

METHOD AND SYSTEM FOR OPTICAL DISTANCE AND ANGLE MEASUREMENT

FIELD OF THE INVENTION

The present invention relates generally to the field of sensors, and more
5 specifically, to the use of fiber optic sensors for determining spatial distance,
speed and relative angular displacement of a moveable object.

BACKGROUND OF THE INVENTION

In the commercial and defense industries, users are demanding
technology integration that increases product life, simplifies operation and
10 maintenance, and provides integration that improves safety and reliability.
However, any technology offered must also support a positive, quantitative
cost/benefit analysis.

Fiber optic sensors have been used for the measurement of relative
position for decades, but, until the present invention, their utility has not been
15 extended to self-calibrating, precision absolute, position measurement systems.
While conventional systems using fiber optic sensors offer only a relative
measurement capability, they usually require repetitive calibration between uses
because they are sensitive to the angle of the surface being measured and the
distance between the sensor and the surface being measured. Indeed, some of
20 those skilled in the art may believe that precision absolute position
measurement systems could not be accomplished with fiber optic sensors.

Most sensor prognostic systems require exorbitant amounts of
processing power for determining statistical probabilities or require precise

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measurements of physical properties for which current sensor technology does not exist. For example, in prognostic measurements of a moveable shaft (such as may be found in an aircraft engine or similar vehicle engine), the operational characteristics of the shaft must be known to ensure safe aircraft operation. Some operational characteristics required include monitoring of shaft lateral displacement, shaft misalignment, shaft speed and torque, all characteristics which are difficult or impossible to capture with current non-contact sensor technology. These characteristics may be necessary to determine in such applications as turbogenerators, power generation stations, ships, submarines and earth moving equipment.

The need to measure drive shaft alignment has existed for some time. In flexible or fairly rigid structures, a moveable shaft (for example, one that is rotating) can move out of alignment, bend beyond its stress points or move off a set axis, thereby resulting in a damaged structure, engine or system. For example, aircraft safety depends in part on determining the drive's operational characteristics as torque is transmitted to any engine component. Further, the shaft's attitude and bending characteristics needs to be non-invasively measured, as well as the shaft's rotational speed and torque. Movement, either from the shaft attitude or the bending, needs to be measured to less than 0.254 mm and the RPM and the torque further needs to be monitored.

Two known previous technical approaches to measuring and monitoring the shaft have been unsuccessful. For example, Lucent

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Technologies attempted to use an eddy-current sensor, however, measurements based on

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eddy-current sensing did not provide the accuracy, environmental tolerance, or robustness required for this or similar applications. Others have attempted
5 a design concept that required a magnetic slug embedded in the torque couplers. However, this method similarly proved unsuccessful.

DE-A-4 403 401 is an angular position measuring device for the measurement of a rotational angle of a shaft. That is, the apparatus continuously measures an angular position from 0 to 360 degrees in shaft
10 rotation. The device does not measure absolute distance and relative angular displacement or planar angles of a surface position on a rotating object relative to a measuring device or optical sensor assembly as in the present invention.

Thus, there is a need for a non-obtrusive system that optically measures
15 movement of a large drive shaft or torque coupler in the confined space of an engine such as, for example, an aircraft. The sensor system must not interfere with airflow into the engine, and must accommodate various environmental conditions (such as, for example, high vibration, shock and high temperature conditions). Preferably, the sensor must also be placed between 3.18 mm and
20 12.7 mm from a surface of the face of the drive shaft or coupler assembly due to space constraints. The sensor system must also be capable of capturing absolute measurement of the shaft's movement without calibration. Moreover, the measurement data obtained by the sensor system should be capable of determining movement of 0.254 mm or less in the application as the shaft
25 rotates up to 9000 revolutions per minute (RPM). The system should also

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preferably measure rotation of the shaft at greater than 9000 RPM as well as twisting of the moveable shaft in order to calculate torque. The system should also be able to measure absolute distance from each sensor to a surface on the torque coupler knowing that the surface may vary not only in axial distance away from the sensors but also in complex angles relative to the sensors. The ability to non-obtrusively measure absolute movement versus relative movement, high-resolution shaft displacement, and twisting in the moving shaft has never been accomplished before the present invention.

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A self calibrating, precision absolute position measuring system, such as disclosed in the present invention, is also supported by the defense community. The Secretaries of the Army, Navy and Air Force have all directed, by policy, that new procurements must incorporate diagnostic and prognostic system health management prior to funding approval. This has been emphasized in new development programs including the Crusader for the Army, the Advanced Amphibious Attack Vehicle for the Marines, and the Joint Strike Fighter (JSF) for the joint services. However, until the present disclosure, there was a gap between the need and the technology available to meet that need.

10 **BRIEF SUMMARY OF THE INVENTION**

The following summary of the invention is provided to facilitate an understanding of some of the innovative features unique to the present invention, and is not intended to be a full description. A full appreciation of the various aspects of the invention can only be gained by taking the entire specification, claims, drawings, and abstract as a whole.

The present invention comprises a non-invasive precision, optical distance and angle measurement system which optically measures the position of a moveable object (such as a shaft in an engine), the bending of the moveable object, the torque applied to the object and the object's rotational velocity. The present invention includes a plurality of optic sensors placed around and adjacent to the object which transmit optic signals via fiber optic bundles to a target marker means on a surface of the object and receives the optic signals when the target marker means are sensed. The

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received optic signals are then processed by non-linear estimation techniques known to those of skill in the art to obtain the desired information. The present invention is intended for vehicular engines (such as are found in commercial or military aircraft), but can be applied to other applications, such as, for examples, in tanks, power generation equipment, shipboard power plants and other applications requiring moveable machinery.

The novel features of the present invention will become apparent to those of skill in the art upon examination of the following detailed description of the invention or can be learned by practice of the present invention. It should be understood, however, that the detailed description of the invention and the specific examples presented, while indicating certain embodiments of the present invention, are provided for illustration purposes only because various changes and modifications within the spirit and scope of the invention will become apparent to those of skill in the art from the detailed description of the invention and claims that follow.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying figures, in which like reference numerals refer to identical or functionally-similar elements throughout the separate views and which are incorporated in and form part of the specification, further illustrate the present invention and, together with the detailed description of the invention, serve to explain the principles of the present invention.

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Figure 1 is a side perspective view of one embodiment of the present invention attached to a mounting structure which partially surrounds a moveable shaft attached to a torque coupler;

5 Figure 2 graphically illustrates the response curve from a commercially available fiber optic concentric ring-type sensor;

Figure 3 is a three-dimensional plot of the response of a concentric ring fiber optic sensor. This shows the sensitivity of the sensor to distance and angle variations and shows the non-linear characteristics of the sensor to
10 these variations.

Figure 4a is an end view of a torque coupler with attached multifaceted target markers, which, when the coupler moves, pass in front of sensor assembly means to provide signals for processing;

Figure 4b illustrates the multifaceted target markers as shown in Figure
15 4a;

Figure 5 is a block diagram of the signal processing functions required to derive the coupler attitude information from voltages sensed by the sensor assembly means as each target marker passes each sensor assembly means;

Figure 6 is a system diagram illustrating a preferred sensor estimator
20 shown in Figure 5.

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DETAILED DESCRIPTION OF THE INVENTION

The present invention is a precision, non-invasive optical distance and angle measurement system which, by a plurality of sensor assembly means, transmits optical signals to predefined surface areas on a moveable torque coupler or like structure, measures the reflectance of the optical signals and
5 by a signal processing software means which accounts for the sensor and target models, and processes the desired information relating to the shaft's operational characteristics.

Referring to Figure 1, the present invention includes a plurality of optic
10 sensor assembly means $11_1 - 11_n$ placed on at least one mounting structure 21 adjacent to a torque coupler 31 which engages and surrounds a moveable shaft S; at least one stepped target marker means 33_n attached preferably to a surface 35 of the torque coupler 31 or alternatively directly to a surface of the shaft S; control electronics 41 communicating with each optic sensor
15 assembly means 11_n via communications bus 43; and signal processing software means 51 loaded and stored in control electronics 41.

As seen in Figure 1, each sensor assembly means 11_n is attached to a mounting structure 21 of conventional design which is proximately adjacent to a torque coupler 31 attached to a moveable shaft S. Each sensor assembly
20 means 11_n is preferably placed equidistantly on mounting structure 21 and thus, circumferentially around the moveable shaft S. In the preferred embodiment, three sensor assembly means $11_1, 11_2, 11_n$ are placed evenly around shaft S as seen in Figure 1, however, those of skill in the art will realize that as little as two sensor assembly means could be used to

accomplish the results dictated by the present invention. Each sensor assembly means 11_1 - 11_n is preferably disposed between 3.81 mm and 10.16 mm away from the surface face 35 of the moveable torque coupler 31. Each sensor assembly means 11_1 - 11_n is also preferably a conventional fiber optic concentric ring-type sensor, which has multiple fiber optic bundles per sensor, and more specifically, is a fiber-optic sensor which transmits optical signals to the surface 35 of the torque coupler 31, which receives optical signals from a target marker means 33_n formed on or attached to surface 35, and which transmits voltages corresponding to shaft information to the control electronics 41 for processing by the signal processing software means 51. However, those of skill in the art will realize that other sensors could be used (such as, for example and without limitation, other coherent light sensors, non-coherent light sensors, incandescent sensors, wide band sensors, multiple wavelength sensors or other fiber optic sensors) and remain within the spirit of this invention. As each target marker means 33_n rotationally passes each sensor assembly means 11_1 - 11_n , each sensor assembly 11_1 - 11_n continuously, and thus in real-time, measures reflected light from the moveable surface 35 based on the intensity of the reflected transmitted optical signal when the transmitted signal reflects off of any of the target marker means 33_n . Thus, in the preferred embodiment, three precise distances to the measured surface 35 can be obtained so that the attitude of the measured surface 35 (and thus, the coordinate plane of the coupler) can be estimated relative to a fixed reference coordinate system, thereby allowing direct measurements of the shaft's S coordinate angular displacement and

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distance from each sensor assembly means 11₁ relative to each sensor assembly means 11_n.

Typical concentric ring fiber optic sensors (such as the type preferred
5 in the present invention) utilize a central bundle of illuminator transmit fibers surrounded by a concentric ring of sense fibers which are coupled to a photonic detector. Invasively moving the concentric ring sensor a distance relative to a reflective surface provides a detected response curve characteristic similar to that illustrated in Figure 2. Applications which employ
10 commercially available sensors that exhibit this type of response curve utilize only the linear portions near either side of the peak of this response curve as illustrated in Figure 2, the linear range of a typical commercial fiber optic sensor being about 2.54 mm. However, use of the operational characteristics of the linear portion of this curve severely limits the operational range of the
15 sensor assembly means, and further, provides no means for absolute calibration of the sensor. The present invention, in contrast, employs the non-linear operational characteristics of this curve for data processing by the signal processing software means 51.

Referring to Figure 3, Figure 3 illustrates a three-dimensional plot of
20 the response of a concentric ring fiber optic sensor of the type preferred in the present invention. As shown, this type of sensor is highly sensitive to angle variations, and thus, the effects of small angle changes on the characteristic response of such a sensor must be modeled in order to achieve the level of precision desired. The characteristic response is also a function of the
25 reflecting surface material. Thus, when using these types of sensors, it is

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preferred that a three-dimensional response (or map) of each sensor first be captured and modeled. This can be accomplished, for example, by placing each sensor in an automated high precision fixture and capturing the response of each sensor from a known target material as the automated
5 characterization system varies the distance and the two orthogonal angles of the sensor relative to the characterization target facet. The resulting mapped information can then be stored in the signal processing software means 51 for subsequent calculations.

At least one multifaceted target marker means 33_n is attached to a
10 measured surface 35 of coupler 31 by conventional methods, and are spatially well distributed on surface 35 to allow the determination of the plane of surface 35, which in turn, allows the geometric determination of the angle of the shaft S. Preferably, each target marker means 33_n is spaced apart 120 degrees from each other on surface 35. Each target marker means 33_n is
15 optically reflective, being able to reflect optical signals transmitted by each sensor 11_n. In the preferred embodiment, each target marker means 33_n is of a predetermined height to an arbitrary center point C, is manufactured from a highly reflective compatible material (such as, for example, nickel-plated aluminum) and includes five faceted facets 37₁ - 37_n, as seen in Figure 4a.
20 Using simulations which model the sensor assembly means' 11_n performance, it was determined that five facets would optimally allow the recursive sensor estimators (as seen in Figure 6) to converge to a solution rapidly. The first three facets 37₁ - 37₃ produce fixed, precise changes in displacement. The fourth facet 37₄ produces a fixed, precise angle change in

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the axis of rotation of the coupler 31. The fifth facet 37₅ produces a fixed, precise angle change in the axis perpendicular to the rotation of the coupler 31. Those of skill in the art will appreciate that many reflective materials could be substituted for the preferred embodiment of the target marker means of the present invention (such as, for example, nickel, aluminum, stainless steel, titanium and first surface or second surface glass mirrors), yet still remain within the spirit and the scope of the present invention. By tracking the location of each facet 37_n on surface 35 in space and time, a comparison can be made between measured voltages (which are proportional to the distance to the surface and the surface's angles) and a model of the sensor response for an estimated distance and angles (stored in control electronics 41) in order to calculate the coupler's 31 estimated absolute distance from each sensor 11_n and also the angle of each target marker means 33_n relative to each sensor 11_n.

The information corresponding to the captured signal reflectance from each sensor assembly means 11_n is then communicated via communications bus 43 (such as, for example, a fiber optic data bus or bundle) by the control electronics 41 to the signal processing software means 51. The signal processing software means 51, in turn, is programmed by conventional means to determine whether the moveable shaft S is moving in any plane to within 0.254 mm over 11.43 mm and 0.1 degree over 2.5 degrees. Simultaneously, the signal processing software means 51 monitors the rotational speed of shaft S at up to 9000 RPM.

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In the preferred embodiment of the present invention, as illustrated in Figure 5, the signal processing software means 51 includes a target identification and RPM estimator 61, a plurality of sensor estimators 63,
 5 corresponding to each sensor assembly means 11_n employed, and a torsion coupler plane estimator 65, where:

d_1 = distance from sensor 1 to surface position
 d_2 = distance from sensor 2 to surface position
 d_3 = distance from sensor 3 to surface position
 10 A = Attenuation
 V_1 = Voltage Measured from Sensor 1 Signal
 V_2 = Voltage Measured from Sensor 2 Signal
 V_3 = Voltage Measured from Sensor 3 Signal
 T_{1i} = Target Data for Sensor 1/Target 1
 15 T_{2i} = Target Data for Sensor 2/Target 2
 T_{3i} = Target Data for Sensor 3/Target 3
 ij - tip ($j=1$) and tilt ($j=2$) of plane relative to sensor (i) coord system
 1_1 = sensor 1 along track angle
 1_2 = sensor 1 cross track angle
 20 2_1 = sensor 2 along track angle
 2_2 = sensor 2 cross track angle
 3_1 = sensor 3 along track angle
 3_2 = sensor 3 cross track angle
 D = shaft displacement
 θ = coupler along track angle
 25 ϕ = coupler cross track angle.

In operation, each sensor assembly means 11_n generates a continuous
 signal obtained from reflections from the rim of the coupler 31 as the coupler
 30 31 rotates. In the preferred embodiment of the present invention, the space
 (or, regions) between each target marker means 33_n on the rim of coupler 31
 are typically darkened with non-reflective material. Thus, each target marker
 means 33_n, as it rotationally passes each sensor, has a much higher return
 (or, reflected) signal. A small stripe of reflective material (not shown) is
 35 optionally placed on the rim of the coupler at a predetermined location to
 provide a fiducial mark on the rim of the coupler. The stripe provides a

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reference point for determining the rotational angle of the coupler. When the stripe is sensed by each sensor assembly means 11_n, it is an indication that the next target marker means 33_n sensed by the sensor assembly means 11_n will be target marker means 33₁. This will be followed by target marker means 33₂, 33₃ up to 33_n. The target identification and RPM estimator 61 computationally locates the fiducial marker, locates each target marker means, locates each facet of each target marker means, obtains the sensor response of each facet 37_n of each target marker means 33_n to transmit this data to the sensor estimators 63_n, and by using the sampling rate of each sensor assembly means 11_n, determines the rotational velocity of the

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shaft by the information corresponding to the passage of the fiducial marker on each rotation.

Referring now to Figure 6, each sensor estimator 63_n correlates to
 5 each sensor assembly means 11_n employed, and computationally generates a distance and two orthogonal angle estimates based on voltages from the five facets 37₁ - 37₅ of each of the target marker means 33_n, where:

10 T_i = target data
 V = measured sensor voltage
 $\hat{X}$ = current parameter estimate
 $\hat{Z}$ = measurement estimate
 Y = measurement innovation
 K_s = forward gain
 C_s = sensor model
 15 I_p = plant model
 Z^{-1} = Z transform delay.

In addition, in order accommodate variations in the overall gain of the optics and electronics employed in the present invention, an attenuation
 20 parameter is also utilized in each sensor estimator 63_n. Models of the characteristic responses of each sensor used (e.g., how they respond to predefined target marker means 33_n) are necessary in order to recursively estimate these parameters and are stored within signal processing software means 51. Such models are derived by known methods of off-line
 25 characterization of each sensor assembly means 11_n employed.

As illustrated in Figure 6, each sensor estimator 63_n compares the voltage response from each sensor assembly means 11_n obtained in response to reflected light from each facet 37_n to an estimated voltage

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measurement (being previously derived from models of the sensor and target), and multiplies the difference by a gain matrix. The gain matrix (being previously derived) should minimally account for the noise, target and sensor
5 characteristics. The result is applied to the previous estimate of the state and a new estimate is produced. This new estimate of distance, angle, and attenuation is applied to the non-linear sensor model and subsequently, the target model to generate the next measurement estimate.

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Torsion coupler plane estimator 65 takes three precise distances from the sensor estimators 63_n and uses these distances to determine the attitude of the coupler's 31 plane via a recursive Kaman estimator which is similar in form to that of the sensor estimators. Those skilled in the art will note that there are several methods to accomplish this method, however, the recursive Kaman estimator is preferred because it allows readings for the coupler plane to be continuously generated.

In the preferred embodiment, the signal processing software means is programmed to obtain the desired information in MatLab and Mathematica by methods known to those of skill in the art. These software programming languages were used for prototype expediency, but those of skill in the art will appreciate that other methods may be used (such as, for example, by hardware means such as preprogrammed ASICs or by embedding the software in microcontrollers). Because each target marker means 33_n is coupled to the moveable coupler, the present non-invasive optical distance and angle measurement system allows collection of measurements multiple times per revolution in order to calculate the precise attitude, speed and torque of the moveable shaft S. As will now be appreciated by those of skill in the art, obtaining multiple measurements is especially useful in those applications where the measured surface or plane is not truly flat, and multiple measurements may help in mapping the uneven surface to an idealized coupler surface.

Further, the signal processing software means 51 is programmed to use the information from the reflected optical signals to automatically

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determine shaft characteristics, despite the conditions of the surrounding environment, by non-linear estimation of absolute displacement of shaft S and angular displacement of shaft S by light returned from the target marker means 33₁₁. For example, the gradient of the reflected light intensity is
5 influenced by many factors such as air quality, humidity, temperature, unexpected obstructions (including dust particles), the reflective quality of the target's surface, the light source's intensity and operational characteristics, and the angle of incidence on the target. Thus, in the preferred embodiment of the present invention, the signal processing software means 51 further
10 includes signal processing means for providing an adaptive gain to accommodate variations in the optical path, sense electronics or fiber bundle variations.

Other variations and modifications of the present invention will be apparent to those of ordinary skill in the art, and it is the intent of the appended claims that such variations and modifications be covered. The particular values and configurations discussed above can be varied, are cited to illustrate particular embodiments of the present invention and are not intended to limit the scope of the invention. It is contemplated that the use of the present invention can involve components having different characteristics as long as the principle, the presentation of a non-invasive precision, optical distance and angle measurement system, is followed.

CLAIMS

1. A system for measuring an absolute optical distance and a planar angle relative to an optical sensor assembly (11_1 , 11_2 , 11_n) for a shaft assembly (S), the shaft assembly (S) including a movable shaft coupled to a rotatable torque coupler (31), the system comprising:

a mounting structure (21) affixed adjacent to the shaft assembly (S)

at least two optic sensor assembly means (11_1 , 11_2 , 11_n) disposed upon the mounting structure (21);

at least one target marker means (33_n) comprising a plurality of faceted faces coupled to a surface portion (35) of the shaft assembly (S);

control electronics (41/51), each optic sensor assembly means (11_1 , 11_2 , 11_n) in communication with the control electronics (41/51) by a communications bus (43); and

signal processing software means (Fig. 5) loaded and stored in the control electronics (41/51); each optic sensor assembly means (11_1 , 11_2 , 11_n) transmitting optical signals to the surface portion (31), receiving a reflected optical signal from each target marker means (33_n) as each target marker means (33_n) passes each optic sensor assembly (11_1 , 11_2 , 11_n) and transmitting information corresponding to characteristics of the shaft (S) to the control electronics (41/51) for processing by the signal processing software means (Fig. 5).

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2. The invention of Claim 1 wherein each sensor assembly means (11₁, 11₂, 11_n) is proximately located between 3.81 mm and 10.16mm away from the target marker (33_n) coupled to the surface portion (35).

3. The invention of Claim 2 wherein each sensor assembly means (11₁, 11₂, 11_n) is disposed on the structure equidistantly from an adjacent sensor assembly means (11₁, 11₂, 11_n).

4. The invention of Claim 3 wherein each sensor assembly means (11₁, 11₂, 11_n) is a sensor selected from the group consisting of a fiber optic concentric ring-type sensor, an incandescent sensor, a coherent light sensor, a noncoherent light sensor or a multiple wavelength sensor.

5. The invention of Claim 4 further comprising a plurality of target marker means (33_n) each comprising a plurality of faceted faces.

~~6.~~ The invention of Claim 5 wherein the signal processing software means (Fig. 5) further includes a target identification and RPM estimator (A), a sensor estimator (B₁, B₂, B₃) corresponding to each sensor assembly means (11₁, 11₂, 11_n), and a surface portion plane estimator (C); the target identification and RPM estimator (A) computationally locating each target marker means (33_n), computationally locating each facet (37₁-37_n) of each target marker means (33_n) to obtain a reflective response and determining the

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rotational velocity of the surface portion; each sensor estimator (B_1 , B_2 , B_3) computationally generating distances to the surface portion (35)

and at least two orthogonal angle estimates from a voltage response of each optic sensor assembly (11_1 , 11_2 , 11_n); the surface portion plane estimator (C)

computationally obtaining the distances to determine the two dimensional planar angle of the surface portion (35).

7. The invention of Claim 6 wherein each target marker means (33_n) further includes a first facet (37_1), a second facet (37_2), a third facet (37_3), a fourth facet (37_4), and a fifth facet (37_5), the reflected optical signal from the first (37_1), second (37_2), and third facets (37_3) corresponding to an angular displacement of the shaft (S), the reflected optical signal from the fourth facet (37_4) corresponding to an angular change in an axis of the coupler's (31) movement and the reflected optical signal from the fifth facet (37_5) corresponding to an angular change in the coupler's axis perpendicular to the movement of the coupler (31).

8. A method for measuring absolute distance and planar angles relative to an optic sensor assembly means (11_1 , 11_2 , 11_n) for a shaft assembly (S), the method comprising the steps of:

mounting a structure (21) adjacent to the shaft assembly (S);

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locating at least two optic sensor assembly means (11₁, 11₂, 11_n) upon the mounting structure (21);

coupling at least one target marker means (33_n) wherein the target marker means comprises a plurality of faceted faces to a surface portion (35) of the shaft assembly (S);

using control electronics (41/51) to communicate with each optic sensor assembly means (11₁, 11₂, 11_n) by a communications bus (43), each optic sensor assembly means (11₁, 11₂, 11_n) transmitting optical signals to the surface portion (35), receiving a reflected optical signal from each target marker means (33_n) as each target marker means (33_n) passes each optic sensor assembly means (11₁, 11₂, 11_n), generating information corresponding to characteristics of the shaft (S) and transmitting the information to the control electronics (41/51); and

allowing signal processing software means (Fig. 5), loaded and stored in the control electronics (41/51), to receive the information from the control electronics (41/51) for processing.

9. The method of claim 8 wherein each sensor assembly means (11₁, 11₂, 11_n) is proximately located between 3.81mm and 10.16mm away from the target marker means (33_n) coupled to the surface portion (35).

locating at least two optic sensor assembly means (11₁, 11₂, 11_n) upon the mounting structure (21);

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10. The method of claim 8 wherein the step of locating the at least two optic sensor assembly means (11_1 , 11_2 , 11_n) comprises locating each sensor equidistant to an adjacent optic sensor assembly means (11_1 , 11_2 , 11_n).