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Polites et al.

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[54] **MEANS FOR POSITIONING AND REPOSITIONING SCANNING INSTRUMENTS**

[75] Inventors: **Michael E. Polites; Dean C. Alhorn,** both of Huntsville, Ala.

[73] Assignee: **The United States of America as represented by the Administrator of the National Aeronautics and Space Administration**, Washington, D.C.

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[52] **U.S. Cl.** .... **73/1 E**; 364/571.05

[58] **Field of Search** . 73/1 E, 1 R; 364/571.01–571.08; 74/61

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,488,249	12/1984	Baker	73/1 E X
4,498,778	2/1985	White	364/571.02 X
4,791,591	12/1988	Asanuma et al.	364/571.04
5,129,600	7/1992	Polites	74/61 X
5,396,815	3/1995	Polites et al.	74/61
5,430,666	7/1995	De Angelis et al.	73/1 R X

OTHER PUBLICATIONS

Patent Abstracts of Japan Grp p. 151 vol. 6, No. 212 ABS Pub. Date Oct. 26, 1982 (57–118165) "Device for Measuring Electric Field Intensity".

Patent Abstracts of Japan Grp p. 544 vol. 11, No. 40 Abs. Pub. date Feb. 5, 1987 (61–210318) "Laser Beam Scanner".

Primary Examiner—Thomas P. Noland
Attorney, Agent, or Firm—Jerry L. Seemann

[57] **ABSTRACT**

A method for positioning a scanning instrument to point toward the center of the desired scan wherein the scan is achieved by rotating unbalanced masses (RUMs) rotating about fixed axes of rotation relative to and associated with the instrument, the RUMs being supported on drive shafts spaced from the center of the mass of the instrument and rotating 180 degrees out-of-phase with each other and in planes parallel to each other to achieve the scan. The elevation and cross-elevation angles of the instrument are sensed to determine any offset and offset time rate-of-change and the magnitude and direction are converted to a RUM cycle angular velocity component to be superimposed on the nominal velocity of the RUMs. This RUM angular velocity component modulates the RUM angular velocity to cause the speed of the RUMs to increase and decrease during each revolution to drive the instrument toward the desired center of the scan.

6 Claims, 1 Drawing Sheet

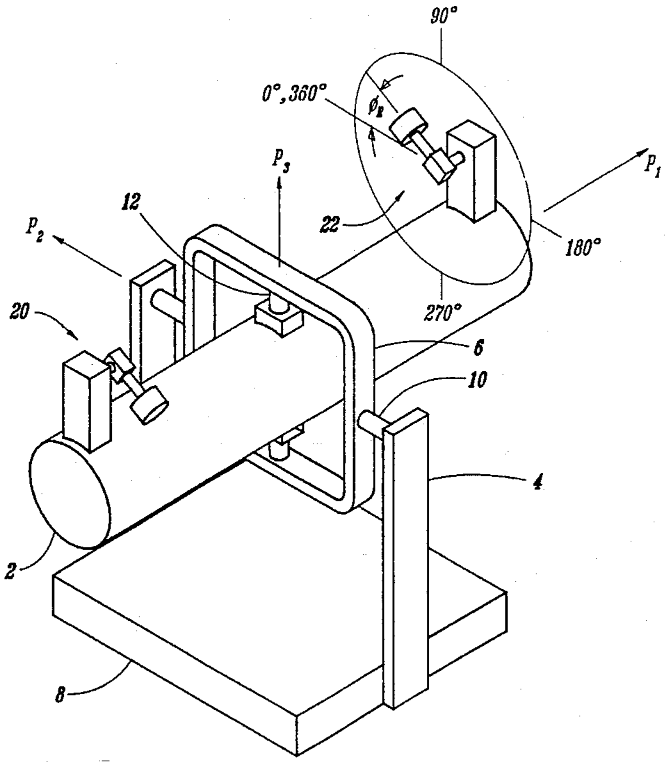
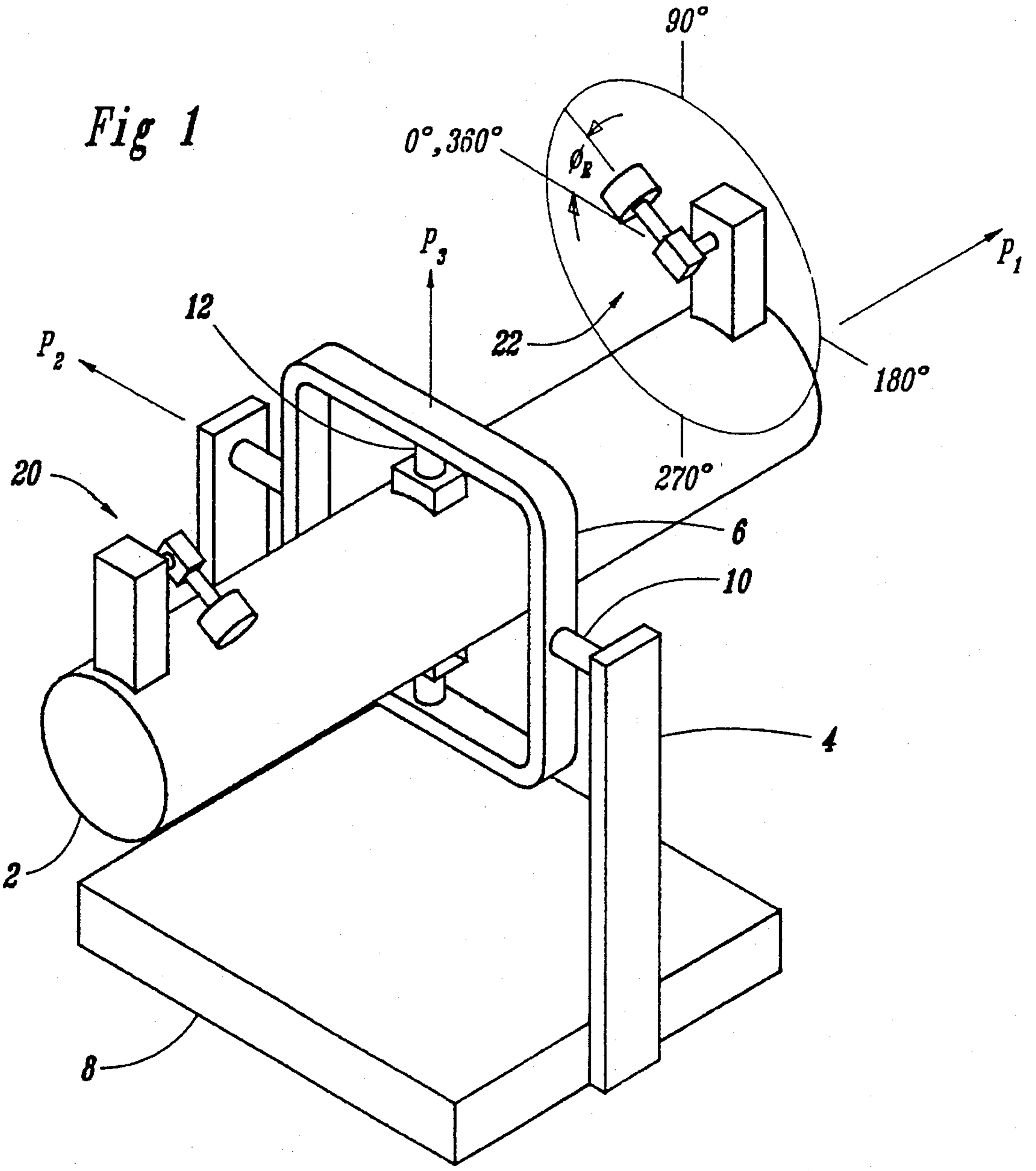


Fig 1



MEANS FOR POSITIONING AND REPOSITIONING SCANNING INSTRUMENTS

ORIGIN OF THE INVENTION

The invention described herein was made by employees of the United States Government and may be manufactured and used by or for the Government of the United States of America for Governmental purposes without payment of any royalties thereon or therefor.

FIELD OF THE INVENTION

This invention in one of its aspects relates to scanning devices or instruments focused on objects in or from outer space. In a more specific aspect the invention is concerned with instruments whose scanning is produced by rotating unbalanced-mass devices, and particularly gimballed scanning instruments. In a still more specific aspect the invention pertains to means for positioning and repositioning such scanning instruments.

BACKGROUND OF THE INVENTION

As can be imagined, scanning instruments are an important aspect of space science. In addition to their use in scanning the earth and other planets, x-ray, gamma-ray, and similar scanning instruments perform additional functions important in space exploration. Examples of such instruments are sensors, telescopes and electronic devices carried by space platforms such as a space shuttle, a space station, by experimental balloons, and by free-flying spacecraft.

To achieve the scan pattern a drive means must be provided which impart to the payload an oscillatory motion. Such drive means are generally known, particularly in space exploration. Various forms of machines or apparatus have been employed for controllably conferring on scanning instruments predetermined scan patterns. They include control moment gyroscopes, reaction wheels, torque motors, reaction control systems, and various combinations of such apparatus.

One disadvantage of utilizing such scan generating devices is power consumption. For this reason, whether scanning with a ground-based, space-based, or balloon-borne gimballed payload a preferred drive means which is particularly effective is a rotating unbalanced-mass, or RUM, device. This device is the subject of our U.S. Pat. No. 5,129,600.

RUM devices are a new and efficient way to generate scan patterns using gimballed payloads such as x-ray telescopes or other scientific instruments. A RUM device consists of a mass, m, on a lever arm r, located at a distance, d, from the center-of-mass of the gimballed payload on which it is mounted. The mass is driven at a constant angular velocity ω which produces a cyclical centrifugal force $m\omega^2r$ on the payload. This force, in turn, produces a cyclic torque, about the payload center-of-mass, with an amplitude of $m\omega^2rd$. The period of this cyclic torque is the same as the period of rotation of the RUMs. Two RUM devices are required to scan with-gimballed payloads. RUMs are mounted on each end of the payload and they rotate 180° out-of-phase producing a cyclic torque couple having an amplitude of $2m\omega^2rd$.

RUM devices are superior to previous scanning devices in terms of power, weight, cost, and accuracy, but such apparatus is still not totally satisfactory. Even though operating

power requirements are less than those required for operating other scan generating devices, the required positioning and repositioning, or pointing, means are subject to improvement. RUM devices currently require an auxiliary control system to position and reposition the scan pattern relative to a target or a number of targets. Such control means confer on the payload or instrument a slow complementary motion that keeps the Scan centered on the target.

Prior methods of generating control torques for pointing freeflying/tethered satellites and gimballed payloads employed reaction wheels, control moment gyroscopes (CMGs), reaction control system (RCS) thrusters, and gimbal torque motors.

Pointing and scanning with reaction wheels, CMGs, and gimbal torque motors characteristically require a great deal of power. Reaction wheels and CMGs also require a momentum desaturation system. RCS systems can only generate control torques until the RCS propel]ant is depleted. In addition, they are also normally nonlinear devices that produce either full thrust or no thrust. This characteristic makes them unsuitable for applications where precise pointing and scanning are required. Gimbal torque motors require gimbals and a base structure to torque against, which renders them unsuitable for free-flying spacecraft and satellites. Also, reaction forces and torques acting against the base structure tend to couple back into the payload or instrument being pointed, causing pointing/scanning errors and/or stability problems. It can be seen, then, that despite the desirability of RUMs, there is room for improvement in their operation. A needed improvement is the elimination of such pointing, that is, positioning and repositioning, equipment, normally referred to as auxiliary control systems. We have now found that this can be accomplished.

SUMMARY OF THE INVENTION

As indicated hereinbefore, pointing means are provided for positioning and repositioning a scanning instrument when the instrument is offset from its center-of-scan and must be pointed to that center-of-scan. The scanning instrument is the type whose scan pattern is achieved by rotating unbalanced-masses (RUMs). Mounted on the scanning instrument are first and second RUMs supported on respective drive shafts. They are spaced from the center-of-mass of the instrument, and adapted to rotate 180 degrees out-of-phase with each other, with their planes-of-rotation parallel to each other, and at a constant angular velocity. The centrifugal forces caused by rotation of the RUMs create time-varying relatively large-amplitude/high-frequency operating or nominal reaction forces and torques which act on the instrument to move its line-of-sight in a predetermined, repetitive, scan pattern. This invention is thus based on the discovery that, in RUM operation, if we superimpose a cyclic angular velocity component on top of, or in addition to, the nominal constant angular velocity component of the rotating RUMs, we can introduce an additional force, and hence a torque, on the device on which the RUMs are mounted in order to position and reposition the scan center. And, as indicated, the period of this cyclic component is the same as the period of rotation of the RUMs. The means for pointing the RUM-mounted instrument according to the invention hence include sensing means producing elevation and cross-elevation departure angles from a given center-of-scan, and sensing means producing the rate of change in the elevation and cross-elevation departure angles. Also included is a programmable logic controller means determining scan errors and rate-of-change in the scan errors in both elevation and cross-elevation axes from the departure angles and their rate-of-change, and for converting these errors and error rates-of-change to a RUM cyclic angular velocity component and to a locus in the RUM orbit where the peak of this cyclic component is to be applied. Means responsive to the controller means superimpose on the RUM constant angular velocity during a given cycle, the cyclic component phased in the RUM cycle to induce a torque which when combined with the operating high frequency torque produces a resultant torque vector over the RUM cycle which acts to compensate for the departure from the center-of-scan.

DETAILED DESCRIPTION OF THE INVENTION

In addition to eliminating an auxiliary control system, and this is important as emphasized in Ser. No. 08/123,629 filed Sep. 15, 1993, and now U.S. Pat. No. 5,396,815, the process of augmenting or modulating the constant angular velocity required for scanning with RUM devices yields some interesting results. These results are quite surprising in the light of what was learned during the operation of RUM devices described in U.S. Pat. No. 5,129,600. Throughout that patent the fact that drive means are adapted for rotatably driving the shaft at a constant angular velocity is confirmed. It is pointed out that when steady state operating conditions are attained, it is desired that the angular velocity of the masses not be accelerated or decelerated. The angular velocity is adjusted up or down for shorter or longer scan periods, but once the scan period is established, the velocity must be constant to maintain that scan period.

Herein the desired scan period is still maintained by retaining a constant angular velocity, but superimposed on that angular velocity, once per cycle, is a modulating cyclic component. Since this cyclic component is introduced on top of, or in addition to, the nominal angular velocity once each revolution by the rotating unbalanced-masses, a net torque is generated each revolution. This generated net torque is, in effect, a vector. It has magnitude and direction. The magnitude of this torque vector is proportional to the amplitude of the cyclic component of the angular velocity, and its direction is a function of the point or locus in the orbit where the cyclic component's peak occurs. It remains, then, to determine the magnitude of the resultant torque vector, and to define the locus in the circle where the cyclic component peak occurs-in other words, where in the 360 degree cycle or RUM orbit the peak of the cyclic component of the RUM angular velocity should be effected. This, of course, is engineering within the skill of the art. Programmable logic controllers are commonly employed in industry which respond to position and rate sensors. They are in wide use in the machine tool industry for lathes, milling machines, and the like. It will be apparent that modifications of these computerized sensing devices can be made to establish the cyclic component's amplitude and phase in a given RUM revolution. From a process point of view, on the other hand, it will be helpful to discuss the steps of the invention herein. This process includes: measuring elevation and cross-elevation angles and the rate-of-change of these angles to determine any offset and offset time rate-of-change, calibrating the magnitude and direction components of the offset about the elevation and cross-elevation axes, converting these components to a RUM angular velocity cyclic component for superimposition on the nominal angular velocity component, and to a locus of the RUM 360 degree orbit where the peak of this cyclic component is to occur, accelerating the speed of the RUMS and decelerating the RUMs each cycle to produce the desired angular velocity, thereby modulating the angular velocity to generate a resultant torque vector each cycle whose direction is dependent upon the location of the locus in the. RUM orbit where the peak of the cyclic component of the RUM angular velocity occurs, and which acts to compensate for the departure from the center-of-scan.

Although the determination of the locus in the RUM orbit where the peak of the cyclic component of the angular velocity occurs and the magnitude of this peak are within the skill of the art, it will also be helpful to describe one method for calibrating and determining these variables. It has been pointed out that the resultant torque vector magnitude is proportional to the magnitude of the cyclic component of the RUM angular velocity, and that its direction is a function of the locus in the orbit where this peak occurs. Considering first the direction of the torque vector, telescope-mounted attitude sensors indicate the orientation of the telescope line-of-sight (LOS) relative to its base, and all angles are calibrated to this 0 degree baseline. Attitude sensors, in the form of gimbal incremental encoders, measure changes in elevation and cross-elevation gimbal angles relative to this baseline. From these changes, every T seconds (e.g. T=0.0075 sec), the elevation and cross-elevation angles are estimated by summing the encoder outputs. The resulting estimated elevation and cross-elevation angles are denoted herein as $\theta_E(nT_{pscan}–jT)$ and $\theta_x(nT_{pscan}–jT)$, respectively, where n=1,2, . . . , j=0,1,2, . . . , N–1, and T_{pscan}=NT. These estimated angles, and the commanded elevation and cross-elevation angles at a time $nT_{pscan}–jT$, denoted by $\theta_{EC}(nT_{pscan}–jT)$ and $\theta_{XC}(nT_{pscan}–jT)$ respectively, can be used to calculate the errors in the scan center. The errors in the scan center at time nT_{pscan}, $Av\theta_{Ec}(nT_{pscan})$ and $Av\theta_{Xe}(nT_{pscan})$, can be derived from equations (1) and (2).

$$Av\theta_{Ee}(nT_{pscan}) = 1/N \sum_{j=0}^{N-1} [\theta_{EC}(nT_{pscan} - jT) - \theta_E(nT_{pscan} - jT)] \tag{1}$$

$$Av\theta_{Xe}(nT_{pscan}) = 1/N \sum_{j=0}^{N-1} [\theta_{XC}(nT_{pscan} - jT) - \theta_X(nT_{pscan} - jT)] \tag{2}$$

It will be noted that the errors in the scan center are an average (Av) of N instantaneous scan errors equally spaced in time over a RUM scan period. These errors in scan, or calculated averages, are components used in combination with the time rate-of-change of the scan errors as will be described.

The time rate-of-change of the scan errors are similarly derived. Tachometers measure the rate-of-change in the gimbal angles. The tachometer outputs are sampled every T seconds or N times over a scan period, T_{pscan} seconds. These sampled tachometer outputs for the elevation and cross-elevation gimbals, denoted by $\Omega_E(nT_{pscan}–jT)$ and $\Omega_X(nT_{pscan}–jT)$ respectively, are subtracted from the commanded gimbal rates $\Omega_{Ec}(nT_{pscan}–jT)$ and $\Omega_{XC}(nT_{pscan}–jT)$ to produce the gimbal rate errors, $\Omega_{Ee}(nT_{pscan}–jT)$, and $\Omega_{Xe}(nT_{pscan}–jT$. These are averaged over N values in a RUM revolution to yield the following equations.

$$Av\Omega_{Ee}(nT_{pscan}) = 1/N \sum_{j=0}^{N-1} [\Omega_{EC}(nT_{pscan} - jT) - \Omega_E(nT_{pscan} - jT)] \tag{3}$$

$$Av\Omega_{Xe}(nT_{pscan}) = 1/N \sum_{j=0}^{N-1} [\Omega_{XC}(nT_{pscan} - jT) - \Omega_X(nT_{pscan} - jT)] \tag{4}$$

It can be seen that the differences between the actual and the commanded elevation and cross-elevation angles are averaged using equations (1) and (2) in order to obtain $Av\theta_{Ee}$

and $Av\theta_{Xe}$. In the same manner, $Av\Omega_{Ee}$ and $Av\Omega_{Xe}$ are determined using equations (3) and (4). Thus, once every scan period, which is T_{pscan} seconds, equations (1) thru (4) are solved to yield the estimated scan errors, and the time rate-of-change of those errors. By using the values for the errors in the center-of-scan and the time rate-of-change of those errors derived from equations (1) thru (4), the parameters $\delta\Omega_{RP2}$ and $\delta\Omega_{RP3}$ can be determined. These parameters are the elevation and cross-elevation components of the desired amplitude for the cyclic component of the RUM angular velocity for the next RUM revolution. To find these parameters, the scan errors and error rates from equations (1) thru (4) are input into proportional-integral controllers with rate feedback. The integrals of the scan errors are thus determined by the following equations.

$$AvI_{Ee}(nT_{pscan})=AvI_{Ee}[(n-1)T_{pscan}]+\theta_{Ee}(nT_{pscan}) \tag{5}$$

$$AvI_{Xe}(nT_{pscan})=AvI_{Xe}[(n-1)T_{pscan}]+\theta_{Xe}(nT_{pscan}) \tag{6}$$

where initially $AvI_{Ee}(0)=AvI_{Xe}(0)=0$.

From these integral values and the averages derived by equations (1) thru (4), $\delta\Omega_{RP2}$ and $\delta\Omega_{RP3}$ can be determined by equations (7) and (8).

$$\delta\Omega_{RP2}(nT_{pscan})=k_R[k_p Av\theta_{Ee}(nT_{pscan})+k_I AvI_{Ee}(nT_{pscan})-Av\Omega_{Ee}(nT_{pscan})] \tag{7}$$

$$\delta\Omega_{RP3}(nT_{pscan})=k_R[k_p Av\theta_{Xe}(nT_{pscan})+k_I AvI_{Xe}(nT_{pscan})-Av\Omega_{Xe}(nT_{pscan})] \tag{8}$$

The desired instantaneous value for the cyclic component of the RUM angular velocity in the (n+1) revolution of the RUMs is given by equation (9).

$$\delta\Omega_{RC}(nT_{PSCAN}+kT)=\delta\Omega_{RP3}(nT_{PSCAN})\mathrm{COS}[\theta_{RC}(nT_{PSCAN}+kT)]-\delta\Omega_{RP2}(nT_{PSCAN})\mathrm{SIN}[\theta_{RC}(nT_{PSCAN})+kT)] \tag{9}$$

where $k=0, 1, 2, \ldots, N-1$. The angle θ_{RC} is the commanded RUM angle that the RUM servos are slaved to follow.

This control law specifies the additional, augmented, RUM rate, $\delta\Omega_{RC}(nT_{PSCAN}+kT)$, desired at a time $nT_{PSCAN}+kT$, to be added to the nominal commanded RUM rate, as determined from the elevation and cross-elevation components previously derived and described. This control law inherently generates the proper cyclic component of the RUM angular velocity, with proper magnitude and phase values, that produces a net torque over the (n+1) RUM cycle that acts to recenter the scan.

THE DRAWING

At this juncture it will be helpful to describe an instrument which is operated by rotating unbalanced-masses. One such instrument is shown in the accompanying drawing.

FIG. **1** is an isometric view of a double-gimballed scanning instrument showing the rotating unbalanced-masses and their rotation orbits.

SPECIFIC EMBODIMENTS

Gimbals can be mounted on a space station, a space shuttle, hung from a scientific balloon, or mounted firmly on the ground. However for the purposes of illustration herein, assume that the body or payload to be pointed, say a telescope **2**, is supported by elevation and cross-elevation gimbals **4** and **6** respectively. The instrument or payload **2** is carried by a gimbal **6** through a known axle system which permits it to move horizontally relative to payload base **8**. Cross-elevation gimbal ring **6** is carried by elevation gimbal **4** permitting vertical movement with respect to base **8**. In some instances gimbal **6** will be a ring. In the embodiment herein the base of gimbal **4** is embedded in or secured to a platform **8**. In order to permit payload movement the axle system includes two axle means **10** and **12**. Herein axis **12** is the P_3 axis and **10** is the P_2 axis. In addition, to discuss front RUM **20** and rear RUM .**22** are shown, along with the telescope line-of-sight (LOS) or P_1 axis. The front of the telescope, then, is the end depicting the direction of RUM rotation. When the line-of-sight of the instrument is perpendicular to the planes-of-rotation of the RUMs, the scan is circular. When the line-of-sight of the instrument is parallel to the planes-of-rotation of the RUMs, the scan is a linear scan.

Positioning and repositioning, or pointing, means, termed auxiliary control systems, are normally a part of a payload operated by RUMs. These include such elements as gears, stepper or torque motors, cams, pitman arms, linkages, and even pulleys. Herein all of those mechanical parts are eliminated and replaced by the operation of the RUMs as described hereinbefore.

Having been given the teachings of this invention, variations and ramifications will occur to those skilled in the art. Whereas a gimballed RUM instrument has been described, it will be appreciated that instrument-mounted optical attitude sensors and gyroscopic inertial rate sensors are available for use on freely suspended instruments, say in space, on tethers, or on balloons. Further, the method for determining the RUM cyclic angular velocity component can best be implemented in a computer program which can more readily iterate the functions and determine solutions to equations (1) thru (9). The key algorithms in the program are set forth in Table a at lines **236** to **356**.

Table a

```
C
      THRBC=THRC
      THRBH=THRBC
      THRBE=0.0
      THRBEI=0.0
C
      THGXCO=+00.00*DTR
      THGXC=THGXCO-THGXCM*COS(THRC)
      OMGXC=OMGXCM*SIN(THRC)
      THGXH=THGXC-(10.0*DTR)
      THGXEI=0.0
C

      THGECO=00.00*DTR
      THGEC=THGECO+THGECM*SIN(THRC)
      OMGEC=OMGECM*COS(THRC)
      THGEH=THGEC-(90.0*DTR)
      THGEEI=0.0
C
      DWRP3=0.0
      DWRP2=0.0
C
      OMGXEA=0.0
      THGXEA=0.0
      WGXIC=0.0
      XN=1.0
C
      OMGEEA=0.0
      THGEEA=0.0
      WGEIC=0.0
      EN=1.0
C
C    INITIAL CONDITIONS FOR PLANT
      THRA=THRAC
      OMRA=0.0
      TAURA=0.0
C
      THRB=THRBC
      OMRB=0.0
      TAURB=0.0
C
      THGX=THGXH
      OMGX=0.0
      OMGXM=0.0
      TAUGX=0.0
C
      THGE=THGEH
      OMGE=0.0
      OMGEM=0.0
      TAUGE=0.0
C
      DO 12 I=1,6
 12   BB(I)=0.
      TMIN=10.0
      WRITE(2,15)
 15   FORMAT (20X,'STEADY STATE CONDITIONS',/,25X,'PEAK VALUES',/,
     *2X,'MA',2X,'T rum A',3X,'T rum B',5X,'T xel',3X,'T el',5X,'THETA
     *xel',3X,'THETA el',5X,'POWER')
C  SIMULATION BEGINS HERE  *********************************************
  100 CONTINUE
C
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```
C  TEST FOR TIME TO CYCLE THRU CONTROL MICROPROCESSOR  ******************
      IF(KNTC.GT.0)GO TO 200
C
C    READ INCREMENTAL ENCODER OUTPUTS:
      DTHRA=THRA-THRAH
      CALL QUANT(IQENC,ENCBTS,ENCRG,DTHRA,DTHRAQ)
      DTHRB=THRB-THRBH
      CALL QUANT(IQENC,ENCBTS,ENCRG,DTHRB,DTHRBQ)
      DTHGX=THGX-THGXH
      CALL QUANT(IQENC,ENCBTS,ENCRG,DTHGX,DTHGXQ)
      DTHGE=THGE-THGEH
      CALL QUANT(IQENC,ENCBTS,ENCRG,DTHGE,DTHGEQ)
C
C    UPDATE ESTIMATED PLANT STATES:
      THRAH=THRAH+DTHRAQ
      THRBH=THRBH+DTHRBQ
      THGXH=THGXH+DTHGXQ
      THGEH=THGEH+DTHGEQ
C
C    SOLVE CONTROL LAW EQS:
C      X-EL GIMBAL CONTROL LAW:
      THGXC=THGXCO-THGXCM*COS(THRC)
      OMGXC=+OMGXCM*SIN(THRC)
      THGXE=THGXC-THGXH
      OMGXE=OMGXC-OMGXM
      THGXEA=(THGXEA*(XN-1.0)/XN)+(THGXE/XN)
      OMGXEA=(OMGXEA*(XN-1.0)/XN)+(OMGXE/XN)
      XN=XN+1.0
C
C      EL GIMBAL CONTROL LAW:
      THGEC=THGECO+THGECM*SIN(THRC)
      OMGEC=OMGECM*COS(THRC)
      THGEE=THGEC-THGEH
      OMGEE=OMGEC-OMGEM
      THGEEA=(THGEEA*(EN-1.0)/EN)+(THGEE/EN)
      OMGEEA=(OMGEEA*(EN-1.0)/EN)+(OMGEE/EN)
      EN=EN+1.0
C
C      CORRECTION TERM FOR POINTING WITH RUM'S:
      DWRC=DWRP3*COS(THRC)-DWRP2*SIN(THRC)
      LDTHRC=DWRC*TS
C
C      RUM A SERVO CONTROL LAW:
      DTHRAE=DTHRAC-DTHRAQ+LDTHRC
      TRAC=IRAH*(KRR*DTHRAE+KRP*THRAE+KRI*THRAEI)
      CALL QUANT(IQTQM,TQMBTS,TQMRG,TRAC,TRACQ)
      TRAM=(1.0+CRTQM*(ABS(SIN(FRTQM*THRA))-1.0))*TRACQ
C
C      RUM B SERVO CONTROL LAW:
      DTHRBE=DTHRBC-DTHRBQ+LDTHRC
      TRBC=IRBH*(KRR*DTHRBE+KRP*THRBE+KRI*THRBEI)
      CALL QUANT(IQTQM,TQMBTS,TQMRG,TRBC,TRBCQ)
      TRBM=(1.0+CRTQM*(ABS(SIN(FRTQM*THRB))-1.0))*TRBCQ
C
C    FOR NEXT COMP CYCLE:
C      READ/COMPUTE NEW COMMANDS, IF CHANGED:
      IF(T.LT.TCHNG)GO TO 150
      DTHRC=2.0*DTHRC
      DTHRAC=2.0*DTHRAC
      DTHRBC=2.0*DTHRBC
      OMGXCM=2.0*OMGXCM
      OMGEC=OMGEC
      TCHNG=T+DTCHNG
  150 CONTINUE
C      UPDATE CONTROLLER STATES:
      THRC=THRC+DTHRC
      IF(ABS(THRC).LE.TWPI)GO TO 155
      THRC=THRC-SIGN(TWPI,THRC)
```

```
C
      OMGXEAS=OMGXEA
      THGXEAS=THGXEA
      WGXPC=KGXP*THGXEAS
      IF(ABS(WGXPC).GT.WGXPCL)WGXPC=SIGN(WGXPCL,WGXPC)
      WGXIC=WGXIC+KGXI*THGXEAS
      IF(ABS(WGXIC).GT.WGXICL)WGXIC=SIGN(WGXICL,WGXIC)
      DWRP3=KGXR*(WGXIC+WGXPC+OMGXEAS)

C
      OMGEEAS=OMGEEA
      THGEEAS=THGEEA
      WGEPC=KGEP*THGEEAS
      IF(ABS(WGEPC).GT.WGEPCL)WGEPC=SIGN(WGEPCL,WGEPC)
      WGEIC=WGEIC+KGEI*THGEEAS
      IF(ABS(WGEIC).GT.WGEICL)WGEIC=SIGN(WGEICL,WGEIC)
      DWRP2=KGER*(WGEIC+WGEPC+OMGEEAS)
C
      THGXEA=0.0
      THGEEA=0.0
      OMGXEA=0.0
      OMGEEA=0.0
      XN=1.0
      EN=1.0
C
  155 CONTINUE
C          RUM A:
      THRAEI=THRAEI+THRAE
      THRAE=THRAE+DTHRAE
      THRAC=THRAC+DTHRAC
      IF(ABS(THRAC).LE.TWPI)GO TO 160
      THRAC=THRAC-SIGN(TWPI,THRAC)
      THRA = THRA-SIGN(TWPI,THRAC)
      THRAH=THRAH-SIGN(TWPI,THRAC)
  160 CONTINUE
C
C          RUM B:
      THRBEI=THRBEI+THRBE
      THRBE=THRBE+DTHRBE
      THRBC=THRBC+DTHRBC
      IF(ABS(THRBC).LE.TWPI)GO TO 165
      THRBC=THRBC-SIGN(TWPI,THRBC)
      THRB = THRB-SIGN(TWPI,THRBC)
      THRBH=THRBH-SIGN(TWPI,THRBC)
  165 CONTINUE
C
C          X-EL GIMBAL:
      THGXEI=THGXEI+THGXE
C          EL GIMBAL:
      THGEEI=THGEEI+THGEE
C        RESET MICROCONTROLLER COUNTER
      KNTC=KNTCM
  200 CONTINUE
C
C  COMPUTE DISTURBANCE TORQUES & SUM WITH CONTROL TORQUES   *************
      SA=SIN(THRA)
      CA=COS(THRA)
      SB=SIN(THRB)
      CB=COS(THRB)
      SX=SIN(THGX)
      CX=COS(THGX)
      SE=SIN(THGE)
      CE=COS(THGE)
C
      TRAD=+RMGA*(THGX*SA*SE-CA*CE)
      TRAF=-TAURA
      TRAT=TRAM+TRAF+TRAD
C
      TRBD=-RMGB*(THGX*SB*SE-CB*CE)
      TRBF=-TAURB
      TRBT=TRBM+TRBF+TRBD
```

```
C
      TGXD=DRMA*OMRA*OMRA*CA+DRMB*OMRB*OMRB*CB
      TGXD=TGXD-MGA*SE*(DA*THGX+RA*CA)
     1                             +MGB*SE*(DB*THGX+RB*CB)
      TGXF=-TAUGX
      TGXT=TGXF+TGXD+TGXDIST
C
      TGED=+MGA*(DA*CE+RA*SA*SE)-MGB*(DB*CE+RB*SB*SE)
     1                        -DRMA*OMRA*OMRA*SA-DRMB*OMRB*OMRB*SB
      TGEF=-TAUGE
      TGET=TGEF+TGED+TGEDIST
C
C  COMPUTE DAHL MODEL PARAMETERS
      DAHLRA=OMRA*SIG*(1.0-(SIGN(1.0,OMRA))*TAURA/TAUM)
      DAHLRB=OMRB*SIG*(1.0-(SIGN(1.0,OMRB))*TAURB/TAUM)
      DAHLGX=OMGX*SIG*(1.0-(SIGN(1.0,OMGX))*TAUGX/TAUM)
      DAHLGE=OMGE*SIG*(1.0-(SIGN(1.0,OMGE))*TAUGE/TAUM)
C
  300 CONTINUE
C
C  COMPUTE STATE DERIVATIVES  ******************************************
      THRAD=OMRA
      OMRAD=TRAT/IRA
      TAURAD=DAHLRA
C
      THRBD=OMRB
      OMRBD=TRBT/IRB
      TAURBD=DAHLRB
C
      THGXD=OMGX
      OMGXD=TGXT/IGX
      OMGXMD=WFTAC*(OMGX-OMGXM)
      TAUGXD=DAHLGX
C
      THGED=OMGE
      OMGED=TGET/IGE
      OMGEMD=WFTAC*(OMGE-OMGEM)
      TAUGED=DAHLGE
C
C  TEST FOR TIME TO STOP  *********************************************
      IF(T.GT.TMAX)THEN
      POWERR=(BB(1)/0.57)**2+(BB(2)/0.57)**2
      POWERG=(BB(3)/0.61)**2+(BB(4)/0.61)**2
      POWER=POWERR+POWERG
      WRITE(2,5)MB,BB(1),BB(2),BB(3),BB(4),BB(5),BB(6),POWER
 5    FORMAT(F4.3,6F10.6,5X,F5.2)
      WRITE(3,50)IGXE,IGX,POWER,BB(5),BB(6)
 50   FORMAT(F5.1,2X,F6.3,2X,F7.2,2X,F10.6,2X,F10.6)
      WRITE(4,60)RAE,RA,POWER,BB(5),BB(6)
 60   FORMAT(1X,6E10.3)
      CALL STAT(SDAT1,NTOTPL,XMEAN,STDEV,RMS)
      DUM=25.0
      WRITE(7,60)DUM,XMEAN,STDEV,RMS
      CALL STAT(SDAT2,NTOTPL,XMEAN,STDEV,RMS)
      DUM=29.0
      WRITE (7,60)DUM,XMEAN,STDEV,RMS
      CALL STAT(SDAT3,NTOTPL,XMEAN,STDEV,RMS)
      DUM=26.0
      WRITE(7,60)DUM,XMEAN,STDEV,RMS
      CALL STAT(SDAT4,NTOTPL,XMEAN,STDEV,RMS)
      DUM=30.0
      WRITE(7,60)DUM,XMEAN,STDEV,RMS
      CALL STAT(SDAT5,NTOTPL,XMEAN,STDEV,RMS)
      POWRMS=(RMS/0.57)**2
      POWRMST=POWRMS
      DUM=40.0
      WRITE(7,60)DUM,XMEAN,STDEV,RMS,POWRMS,POWRMST
      CALL STAT(SDAT6,NTOTPL,XMEAN,STDEV,RMS)
      POWRMS=(RMS/0.57)**2
      POWRMST=POWRMST+POWRMS
      DUM=41.0
      WRITE(7,60)DUM,XMEAN,STDEV,RMS,POWRMS,POWRMST
      CALL STAT(SDAT7,NTOTPL,XMEAN,STDEV,RMS)
      POWRMS=(STDEV/0.61)**2
```

```
      POWRMST=POWRMST+POWRMS
      DUM=42.0
      WRITE(7,60)DUM,XMEAN,STDEV,RMS,POWRMS,POWRMST
      CALL STAT(SDAT8,NTOTPL,XMEAN,STDEV,RMS)
      POWRMS=(STDEV/0.61)**2
      POWRMST=POWRMST+POWRMS
      DUM=43.0
      WRITE(7,60)DUM,XMEAN,STDEV,RMS,POWRMS,POWRMST
      STOP
      ENDIF
C
C  TEST FOR TIME TO PRINT & RESET KNTPR  *******************************
      IF(T.LT.0.0.OR.KNTPR.GT.0)GO TO 400
C
C  PRINT & RESET KNTPR  ************************************************
      KNTPR=KNTPRM
C
  400 CONTINUE
C
C  TEST FOR TIME TO STORE VARIABLES FOR PLOTTING & RESET KNTPL  ********
      IF(T.LT.0.0.OR.KNTPL.GT.0)GO TO 500
C
C  STORE VARIABLES FOR PLOTTING & RESET KNTPL  *************************
      AA(1)=T
C
      AA(2)=THRA
      AA(3)=OMRA
      AA(4)=TAURA
C
      AA(5)=THRB
      AA(6)=OMRB
      AA(7)=TAURB
C
      AA(8)=THGX*RTD
      AA(9)=OMGX
      AA(10)=OMGXM
      AA(11)=TAUGX
C
      AA(12)=THGE*RTD
      AA(13)=OMGE
      AA(14)=OMGEM
      AA(15)=TAUGE
C
C
      AA(16)=THRAC
      AA(17)=THRAH
      AA(18)=THRAE
      AA(19)=THRAEI
C
      AA(20)=THRBC
      AA(21)=THRBH
      AA(22)=THRBE
      AA(23)=THRBEI
C
      AA(24)=(THGXC-THGXCO)*RTD
      AA(25)=(THGXH-THGXCO)*RTD
      AA(26)=THGXE*RTD
      AA(27)=THGXEAS*RTD
C
      AA(28)=(THGEC-THGECO)*RTD
      AA(29)=(THGEH-THGECO)*RTD
      AA(30)=THGEE*RTD
      AA(31)=THGEEAS*RTD
C
      AA(32)=OMGXC
      AA(33)=OMGEC
C
      AA(34)=TRAC
      AA(35)=TRBC
      AA(36)=DWRP3
      AA(37)=DWRP2
C
      AA(38)=DWRC
      AA(39)=LDTHRC
```

```
C
      AA(40)=TRAM
      AA(41)=TRBM
      AA(42)=WGXPC*RTD
      AA(43)=WGEPC*RTD
C
      AA(44)=TRAF
      AA(45)=TRBF
      AA(46)=TGXF
      AA(47)=TGEF
      AA(48)=OMGXEAS*RTD
      AA(49)=OMGEEAS*RTD
C
C     IPLSEL GIVES OPTION OF STORING SOME OTHER VARIABLES FOR PLOTTING
      IF(IPLSEL.EQ.0)GO TO 450
      AA(2)=THRAD
      AA(3)=OMRAD
      AA(4)=TAURAD
C
      AA(5)=THRBD
      AA(6)=OMRBD
      AA(7)=TAURBD
C
      AA(8)=THGXD
      AA(9)=OMGXD
      AA(10)=OMGXMD
      AA(11)=TAUGXD
C
      AA(12)=THGED
      AA(13)=OMGED
      AA(14)=OMGEMD
      AA(15)=TAUGED
C
  450 CONTINUE
      WRITE(1,452)AA
      NTOTPL=NTOTPL+1
      SDAT1(NTOTPL)=AA(25)
      SDAT2(NTOTPL)=AA(29)
      SDAT3(NTOTPL)=AA(26)
      SDAT4(NTOTPL)=AA(30)
      SDAT5(NTOTPL)=AA(40)
      SDAT6(NTOTPL)=AA(41)
      SDAT7(NTOTPL)=AA(42)
      SDAT8(NTOTPL)=AA(43)
  452 FORMAT(6E10.4)
      IF (T.LT.TMIN)GO TO 455
C     WRITE(40,*)AA(40)
C     WRITE(41,*)AA(41)
C     WRITE(42,*)AA(42)
C     WRITE(43,*)AA(43)
C     WRITE(26,*)AA(26)
C     WRITE(30,*)AA(30)
      CALL ARRFIL(AA,BB)
 455  CONTINUE
      KNTPL=KNTPLM
C
  500 CONTINUE
C
C  TEST FLAG IN MODIFIED-EULER INTEGRATION ROUTINE  ********************
      IF(INTFLG.GT.0)GO TO 600
C
C  PROJECT STATES & UPDATE INT. ROUTINE FLAG  **************************
      DO 505 I=1,N
      XP(I)=X(I)
      XDP(I)=XD(I)
  505 X(I)=XP(I)+XDP(I)*DT
      INTFLG=1
      GO TO 300
C
  600 CONTINUE
```

```
C
C  UPDATE STATES & TIME; RESET INT. ROUTINE FLAG; DECREMENT COUNTERS  **
      DO 605 I=1,N
      XDP(I)=0.5*(XDP(I)+XD(I))
  605 X(I)=XP(I)+XDP(I)*DT
  620 T=T+DT
      INTFLG=0
      KNTC=KNTC-1
      IF(T.GE.0.0)KNTPR=KNTPR-1
      IF(T.GE.0.0)KNTPL=KNTPL-1
      GO TO 100
      END
C**********************************************************************
      SUBROUTINE QUANT(IQFLG,NBITS,XMAX,X,XQ)
      XQ=X
      IF(IQFLG.EQ.0)GO TO 20
      XLSB=(2.0*XMAX)/(2.0**NBITS)
      XMAXP=XMAX-XLSB
      XMIN=-XMAX
      XDUM=XQ
      IF(XDUM.LT.XMIN)XDUM=XMIN
      IF(XDUM.GT.XMAXP)XDUM=XMAXP
      XDUM=XDUM+XMAX+XLSB/2.0
      XDUM=XDUM/XLSB
      IXDUM=XDUM
      XDUM=IXDUM
      XDUM=XDUM*XLSB
      XQ=XDUM-XMAX
   20 CONTINUE
      RETURN
      END
C**********************************************************************
      SUBROUTINE ARRFIL(AA,BB)
      REAL AA(50),BB(6)
C     IF(T.LT.TMIN)GO TO 20
      IF(ABS(AA(40)).GT.BB(1)) BB(1)=ABS(AA(40))
      IF(ABS(AA(41)).GT.BB(2)) BB(2)=ABS(AA(41))
      IF(ABS(AA(42)).GT.BB(3)) BB(3)=ABS(AA(42))
      IF(ABS(AA(43)).GT.BB(4)) BB(4)=ABS(AA(43))
      IF(ABS(AA(26)).GT.BB(5)) BB(5)=ABS(AA(26))
      IF(ABS(AA(30)).GT.BB(6)) BB(6)=ABS(AA(30))
C  20 CONTINUE
      RETURN
      END
C**********************************************************************
      SUBROUTINE STAT(X,NTOTPL,XMEAN,STDEV,RMS)
      DIMENSION X(NTOTPL)
      XMEAN=0.0
      XMEANSQ=0.0
      DO 10 I=1,NTOTPL
      RI=I
      RIM1=RI-1.0
      RATIO=RIM1/RI
      XMEAN=(RATIO*XMEAN)+(X(I)/RI)
   10 XMEANSQ=(RATIO*XMEANSQ)+(X(I)*X(I)/RI)
      RMS=SQRT(XMEANSQ)
      STDEV=SQRT(XMEANSQ-(XMEAN*XMEAN))
      RETURN
      END
C**********************************************************************
```

EXAMPLE 1

The program in Table a was used for a telescope with inertias $I_E=I_X=26$ slug-ft^2 and RUMs, each with a mass m=5 lb, mounted a distance d=2.5 ft from the center of gravity of the telescope. The RUM lever arm lengths were r=0.5 ft, and the scan period was $T_{pscan}=1$ sec. The control computer computation cycle time was T=0.0075 sec. Control law parameters were $k_I=0$, $k_p=0.44$, and $k_R=19$.

Assuming now that the telescope was initially mispointed −1 degree=−0.01745 radian in both the elevation and cross-elevation axes, then the control algorithms, equations (1) thru (9), solved by the program (see lines **236** to **356**) yield the following numerical results at T=1 sec.

$Av\theta_{Ee}(1\text{ sec})=+0.01745$ rad

$Av\theta_{Xe}(1\text{ sec})=+0.01745$ rad

$Av\Omega_{Ee}(1\text{ sec})=0.0$

$Av\Omega_{Xe}(1\text{sec})=0.0$

$AvI_{Ee}(1\text{ sec})=0.0$

$AvI_{Xe}(1\text{ sec})=0.0$

$\delta\Omega_{RP2}(1\text{ sec})=0.146$ rad/sec

$\delta\Omega_{RP3}(1\text{ sec})=0.146$ rad/sec

Over the next scan cycle the results are:

$$\begin{aligned}\delta\Omega_{RC}(1+kT) &= 0.146\cos(\theta_{RC})-0.146\sin(\theta_{RC})\\ &= 0.146\cos(\Omega_{RC}kT)-0.146\text{Sin}(\Omega_{RC}kT)\\ &= 0.146\cos(2\pi kT)-0.146\text{Sin}(2\pi kT)\end{aligned}$$

where kT=0.0075 sec, 0.015 sec, . . . , 0.9925 sec.

The nominal RUM rate, Ω_{RCN}, is equal to $2\pi/T_{pscan}=6.28$ rad/sec. Hence the next scan cycle will have a total RUM rate of

$$\begin{aligned}\Omega_{RCT}(1+kT) &= \Omega_{RCN}+\Omega_{RC}(1+kT)\\ &= 6.28+0.146\cos(2\pi kT)-0.146\text{Sin}(2\pi kT)\end{aligned}$$

It can be seen that by the practice of this invention the center-of-scan can be positioned accurately and automatically merely by the use of customary encoders and tachometers. In addition to utilizing RUMs for both pointing and scanning by the invention in order to eliminate the need for an auxiliary control system to keep the scan on target, a momentum desaturation system is not required. The RUMs do not momentum saturate as do reaction wheels and CMGs. And although a platform has been shown in the drawing for the purpose of illustration, RUMs used for pointing and scanning do not require gimbals and a base structure to torque against. A space-based, balloon-borne, or ground-based payload can be attached by means of a cable, a tether, or a rigid arm provided with a ball-and-socket or universal joint. The entire system is thus simplified. The use of RUMs for pointing and scanning insures that a gravity-gradient stabilized satellite stays pointed at the earth in spite of aerodynamic torques which tend to tumble or spin it. RUMs utilized as described herein can also potentially eliminate unwanted motions, such as skip rope motions and pendulous vibrations of tethered satellites. Use of RUMs for pointing and scanning according to this invention thus provides a far-reaching potential for the future of pointing control systems for free-flying spacecraft/satellites and space-based/balloon-borne/ground-based payloads.

What is claimed is:

1. A method for positioning and repositioning, that is pointing, a scanning instrument when the instrument is offset from a center-of-scan thereof and must be pointed to that center, wherein the instrument is a type whose scanning is accomplished by rotating unbalanced-masses (RUMS) rotating in fixed axes rotation relative to and associated with the instrument, and wherein the rotating unbalanced-mass instrument has first and second rotatable unbalanced-masses supported on respective drive shafts spaced from the center-of-mass of the instrument, and adapted to rotate 180 degrees out-of-phase with each other, with planes-of-rotation thereof parallel to each other, and at a constant nominal angular velocity so that centrifugal forces caused by rotation of the RUMs create a time-varying relatively large-amplitude/high-frequency reaction forces and torques which act on the instrument to move its line-of-sight in a predetermined, repetitive, scan pattern, the pointing method including the steps of: measuring elevation and cross-elevation angles and the rate-of-change of these angles to determine any offset and offset time rate-of-change, calibrating magnitude and direction components of the offset about elevation and cross-elevation axes, converting these components to a RUM cyclic angular velocity component on top of the nominal velocity, and to a locus of the RUM 360 degree orbit where a peak of this cyclic component is to occur, accelerating the speed of the RUMS and decelerating the RUMs each cycle to produce the required angular velocity, thereby modulating the angular velocity to generate a torque which when combined with the high-frequency torque produces a resultant torque vector each cycle whose direction is dependent upon the location of the locus in the RUM orbit where a peak of the cyclic component of the RUM angular velocity occurs, and which acts to compensate for the offset from the center-of-scan.

2. The pointing method of claim **1** wherein the line-of-sight of the instrument is perpendicular to the planes-of-rotation of the RUM masses.

3. The pointing method of claim **1** wherein the line-of-sight of the instrument is parallel to the planes-of-rotation of the RUM masses.

4. The pointing method of claim **1** wherein the speed of the RUMs is gradually increased and decreased during each revolution to achieve the required magnitude and direction of the resultant torque vector for recentering the scan.

5. The pointing method of claim **1** wherein the elevation and cross-elevation angles and their rates-of-change are differenced with desired values thereof and then averaged over each RUM orbit to determine the offset in the scan center and the time rate-of-change of this offset.

6. The pointing method of claim **5** wherein the averaging and RUM angular velocity modulation steps are iterated over several cycles, with each approaching the required center-of-scan position, and continuing the iteration until the required center-of-scan position is reached.

* * * * *