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Simon et al.

[11] **3,866,212**

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[54] **POSITION CONTROL SYSTEM WITH PLURAL SIGNAL TRANSMISSION THROUGH COMMON INDUCTIVE DEVICE**

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[52] **U.S. Cl.** ..... **340/347 DA,** 340/47 SY, 318/625

[51] **Int. Cl.** **H03k 13/02,** G08c 9/04

[58] **Field of Search** ..... 340/347 DA, 347 SY; 235/151.11, 92 MP, 92 PS; 318/594, 660, 625, 605, 490, 563, 565

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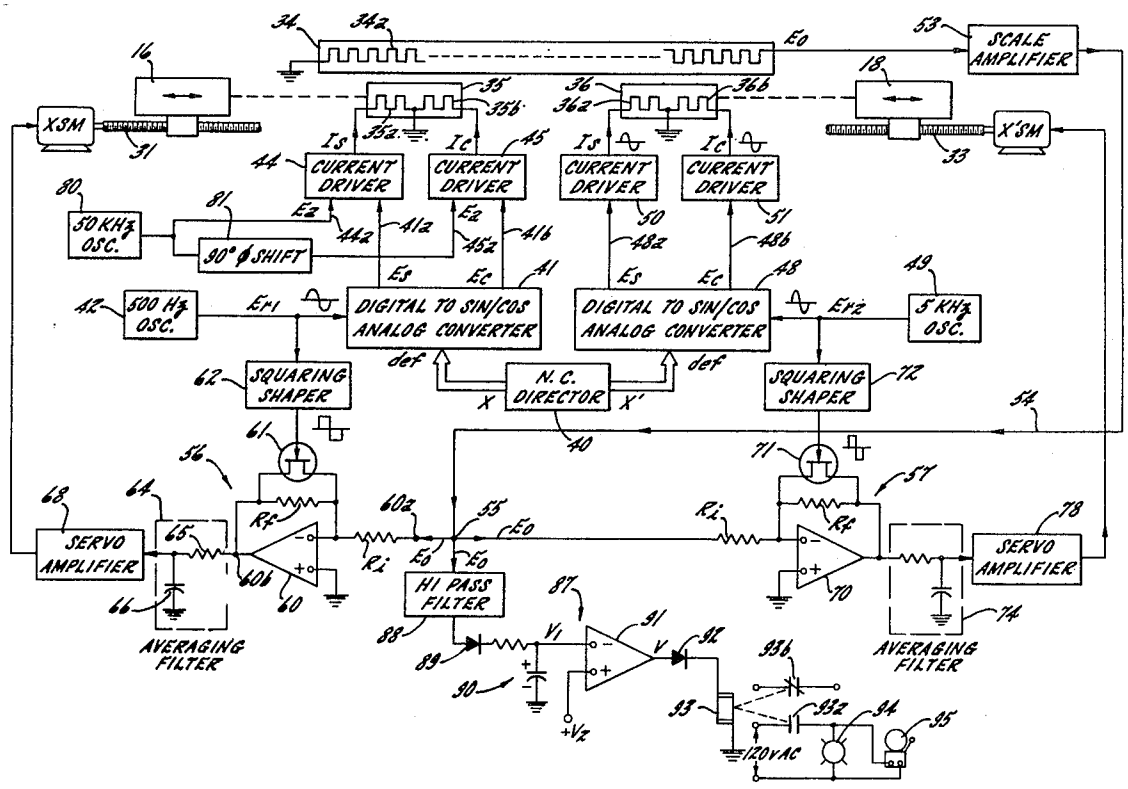
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Attorney, Agent, or Firm—Wolfe, Hubbard, Leydig, Voit & Osann, Ltd.

[57] **ABSTRACT**

A postion-controlling system associated with one or more movable members and utilizing a resolver type inductive coupling device such as a "linear Inductosyn," characterized by the transmission of alternating voltages having more than one frequency through the device. In the preferred form, analog signals of first and second frequencies are applied to excite two sets of input windings and the signal from a single output winding is split into its frequency components so as to produce error signals for driving two members to commanded positions along a common path; and an input of third frequency is superimposed upon the excitation for one set of input windings with the subsequent separation of that frequency from the output signal to monitor and confirm the operability of the inductive device and its associated components. The simultaneous control of two members may be employed without the monitoring, or the monitoring may be employed in a system controlling the position of a single member.

7 Claims, 4 Drawing Figures



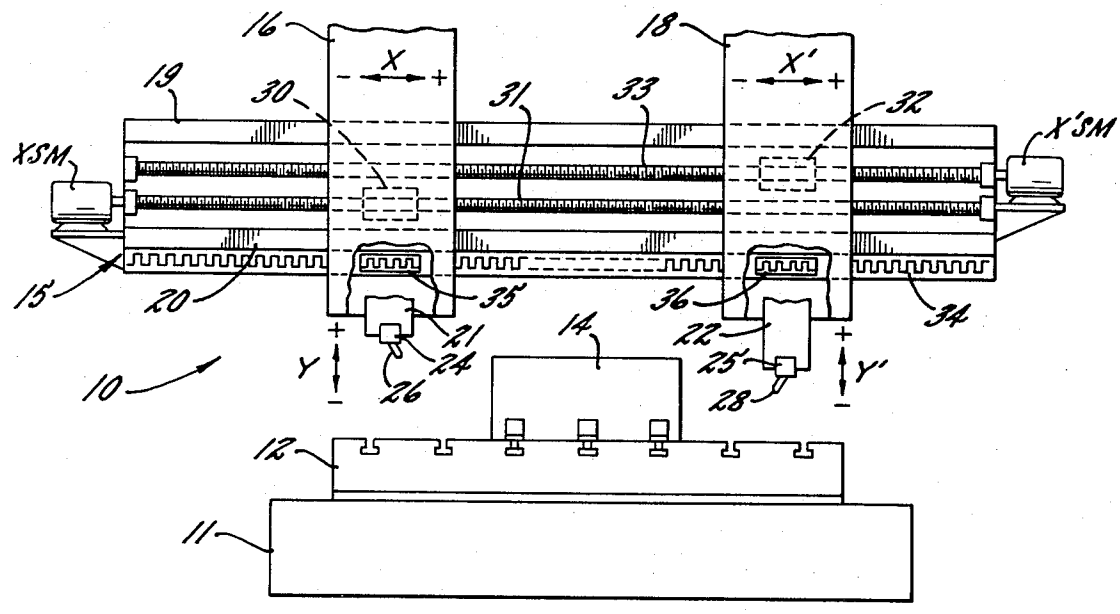


Fig. 1.

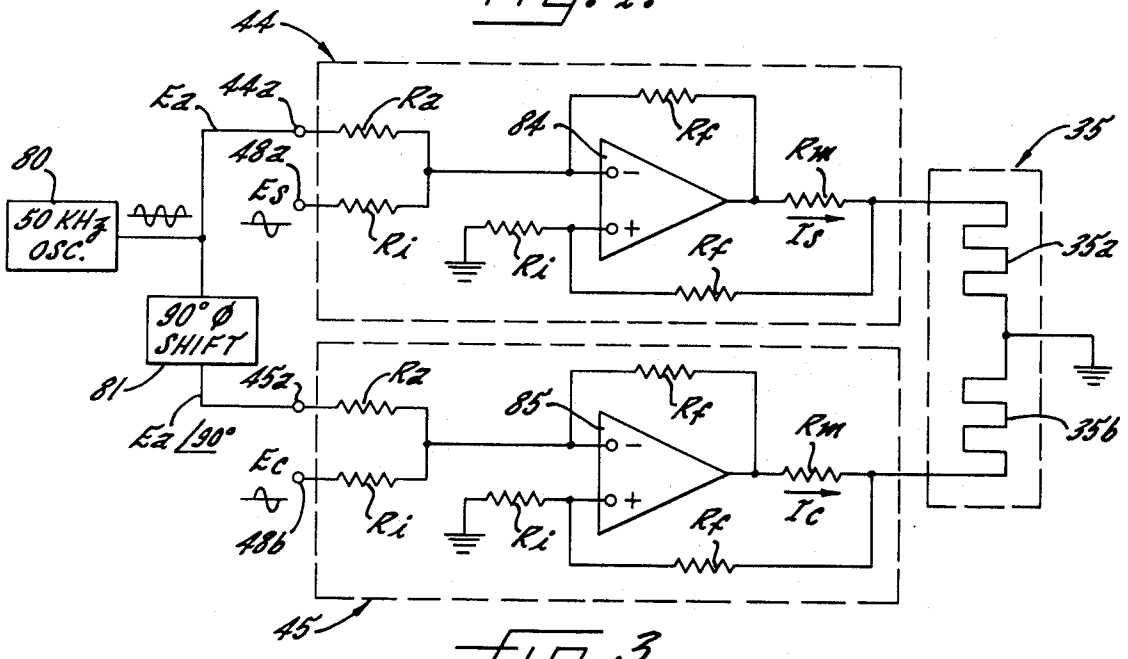


Fig. 3.

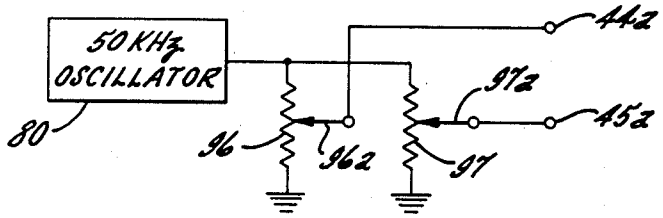


Fig. 4.

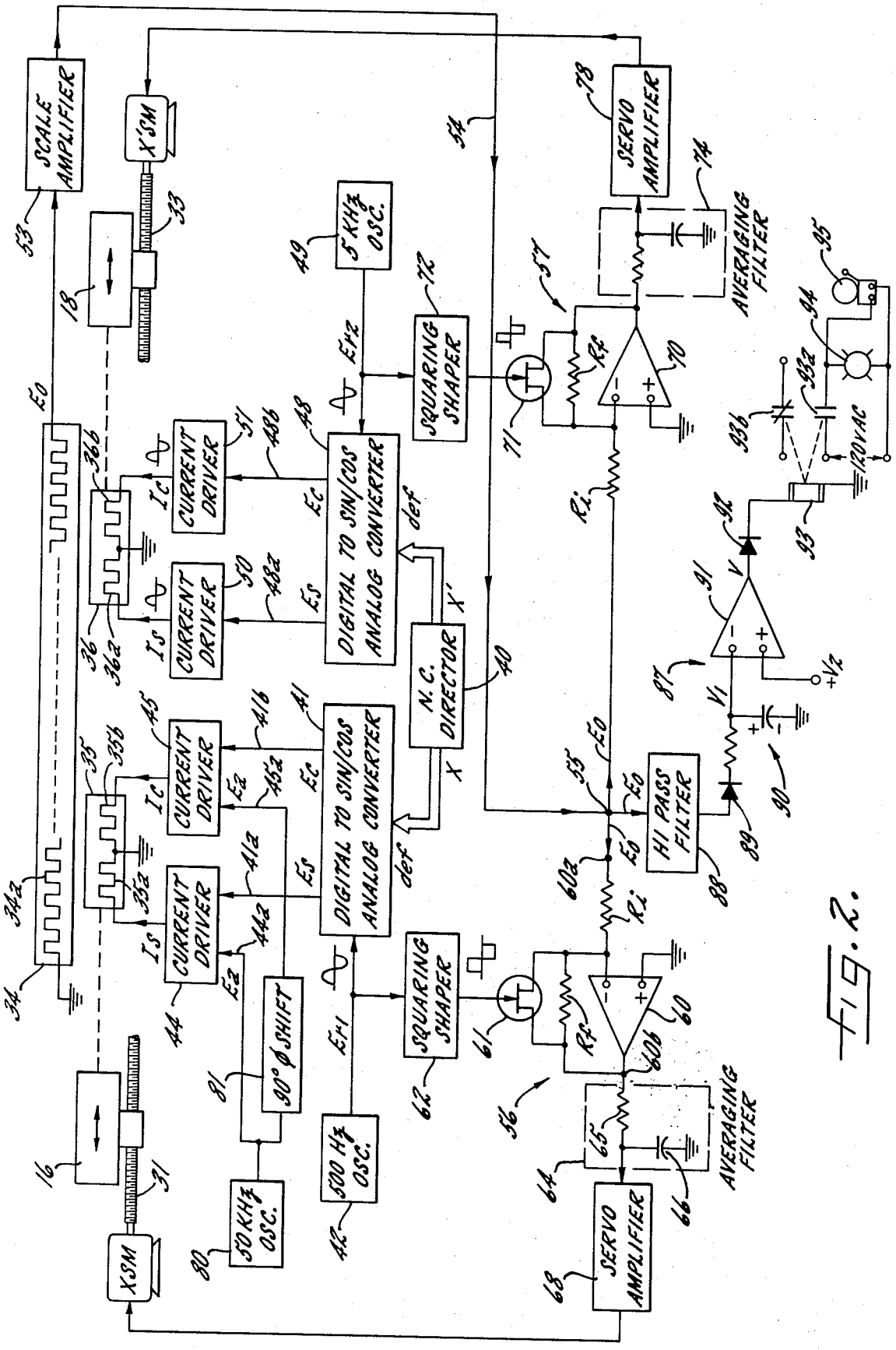

SCALE AMPLIFIER
X'SM
XSM
SERVO AMPLIFIER
AVERAGING FILTER
5 KHz OSC.
SQUARING SHAPER
CURRENT DRIVER
DIGITAL TO SIN/COS ANALOG CONVERTER
N.C. DIRECTOR
90° ϕ SHIFT
500 Hz OSC.
50 KHz OSC.
HI PASS FILTER
120VAC
+V/2

FIG. 2.

POSITION CONTROL SYSTEM WITH PLURAL SIGNAL TRANSMISSION THROUGH COMMON INDUCTIVE DEVICE

FIELD AND SUMMARY OF THE INVENTION

The present invention relates in general to position control or position error-signaling systems associated with movable members driven along predetermined paths. It relates more particularly to such systems which employ resolver type devices in the signal processing path. Although susceptible of other advantageous uses, the invention is especially suited for applications in either point-to-point or contouring path numerical control apparatus associated with machine tools or the like.

The name "resolver type device" is here used as a generic designation for that class of well known inductive coupling devices exemplified by (a) a standard wound-rotor and wound-stator induction resolver, (b) a rotary Inductosyn unit, or (c) a linear Inductosyn unit. The linear Inductosyn is familiar to those skilled in the art, but various publications describing it in detail (e.g., *Journal of British I.R.E.*, Vol. 17, No. 7, pps. 369–383, July 1957) may be reviewed by the reader if he wishes to refresh his memory.

In the use of resolver type devices excited in the variable amplitude mode (as contrasted to the phase-shift mode), the feedback signal is an alternating voltage which varies in amplitude according to the displacement or error of the controlled member from the commanded position which is represented by the amplitudes of exciting input voltages. The feedback signal thus goes to zero amplitude when the position error is zero, i.e., when the system is in a desired steady state condition. If there should be a failure or malfunction of any component in the train for signals produced and applied to the device, or fed back therefrom, so as to make the feedback signal zero, this would not be readily apparent. Even though malfunctioning, the system would appear and behave as if the position error were zero, as it is during steady state conditions when the system is functioning properly.

It is the general aim of the present invention to lessen the possibility of undetected malfunctioning of position-controlling or error-signaling systems of the category which employ resolver type devices to sense the actual position of a movable member.

It is a coordinate object of the invention to make possible the controlled positioning of two or more members movable along a common path through the use of only one common element of a resolver type device, rather than a complete two-part device associated with each member.

An important object of the invention is to obtain plural functions from a single resolver type device, or a single element forming one of the two parts of such a device, by the simultaneous transmission of plural signals therethrough, and the subsequent separation and individual utilization of such signals.

These and other objects and advantages will become apparent as the following description proceeds, taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a diagrammatic and fragmentary front elevation of a machine tool having two members movable along a common path or axis, this serving to illustrate an exemplary environment in which the invention may be employed.

FIG. 2 is a schematic diagram, partly in block-and-line form, of a control system embodying the features of the present invention;

FIG. 3 is a schematic diagram showing in greater detail two of the current drivers which appear in block form within FIG. 2; and

FIG. 4 is a diagram showing an alternative arrangement for injecting a monitor signal into the apparatus shown in FIGS. 2 and 3.

DESCRIPTION OF THE INVENTION

While the invention has been shown and will be described in some detail with reference to a particular but exemplary embodiment, there is no intention thus to limit it to such detail. On the contrary, it is intended here to cover all alternatives, modifications and equivalents which fall within the spirit and scope of the invention as defined by the appended claims.

Referring now to FIG. 1, an exemplary machine tool, here a vertical lathe **10**, is shown fragmentarily as comprising a base **11** supporting a table **12** rotatable about a vertical axis and adapted to carry a workpiece **14**. The lathe includes a cross rail **15** slidably supporting first and second saddles **16** and **18** which may be considered as first and second members movable along a common horizontal path defined by ways **19** and **20** on which they are guided. The saddles carry rams **21** and **22** vertically slidable therein (in guideways and by actuation of motor-driven lead screws, not shown) so as to vary the elevations of cutter supports **24** and **25** mounting cutting tools **26** and **28**.

The lathe **10** is somewhat unusual but not totally uncommon in its organization in that the two saddles **16** and **18** are supported by the single rail **15** and are thus independently movable to the left or right along the same horizontal path. In this arrangement, either of the cutters **26** or **28** may act at one time on the rotating workpiece **14**, or both may act simultaneously. For example, one cutter may be moving radially across the upper surface of the workpiece to take a face cut while the other is moving vertically along the outer periphery of the workpiece to take a lengthwise cut. In the parlance of the machine tool industry, it may be said that the cutter **26** is movable to different positions along a horizontal X-axis by translation of the saddle **16** along the rail **15**, and is movable to different positions along a vertical Y-axis by motion of the ram **21** relative to that saddle. Correspondingly, the cutter **28** is movable along a horizontal X′-axis and a vertical Y′-axis, but in reality the X and X′-axes are a single axis lying on a common horizontal path.

It is a known practice to control simultaneously the velocities and the dynamically changeable positions of a cutter relative to a workpiece by numerical control systems associated with machine tools such as the one diagrammatically illustrated in FIG. 1. Each axis involves a servomotor to drive the controlled member, together with means for signaling (a) the instantaneously commanded or desired position along the axis and (b) the instantaneous actual position along the axis, or the error between the commanded and actual positions. The servomotor, in any case, is energized to keep the difference or error between the commanded and actual positions very small at all times and substantially zero under steady state conditions.

In "double cutter" or "double saddle" machines of the sort exemplified in FIG. 1, the two members or saddles 16, 18 which move on common ways along a common path are usually equipped with servomotors driving lead screws which do not extend over the whole range of travel from the right to the left end of the rail 15. Moreover, each member or saddle has its entirely independent feedback means for sensing the actual position of that member in order to produce a signal indicative of either the actual position or the position error. If a linear Inductosyn device is employed for feedback in association with each of the controlled members, it does not extend over the full range of travel. This limits the flexibility of the machine, since with the left saddle 16 parked at the left extremity of the X-axis, the right saddle 18 cannot be moved to work along the left portion of the rail 15. To give that capability, two full length Inductosyn scales would be required under the prior art practice.

In the physical arrangement of FIG. 1, however, the saddle 16 carries a nut 30 threadably engaged with a lead screw 31 which extends the full length of the rail 15 and is rotationally driven by a reversible servomotor XSM. In a similar fashion, the saddle 18 carries a nut 32 engaged with a lead screw 33 which extends the full length of the rail and is rotationally driven by a reversible servomotor X'SM. In accordance with the present invention to be described, a position-sensing means is associated with each of the saddles 16 and 18, but is embodied in a resolver type device having a single principal part which serves in the servo positioning loops for both saddles. As here illustrated, a linear Inductosyn is the specific form of the resolver type device employed. It includes a first part or "scale" 34 which is stationary or fixed upon the rail 15 and extends the full length of the rail. For cooperating with that Inductosyn scale, there is mounted in or on the saddle 16 an Inductosyn slider 35, and a similar slider 36 is mounted on or in the saddle 18. The two sliders 35 and 36 are so disposed as to be closely and uniformly spaced from the scale 34 in all positions of the saddles 16 and 18 as the latter move to different horizontal positions along the rail, thereby assuring that the conductors or windings within the scale 34 have magnetic couplings to the conductors which are within the sliders 35 and 36.

The construction and operation of linear Inductosyn devices is per se known, for example from the disclosures of U.S. Pat. No. 2,650,352; 2,671,892 and 2,799,835. Briefly, the scale 34 is an elongated part (which may be made up of several sections mounted end-to-end with their conductors connected in series) comprising a non-magnetic support such as glass carrying a flat copper ribbon conductor or "winding" 34*a* shaped physically like an alternating square wave pattern. The "pole spacing" of the pattern, i.e., the space between adjacent conductor positions lying transverse to the direction of travel, is chosen to have some predetermined small value such as 0.05 inch, giving an electric cycle of 360° spanning 0.1 inch. The slider 35, on the other hand, is a shorter part formed of non-magnetic material such as glass and supporting two "windings" or flat ribbon conductors, here designated sine and cosine windings 35*a* and 35*b* (see FIG. 3). These windings both have the same physical shape and pole spacing dimensions as the winding 34*a*, but they are offset from one another by a distance corresponding to 90 electrical degrees. When one of the slider windings is alined with the scale winding elements to make its inductive coupling a maximum, the other has its minimum inductive coupling to the scale winding.

The input windings 35*a* and 35*b* are excited with in-phase sinusoidal alternating voltages which in amplitude are respectively proportional to sin θ and cos θ, where θ can take on any value between 0° and 360°. If the 360° range is divided into 1,000 parts, then the relation of amplitudes of the two exciting voltages may establish 1,000 different relative positions, within a given cycle span, at which the output signal induced in the scale winding 34*a* become zero or null. With any null location so established, the output voltage from the scale winding will in amplitude be substantially a sine function of the distance by which the scale is displaced from that null position. For small displacements, the scale output voltage is essentially a linear function of the error displacement.

To excite a linear Inductosyn in accordance with a changeable command number, the sine and cosine winding input voltages are made in amplitude proportional to the sin n (0.36°) and cos n (0.36°), where n can take on any value between 0 and 999. To speak in terms of inches for an Inductosyn having a cycle span of 0.1 inch, the amplitudes may be proportional to sin n (0.36°)(10^4) and cos n (0.36°)(10^4) where n can take on any value between 0.0000 and 0.0999. The nulls can thus be set at any one of one thousand locations spaced apart by 0.0001 inch within the 0.1 inch cycle span. If a commanded position number N is signaled with six decimal digit places ab. cdef such that any digit can have any value 0 through 9, the three lower order digit places def may serve as the number n in deriving corresponding amplitudes for the sine and cosine input voltages. Thus, the two voltages take on amplitudes of sin 0.0def (0.36°)(10^4) and cos 0.0 def (0.36°)(10^4) where the first factor 0.0def can have any value between 0.0000 and 0.0999. If the number N is progressively increased or decreased and the slider is moved dynamically such that it does not fall more than 90 electrical degrees behind the represented but changing null location, the slider may be commanded to move to, and will reach, any commanded position over the entire range of the scale and with an accuracy to approximately the nearest ten thousandth of an inch.

With the foregoing as a review, the features of the invention may now be considered with reference to the exemplary embodiment of FIGS. 1 and 2. Rather than the ordinary arrangement of two completely separate linear Inductosyn devices (each with its own slider and scale) respectively associated with the two movable members or saddles 16, 18, the apparatus here shown employs but a single scale 34 fixed on the rail 15 and closely spaced to the respective sliders 34 and 35 as the latter move with their saddles along the common path. The windings of both sliders are thus disposed for inductive or magnetic coupling with the common scale winding 34*a*.

To enable the positioning of either or both of the saddles 16, 18 at commanded locations designated X and X', means are provided to excite the slider windings 35*a* and 35*b* (FIG. 2) with alternating voltage of a first predetermined frequency and which in amplitude represents the analog of the commanded position for the saddle 16. For this purpose, a command number X is digitally signaled by a numerical control director 40 in the manner well known in the art, and the multi-bit sig-

nals representing its lower order digits def are fed as inputs to a digital to sin/cos analog converter **41.** This converter may take various forms known to those skilled in the art, and indeed may be constructed like that described in detail by U.S. Pat. No. 3,594,783 issued July 20, 1971. It will suffice to observe that a reference sinusoidal voltage E_{r1} is supplied to the converter **41** with a first predetermined frequency from a suitable source here shown as a 500 Hz. oscillator **42.** As the signaled numerical input def takes on different values from 000 to 999, the output voltages E_s and E_c on lines **41***a* and **41***b* are sinusoidal in form, in phase, have the same frequency (500 Hz.) as the reference E_{r1}, but in amplitude are so proportioned that

$$E_s/E_c = \tan 0.0 \text{ def } (0.36°)(10^4)$$

Because $\tan \theta = \sin\theta/\cos\theta$, this is tantamount to the voltages E_s and E_c being in amplitude respectively $E_s = E_{r1} \sin 0.0\text{def } (0.36°)(10^4)$ and $E_c = E_{r1} \cos 0.0\text{def } (0.36°)(10^4)$. The voltages E_s and E_c are thus an analog representation of the commanded position represented by the numerical value of 0.0def.

These two voltages are supplied respectively to current drivers **47** and **45** which in turn excite the windings **35***a* and **35***b* with corresponding currents I_s and I_c. Ignoring for the moment the secondary inputs **44***a* and **45***a* shown for these drivers, the currents I_s and I_c are proportional to the voltages E_s and E_c and thus are the same as if the voltages E_s and E_c were applied directly to the windings **35***a* and **35***b*, provided those windings were exactly equal and balanced in their impedances. The current drivers are preferably identical to those disclosed in U.S. Pat. No. 3,546,570 issued Dec. 8, 1970 and serve the purpose of assuring that currents I_s and I_c are indeed proportional by the same factor to the voltages E_s and E_c even if the two windings **35***a* and **35***b* do not have exactly the same impedance.

With the slider windings so excited, an error voltage is induced in the scale winding **34***a* with a frequency of 500 Hz. In amplitude, that error voltage is a sine function of the displacement (within the nearest electrical cycle span) of the slider **35** (and the saddle **16**) from the null location represented by the then existing value of the signaled command number def. The phase polarity (in phase with, or 180°out of phase from, the reference E_{r1}) of the induced error voltage agrees with the sense of the position error. This error voltage is employed (as described below) to energize the motor XSM such that the saddle **16** and the slider **35** are moved to a position at which the error voltage is reduced substantially to zero.

For the controlled positioning of the second member or saddle **18,** a similar excitation arrangement is associated with the slider **36,** with the essential difference that the excitation voltages for the latter have a second and different predetermined frequency. More specifically, the director **40** produces signals numerically representing a command number X′, the signals for the lower order digits def being fed as the input to a digital to sin/cos analog converter **48.** In this instance, however, the converter receives a reference voltage E_{r2} from a suitable source such as a 5KHz. sinusoidal ocillator **49.** Thus, the output lines **48***a*, **48***b* receive voltages E_s and E_c which are sinusoidal, of the same frequency, but which in amplitude are, in effect, proportional to the sine and cosine of the then-signaled value of the input number def constituted by the lower order digits of the command number X′. The converter **48** is constructed and functions exactly like the converter **41** except that its reference input E_{r2} and its two output signals E_s and E_c have a frequency of 5KHz. rather than 500 Hz.

The converter output lines **48***a*, **48***b* form the inputs to current drivers **50, 51** which in turn excite the sine and cosine windings **36***a*, **36***b* of the slider **36.** The drivers **50** and **51** are constructed as disclosed in U.S. Pat. No. 3,546,570. With the slider windings **36***a*, **36***b* so excited, an error voltage is induced in the scale winding **34***a* with a frequency of 5KHz. In amplitude, that error voltage is a sine function of the displacement (within the nearest electrical cycle span) of the slider **36** (and the saddle **18**) from the null location represented by the then-existing values of the signaled command number def forming a part of the number X′. This error voltage is employed (as described below) to energize the motor X′SM so as to drive the saddle **18** and slider **36** to a position at which the error is reduced substantially to zero.

It will be understood that the two error voltages induced in the scale winding **34***a* from the sliders **35** and **36** are superimposed upon one another, creating a composite signal E_o at the scale winding output terminal which is the sum of two sinusoidal components of different frequencies (in this example, 500 Hz. and 5 KHz.). This introduces no special difficulties, however, and the composite scale output signal E_o may be passed through a broad band scale amplifier **53,** as shown, where it appears with increased strength on a conductor **54** leading to a junction **55.**

In order to produce error signals which in magnitude and polarity correspond to the position errors sensed only and respectively by the sliders **35** and **36,** means in the form of discriminators **56** and **57** are responsive only to the first and second frequency components of the composite induced voltage E_o. As here shown, the discriminator **56** is formed by a high gain operational amplifier **60** to the inverting input terminal (−) of which the composite voltage E_o is applied through an input resistor R_i from a main input terminal **60***a*. Negative feedback from the output to the inverting input is provided by a feedback resistor R_f, and the non-inverting input terminal (+) is tied to reference or ground potential. The feedback resistor R_f is selectively shunted, however, by a field effect transistor (FET) **61** having its source and drain connected across that resistor and its gate coupled to receive the output of a squaring shaper **62** receiving the 500 Hz. reference wave E_{r1}. Since the gain of the amplifier **60** is extremely high, and as is well known, the output voltage at terminal **60***b* is a function of the ratios of the resistors R_i and R_f and the input voltage at input terminal **60***a*, such that

$$e_o = e_i R_f / R_i$$

When FET **61** is conductive, it makes the effective value of resistor R_f substantially zero, and thus the output voltage at terminal **60***b* zero. Thus, the input signal E_o applied to terminal **60***a* is amplified and transmitted to the output terminal **60***b* only when the 500 Hz. square wave from the shaper **62** is in a negative half cycle and the FET **61** is turned off. If the 500 Hz. component of the signal E_o is in phase with the reference voltage E_{r1}, successive negative half cycles are transmitted with inversion, to the terminal **60***b*. If that component is out of phase with the reference voltage E_{r1},

successive positive half cycles are are transmitted, with inversion, to the terminal **60***b*. The discriminator **56** thus acts as a half wave rectifier which passes either positive or negative half cycles of the 500 Hz. Component when the latter is in or out of phase with the 500 Hz. reference signal E_{r1}. The average dc. value of the half cycles appearing on the terminal **60***b* is thus proportional to the amplitude of the 500 Hz. component in the signal E_o.

During the intervals when the FET **61** is turned on, the amplifier **60** also transmits several full cycles of the 5 KHz. component in the signal E_o. These have an average value of zero, however.

The output from amplifier **60** is converted into a dc. error signal which varies in magnitude according to the amplitude of the 500 Hz. component in the scale output signal E_o, and which in polarity is dependent upon the sense of the position error sensed by the slider **35.** For this purpose, the amplifier output is passed through a low-pass or averaging filter **64** made up of a series resistor **65** and a shunt capacitor **66.** Because each full cycle of the 5 KHz. full wave signal applied to the filter **64** causes equal charging and discharging of the capacitor **65,** it does not contribute to the dc. output of the filter and the 5 KHz. component is thus rejected.

The dc. error signal is amplified by a servo amplifier **68** and then applied to the reversible servomotor XSM. Thus, when an error between the commanded position of the saddle **16** and its actual position (as sensed by the slider **35**) exists, the saddle **16** and the slider **35** are driven to the right or left, as required, until the position error is reduced to zero.

The discriminator **57** is organized and functions like the discriminator **56,** except that the former receives a control square wave at a 5 KHz. frequency, so that it rejects the 500 Hz. component of the signal E_o and produces a dc. error voltage which in magnitude and polarity corresponds to the amplitude and phase polarity of the 5 KHz. component. More specifically, the scale output E_o is fed through an input resistor R_i to the inverting input terminal (−) of a high-gain operational amplifier **70** having a feedback resistor R_f bridged by a FET **71.** The gate of the latter is controlled by the square wave output of a shaper **72** receiving the 5 KHz. reference voltage E_{r2}, so that the positive or the negative half cycles of the 5 KHz. component in the signal E_o are converted by an averaging filter **74** into a dc. error voltage proportional in magnitude and dependent in polarity upon the sense of the position error detected by the slider **36.** Although the FET **71** is turned on for spaced time intervals corresponding to positive half cycles of the 5 KHz. reference signal E_{r2}, the 500 Hz. component in signal E_o does not contribute to the dc. voltage produced at the output of the filter **74.** The successive short "pulses" of the 500 Hz. component which are transmitted through the amplifier **70** will be of different sizes but over one period of the 500 Hz. component there will be a negative counterpart for each positive pulse, and they average out to zero. Therefore, the dc. error voltage from the filter **74** represents only the 5 KHz. position error component in the signal E_o.

That dc. error voltage is passed through a servo amplifier **78** and applied to the servomotor X'SM. Thus, the saddle **18** and its slider **36** are driven to the left or right, as required, until their actual position agrees with the input number def which forms a part of the command number X', and until the 5 KHz. component in the signal E_o is reduced substantially to zero amplitude.

The apparatus as thus far described accepts two command numbers X and X' designating desired positions for the two saddles movable along a common path. By the use of only a single scale, each is controlled through its closed loop servo to move to positions which agree with its command number. This not only eliminates the cost of a separate scale for the second saddle but also permits the necessary scale **34** to be disposed in the limited space available on certain machine tool members, such as the rail **15.** Because each slider **35** and **36** is excited with analog voltage at different frequency (here, for example, 500 Hz. and 5 KHz.), the output signal E_o from the scale winding **34***a* is a mixture of two frequencies. Yet, each frequency component retains the amplitude which it would have if it were present alone, and it requires only relatively simple and inexpensive discriminators responsive respectively to the first and second frequencies to separate the two components of the signal E_o and to create dc. error signals for energization of the corresponding servomotors XSM and X'SM.

In the use of any resolver type inductive device such as a linear Inductosyn, there is always the danger that the signal transmission path may be interrupted, at one point or another, due to malfunction or breakage of the various elements, circuit components or connecting wires. For example, if the drivers **44, 45** or the slider windings **35***a*, **35***b* or the scale winding **34***a* or the scale amplifier **53,** or the wires connecting these components, should break or malfunction, the 500 Hz. signal component would become zero in the signal E_o. The servo system for the saddle **16** would receive a zero voltage from the filter **64** and would give the appearance of normal steady state conditions with zero position error--even if at that time the command number X were designating a desired position materially different from the actual position of the saddle **16.** In other words, because the error signal from the scale **34** is normally zero when the system is functioning properly at steady state with zero error, a malfunction is not apparent from the fact that the signal transmitted through the Inductosyn device vanishes.

In keeping with another and important aspect of the present invention, provision is made to monitor the integrity or operability of the signal transmission path through a resolver type induction device, and to provide an indication of malfunction or incompleteness even if the primary error signal is zero. To accomplish this a monitor signal is superimposed upon the excitation voltage normally applied to the slider input windings, the monitor signal being separated from the normal error signal in the positioning servo loop, but being applied to an appropriate device which indicates malfunction when and if for any reason the monitor signal disappears.

Referring again to FIG. **2,** a source of sinusoidal alternating voltage at a third predetermined frequency is constituted by a 50 KHz. oscillator **80.** This voltage is superimposed upon the sine and cosine voltages E_s and E_c otherwise applied to the slider windings **35***a* and **35***b*. For this purpose it is applied additively to the auxiliary input lines **44***a* and **45***a* of the respective drivers **44** and **45.** In the preferred arrangement the 50 KHz. signal is fed directly to the driver input **44***a*, but is passed through a 90° phase shifting circuit **81** before application to the driver input **45***a*.

FIG. 3 shows the current drivers **44** and **45** in greater detail and makes clear how the monitor signal at a third predetermined frequency (50 KHz.) is superimposed upon the sine and cosine voltages E_s and E_c which have the first predetermined frequency (500 Hz.). As explained in U.S. Pat. No. 3,546,570 each of the standard current drivers **44** and **45** (without the auxiliary inputs **44***a* and **45***a*) is a constant current generator formed by an operational amplifier having a constant gain, i.e., ratio of output current to input voltage. Each amplifier has the same gain. As here illustrated the driver **44** includes an operational amplifier **84** with extremely high open loop gain coupled with a negative feedback resistor R_f from its output to its inverting input terminal (−). The primary input signal E_s from line **48***a* is applied through an input resistor R_i to that inverting input terminal. To create positive voltage feedback which has the effect of producing negative current feedback, a series resistor R_m is interposed between the amplifier output and the winding **35***a*, and the junction between the resistor R_m and that winding is coupled back to the non-inverting input (+) through another feedback resistor R_f. An input resistor R_i is connected from ground (zero reference) to the non-inverting input. This results in the net feedback via the two resistors R_f being equal to the voltage drop across the resistor R_m, which in turn is proportional to the output current I_s. Due to the almost infinite open-loop gain of the amplifier **84**, the voltage across and the current between the (−) and (+) input terminals are essentially zero, and it can be shown that the transfer function of the driver is:

$$I_s/E_s = R_f/R_i.R_m$$

The pair of input resistors R_i are equal to one another in ohmic value, as are the two feedback resistors R_f. Thus, as the input voltage E_s varies, the current I_s will always be proportional thereto by the factor $R_f/R_i.R_m$ (which is constant) despite variations in the resistance or impedance of the winding **35***a*.

The driver **45** is identical to the driver **44**, employing an amplifier **85** with two input resistors R_i, two feedback resistors R_f and a series output resistor R_m which are matched in value to the corresponding resistors in the driver **44**. Thus, the transfer functions are the same and the currents I_s and I_c will be proportional to E_s and E_c by the same gain factor despite imbalance in the impedances of the two windings **35***a* and **35***b*.

Fortuitously, the operational amplifiers forming the drivers **44** and **45** may also act as algebraic summing devices. Those skilled in the art will immediately recognize that with a second input resistor R_a connected to couple an auxiliary voltage E_a to the inverting (−) input terminal of the amplifier **84** (FIG. **3**), the output current I_s will be proportional to the sum of the two input voltages E_s and E_a, viz.

$$I_s = -E_s\, R_f/R_i.R_m - E_a\, R_f/R_a.R_m$$

If R_a is made equal in value to R_i, the foregoing becomes:

$$I_s = -(E_s + E_a)\, R_f/R_i.R_m$$

Thus, the current I_s in the arrangement shown by FIG. **3** is the sum of two components, one proportional to the analog voltage E_s having a frequency of 500 Hz. and the other proportional to the monitoring voltage E_a having a frequency of 50 KHz. Likewise, the current I_c has two components respectively proportional in amplitude to E_c and E_a and with frequencies of 500 Hz. and 50 KHz. Because of the phase shifter **81**, the E_a component of I_c is 90° out of phase from the E_a component of I_s.

Reverting again to FIG. **2**, it will be apparent that the signal E_o induced in the scale winding **34**a has three components which are of three different frequencies, e.g., 500 Hz., 5 KHz., and 50 KHz. The 500 Hz. and 5 KHz. components will vary in amplitude as the errors between the commanded and actual positions of the saddles **16** and **18** respectively change. But in the preferred arrangement with the windings **35***a*, **35***b* excited with equal amplitude, phase quadrature voltages E_a, the 50 KHz. component induced in the scale winding will be constant in amplitude but will vary in phase as the slider **35** moves over an electrical cycle span. This means that the induced 50 KHz. component will never drop to zero amplitude but will remain at a given strength, providing that none of the physical elements malfunctions.

From the junction **55**, the scale output signal E_o (after amplification at **53**) goes not only to the discriminators **56** and **57** but also to a detection apparatus **87** for indicating the disappearance of the 50 KHz. monitor signal component. The discriminators **56** and **57** do not respond to the 50 KHz. signal component, because its full wave passage through the amplifiers **60** and **70**, when FET's **61** and **71** are turned off, results in cancellation of the positive and negative half cycles in the filters **64** and **74**. Thus, the servo positioning of the saddles **16, 18** is unaffected by the presence of the monitoring component in the voltage E_o. The indicating means includes a high pass filter **88** (which could be a band pass filter) receiving the voltage E_o and operative to transmit substantially only the 50 KHz. component to a rectifying diode **89** followed by a smoothing R-C filter **90**. The output from the latter is thus a dc. voltage V_1 proportional to the amplitude of the monitor signal component, --and which normally will be of constant value.

To actuate an audio or visual alarm in the event of a malfunction which occasions the disappearance or significant reduction of the voltage V_1, an operational amplifier **91** is employed as a voltage comparator. The voltage V_1 is applied to the inverting input terminal (−) and a reference voltage V_2, which is smaller than the normal magnitude of V_1, is applied to the non-inverting input terminal (+). Since the amplifier algebraically sums these two inputs, its output voltage will be negative or positive when the monitor voltage V_1 is respectively greater or less than the voltage V_2. Under normal conditions, therefore, a diode **92** in series between the amplifier output and a relay coil **93** will block current flow through the latter, and the relay will be deactuated. Its normally open contacts **93***a* will thus leave a warning light **94** and an alarm bell **95** deenergized. Auxiliary normally closed contacts **93***b* may be connected in the circuits for the numerical director **40** so as to permit its functioning so long as the voltage V_1 remains greater than V_2.

If the current drivers **44, 45** should present open circuits or the windings **35***a*, **35***b*, **34***a* or the leads to them should break, or if the scale amplifier **53** should cease to function, the monitor signal component of 50 KHz. in the output voltage E_o will disappear or materially decrease (as will the 500 Hz. component and perhaps the 5 KHz. component). In that event, however, the volt-

age V_1 will fall to zero or at least to a magnitude smaller than that of the reference voltage V_2, whereupon the relay coil **93** will be energized and the contacts **93***a* will turn on the warning light **94** and the alarm bell **95.** An operator will be immediately apprised of the malfunction. If the contacts **93***b* are used in the director **40,** their opening may serve to turn off the entire numerical control system until the trouble has been located and corrected.

It is not essential that the monitor signal be applied to the windings **35***a*, **35***b* in phase quadrature. Instead of the phase shifter **81** as shown in FIGS. **2** and **3,** the 50 KHz. monitor voltage may be applied to excite the slider winding in the amplitude mode, as indicated by the example of FIG. **4.** The output of the oscillator **80** is simply applied across two potentiometers **96** and **97** having wipers **96***a*, **97***a* connected to the auxiliary inputs **44***a*, **45***a* of the two current drivers. By adjusting the wipers **96***a*, **97***a* the relative amplitudes of the 50 KHz. voltages applied to the drivers **44, 45** may be set to desired levels. If they are made equal, they will have amplitudes corresponding to sin 45° and cos 45°, and the 50 KHz. component induced in the scale winding **34***a* will thus vary sinusoidally as the saddle **16** moves progressively along the rail **15** through successive electrical cycle spans. Under these conditions, the 50 KHz. component will have a null or zero value whenever the slider **35** is physically at the 45° location within each electrical cycle span of the scale **34.** This would result in a false malfunction indication if the apparatus of FIG. **2** were employed in the exact form shown. However, the high-pass filter **88** may be modified or replaced with an alternative filter such that both the 50 Hz. and the 50 KHz. components of the voltage E_o are transmitted to the rectifying diode **89** and the smoothing filter. In consequence, so long as either of those components exists, and assuming that the reference voltage V_2 is very small, the voltage V_1 will be sufficiently large to hold the relay coil **93** deenergized. If any of the transmission path elements malfunctions, and thereby causes both the 500 Hz. and 50 KHz. components to disappear, the relay coil will be energized to indicate the malfunction. The 500 Hz. and 50 KHz. signals could conceivably both have null values, in the absence of a malfunction, if the slider is commanded to move to and comes to rest at the precise position within an electrical cycle span which corresponds to the angle whose tangent is represented by the ratio of selected voltage amplitudes appearing on the wipers **96***a* and **97***a* in FIG. **4.** The statistical probability of this is so small that it may be neglected. But even this small possibility of a false indication of a malfunction may be avoided if the monitor signal is applied to the slider winding in phase quadrature, as described for the preferred embodiment.

In the preferred and exemplary apparatus shown by FIGS. **1** and **2,** two members **16** and **18** are simultaneously controlled in their positions through the use of a single Inductosyn scale by exciting two sliders with analog voltages representing desired positions, such voltages having first and second, different frequencies. In addition, the integrity of the signal transmission path, especially that associated with the saddle **16,** is continuously monitored by injecting an auxiliary signal having a predetermined third frequency. The discriminators **56** and **57** are frequency selective devices which respond respectively only to the first and second frequencies to produce a dc. error voltage applied to the servomotors XSM and X'SM; and the malfunction detecting apparatus **87** is also frequency selective to respond only to the third frequency (or to both the first and third frequencies, if the alternative of FIG. **4** is adopted). Yet, it will be apparent that the simultaneous control of two (or more) members may be effected in the fashion here taught while omitting the malfunction monitoring capability and the auxiliary signal. Conversely, if but a single member is to be controlled in its position by a resolver type device or linear Inductosyn, the malfunctioning monitoring may be incorporated by superimposing an auxiliary signal at a different frequency upon the analog position command voltage, at a chosen frequency, fed to the Inductosyn unit.

We claim:

1. In apparatus having first and second members movable independently to different positions along a common path by drive from first and second respective motors, the combination comprising

a. a resolver type device including a first part disposed stationarily along said path and second and third parts mounted respectively on said first and second members to move along and in closely spaced relation to the first part as said members move,

b. said first part having an output winding inductively coupled to first and second input windings respectively disposed on said second and third parts,

c. means for exciting said first input windings with alternating voltage of a first predetermined frequency and which in amplitude represents the analog of a commanded position of the first member,

d. means for exciting said second input windings with alternating voltage of a second predetermined frequency and which in amplitude represents the analog of a commanded position of the second member,

e. means for exciting said first input windings with alternating voltage of a third predetermined frequency superimposed upon the voltage of said first frequency,

f. means coupled to receive the output signal induced in said output winding and responsive to the first frequency component therein for producing a first error signal indicative of the difference between the commanded and actual positions of the first member,

g. means coupled to receive the output signal induced in said output winding and responsive to the second frequency component therein for producing a second error signal indicative of the difference between the commanded and actual positions of the second member,

h. means coupled to receive the output signal induced in said output winding and responsive to the third frequency component therein for producing an auxiliary signal, and

i. detector apparatus coupled to receive said auxiliary signal and including means responsive to substantial reduction in the amplitude thereof for indicating a malfunction.

2. In apparatus having first and second members movable independently to different positions along a common path by drive from first and second respective servomotors, the combination comprising

a. a resolver type device including a first part disposed stationarily along said path and second and third parts mounted respectively on said first and second members to move along and in closely spaced relation to the first part as said members move,

b. said first part having an output winding inductively coupled to first and second input windings respectively disposed on said second and third parts,

c. means for exciting said first input windings with alternating voltage of a first predetermined frequency and which in amplitude represents the analog of a commanded position of the first member,

d. means for exciting said second input windings with alternating voltage of a second predetermined frequency and which in amplitude represents the analog of a commanded position of the second member,

e. means for exciting said first input windings with alternating voltage of a third predetermined frequency superimposed upon the voltage of said first frequency,

f. means coupled to receive the output signal induced in said output winding and responsive to the first frequency component therein for producing a first error signal which varies in magnitude and polarity according to the difference between the commanded and actual positions of the first member,

g. means coupled to receive the output signal induced in said output winding and responsive to the second frequency component therein for producing a second error signal which varies in magnitude and polarity according to the difference between the commanded and actual positions of the second member,

h. means coupled to receive the output signal induced in said output winding and responsive to the third frequency component therein for producing an auxiliary signal,

i. means for energizing the first motor in accordance with said first error signal to drive the first member to an actual position in which said first frequency component in said output signal is reduced substantially to zero,

j. means for energizing the second motor in accordance with said second error signal to drive the second member to an actual position in which said second frequency component in said output signal is reduced substantially to zero, and

k. means responsive to the absence of said auxiliary signal for indicating a malfunction or a lack of reliability in the resolver type device or its associated components.

3. The combination set forth in claim **2** further characterized in that said resolver type device is a "linear Inductosyn" device in which said first part is an elongated "scale" and said second and third parts are "sliders" respectively mounted on said first and second members with each slider having a sin and cos input winding; and wherein said alternating voltage of first predetermined frequency includes two ac. voltages related in amplitude to the sine and cosine of the commanded position of the first member; said alternating voltage of second predetermined frequency includes two ac. voltages related in amplitude to the sine and cosine of the commanded position of the second member; and wherein said alternating voltage of third predetermined frequency includes two ac. voltages of constant and equal amplitude separated in phase by 90; whereby in the absence of any malfunction the auxiliary signal remains finite and substantially constant in magnitude as said first and second error signals take on null or zero values.

4. In apparatus having first and second members movable independently to different positions along a common path by drive from first and second respective servomotors, the combination comprising

a. a resolver type device including a first part disposed stationarily along said path and second and third parts mounted respectively on said first and second members to move along and in closely spaced relation to the first part as said members move,

b. said first part having an output winding inductively coupled to first and second input windings respectively disposed on said second and third parts,

c. means for exciting said first input windings with alternating voltage of a first predetermined frequency and which in amplitude represents the analog of a changeable commanded position of the first member,

d. means for exciting said second input windings with alternating voltage of a second predetermined frequency and which in amplitude represents the analog of a changeable commanded position of the second member,

e. means coupled to receive the output signal induced in said output winding and responsive to the first frequency component therein for producing a first error signal which varies in magnitude and polarity according to the difference between the commanded and actual positions of the first member,

f. means coupled to receive the output signal induced in said output winding and responsive to the second frequency component therein for producing a second error signal which varies in magnitude and polarity according to the difference between the commanded and actual positions of the first member,

g. means for energizing the first servomotor in accordance with said first error signal to drive the first member to an actual position which agrees with its commanded position, and

h. means for energizing the second servomotor in accordance with said second error signal to drive the second member to an actual position which agrees with its commanded position.

5. In apparatus having a member movable to different positions along a predetermined path by drive from a motor, the combination comprising

a. a resolver type device including a first stationary part and a second part mechanically coupled to the member to move in accordance with the member's displacements but always remaining in closely spaced proximity to the first part,

b. said first part having an output winding inductively coupled to input windings disposed on said second part,

c. means for applying to said input windings alternating voltage of a first predetermined frequency which in amplitude represents a numerically commanded position,

d. means for exciting said input windings with alternating voltage of a second predetermined fre-

quency superimposed upon the voltage of the first frequency,

e. means connected to said output winding and responsive only to the first frequency component of the induced output signal for producing an error signal which varies in magnitude and polarity according to the difference between the commanded and actual positions of said member,

f. means connected to said output winding and responsive to the second frequency component of the induced output signal for producing an auxiliary monitoring signal, and

g. means coupled to receive said monitor signal and responsive to a substantial reduction of such signal for indicating a malfunction.

6. In apparatus having a member movable to different positions along a predetermined path by drive from a servomotor, the combination comprising

a. a resolver type device including a first stationary part and a second part mechanically coupled to the member to move in accordance with the member's displacements but always remaining in closely spaced proximity to the first part,

b. said first part having an output winding inductively coupled to sin/cos input windings disposed on said second part,

c. means for applying to said sin/cos input windings alternating voltages of a first predetermined frequency which in amplitude are proportional to the sine and cosine of a numerically commanded position expressed as an angle where **360°** represents a predetermined repeating span,

d. means for exciting said sin/cos input windings with alternating voltages of a second predetermined frequency superimposed upon those voltages of the first frequency,

e. means connected to said output winding and responsive only to the first frequency component of the induced output signal for producing an error signal which varies in magnitude and polarity according to the difference between the commanded and actual positions of said member,

f. means connected to said output winding and responsive to the second frequency component of the induced output signal for producing a monitor signal,

g. means for energizing said motor in accordance with said error signal to drive the member to an actual position in which said first frequency component in said output signal is reduced substantially to zero, and

h. a detector coupled to receive said monitor signal and including means responsive to a substantial reduction of such signal for indicating a malfunction.

7. The combination set forth in claim **6** further characterized by means for making said alternating voltages of said second frequency have a phase quadrature relation.

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