost reasons.

APPENDIX A—UNITED STATES PATENT 6,246,228

US006246228B1

(12) **United States Patent**
Alhorn et al.

(10) **Patent No.: US 6,246,228 B1**
(45) **Date of Patent: Jun. 12, 2001**

(54) **NON-CONTACT LINEAR ACTUATOR POSITION SENSOR HAVING A PID-COMPENSATING CONTROLLER**

(75) Inventors: **Dean C. Alhorn**, Huntsville; **David E. Howard**, Hazel Green, both of AL (US)

(73) Assignee: **The United States of America as represented by the Administrator of the National Aeronautics and Space Administration**, Washington, DC (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/209,363**

(22) Filed: **Nov. 27, 1998**

(51) **Int. Cl.**[7] **G01B 7/14**; G01B 1/06; G01R 33/025

(52) **U.S. Cl.** **324/207.12**; 324/207.17; 318/653

(58) **Field of Search** 324/207.17, 207.12, 324/207.19; 318/633, 956

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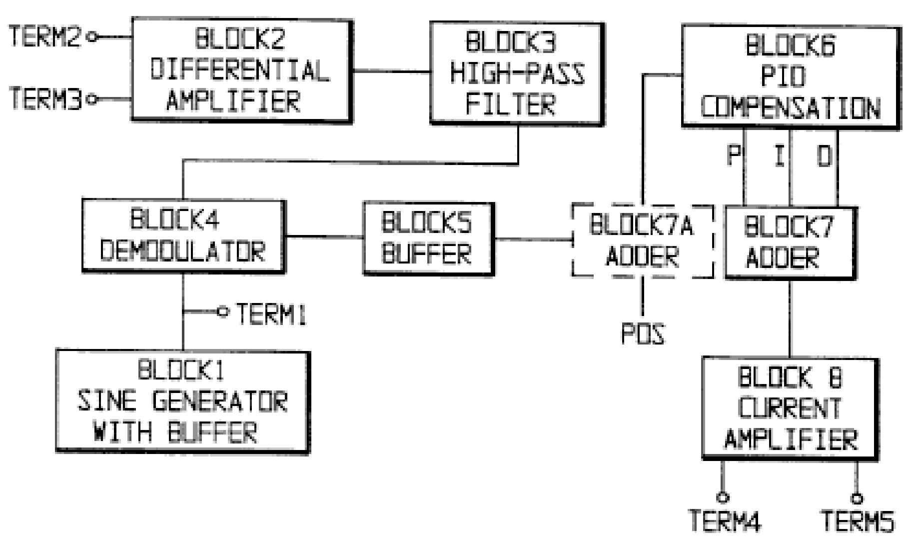
Primary Examiner—Walter E. Snow
(74) *Attorney, Agent, or Firm*—James J. McGroary

(57) **ABSTRACT**

A position sensor or controller generates a response signal in existing armature windings of an actuator and detects the response signal to determine the position of the armature. To generate the response signal, the actuator includes a sensor excitation winding near the armature. Two sensor excitation windings can be provided, above and below the armature, to cancel out z components and thus allow for a variable gap. The sensor excitation winding or windings are supplied with an excitation signal to induce the response signal in the armature windings. The response signal is derived by differentially amplifying and frequency filtering a raw output of the armature windings. The response signal is demodulated to determine position. If a position controller rather than a mere sensor is desired, the position signal can be buffered, PID compensated, amplified, and fed back to the armature windings.

11 Claims, 5 Drawing Sheets



APPENDIX B—UNITED STATES PATENT 6,313,624

US006313624B1

(12) **United States Patent**
Alhorn et al.

(10) **Patent No.: US 6,313,624 B1**
(45) **Date of Patent: Nov. 6, 2001**

(54) **POSITION SENSOR WITH INTEGRATED SIGNAL-CONDITIONING ELECTRONICS ON A PRINTED WIRING BOARD**

(75) Inventors: **Dean C. Alhorn**, Huntsville; **David E. Howard**, Hazel Green; **Dennis A. Smith**, Athens, all of AL (US)

(73) Assignee: **The United States of America as represented by the Administrator of the National Aeronautics and Space Administration**, Washington, DC (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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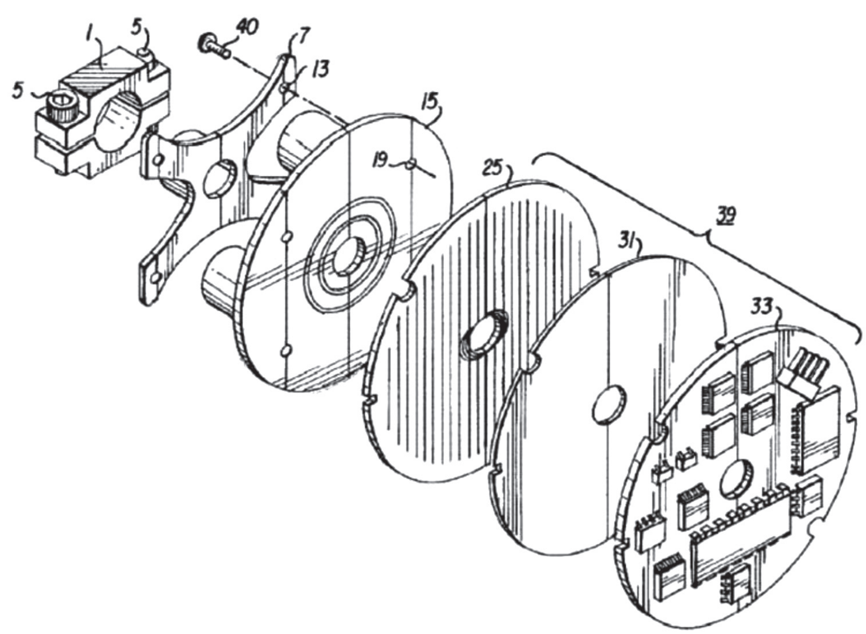
Primary Examiner—Gerard R. Strecker
(74) *Attorney, Agent, or Firm*—James J. McGroary

(57) **ABSTRACT**

A position sensor, such as a rotary position sensor, includes the signal-conditioning electronics in the housing. The signal-conditioning electronics are disposed on a printed wiring board, which is assembled with another printed wiring board including the sensor windings to provide a sub-assembly. A mu-metal shield is interposed between the printed wiring boards to prevent magnetic interference. The sub-assembly is disposed in the sensor housing adjacent to an inductor board which turns on a shaft. The inductor board emanates an internally or externally generated excitation signal that induces a signal in the sensor windings. The induced signal represents the rotary position of the inductor board relative to the sensor winding board.

3 Claims, 5 Drawing Sheets



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13. ABSTRACT *(Maximum 200 words)* The Advanced Sensor Concepts project was conducted under the Center Director's Discretionary Fund at the Marshall Space Flight Center. Its objective was to advance the technology originally developed for the Glovebox Integrated Microgravity Isolation Technology project. The objective of this effort was to develop and test several new motion sensors. To date, the investigators have invented seven new technologies during this endeavor and have conceived several others. The innovative basic sensor technology is an absolute position sensor. It employs only two active components, and it is simple, inexpensive, reliable, repeatable, lightweight, and relatively unobtrusive. Two sensors can be utilized in the same physical space to achieve redundancy. The sensor has micrometer positional accuracy and can be configured as a two- or three-dimensional sensor. The sensor technology has the potential to pioneer a new class of linear and rotary sensors. This sensor is the enabling technology for autonomous assembly of modular structures in space and on extraterrestrial locations.			
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