(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
19 December 2002 (19.12.2002)

PCT

(10) **International Publication Number**
WO 02/101432 A2

(51) **International Patent Classification**^{7}: **G02B 6/00**

(21) **International Application Number:** PCT/US02/03907

(22) **International Filing Date:** 17 January 2002 (17.01.2002)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
60/262,489 17 January 2001 (17.01.2001) US
09/849,765 4 May 2001 (04.05.2001) US

(71) **Applicant: CORNING INCORPORATED** [US/US]; 1 Riverfront Plaza, Corning, NY 14831 (US).

(72) **Inventors: BAUGH, Steven, A.**; 10404 Oso Court NE, Albuquerque, NM 87111 (US). **BRADEN, Dennis, M.**; P.O. Box 60, Sandia Park, NM 87047 (US). **ELERATH, Douglas, E.**; P.O. Box 454, Sandia Park, NM 87047 (US). **NASH, Brian, K.**; 14 Goode Road, Edgewood, NM 87015 (US). **ROGERS, Samuel, C., Jr.**; 5901 Canyon Crest Place, Albuquerque, NM 87111 (US).

(74) **Agent: BEAN, Gregory, V.**; Corning Incorporated, SP TI 3 1, Corning, NY 14831 (US).

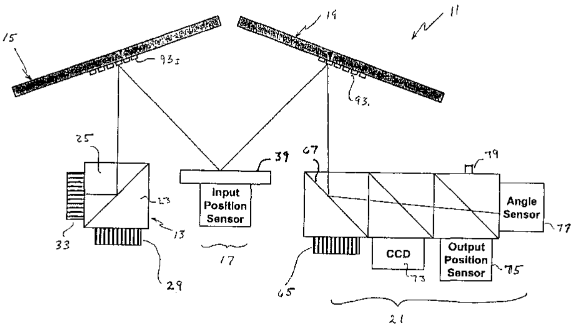
(81) **Designated States** *(national)*: CA, CN, JP.

(84) **Designated States** *(regional)*: European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR).

Published:
— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) **Title:** OPTICAL SWITCH WITH TIME MULTIPLEXING CONTROL SYSTEM ARCHITECTURE



(57) **Abstract:** An optical system for switching a plurality of input communication beams, where each communication beam can be switched from a first output to a second output, and where switching is affected by the use of alignment beams (not the communications beams). This enables the paths to be held even if the associated communication beam is off. The switch includes: *n* communication beam inputs; *n* alignment beam inputs; apparatus for generating*n* alignment beams; apparatus for aligning the communication beams with the alignment beams such that each input communication beam is aligned with a specific alignment beam; an array of*n* input MEMS, each of which is aligned with a specific communication beam input; an array of *n* output MEMS; and *n* outputs, each of which is aligned with a specific output MEMS. The switch also incorporates apparatus for time sequentially energizing the apparatus for generating the alignment beams. This time multiplexing permits the use of a plurality monolithic high bandwidth, high resolution detectors and a single control system. The first input detector is positioned between the input MEMS and the output MEMS, for sensing the positions of all the alignment beams incident from the input beam directing surfaces. The system also includes a controller which is connected to the input beam directing surface, the output beam directing surface, the input position sensor, the angular position sensor and the output position sensor. The controller, the angle position sensor and the output position sensor function in concert to provide the four degrees of control required to properly control the positions of the MEMS.

WO 02/101432 A2

OPTICAL SWITCH WITH TIME MULTIPLEXING CONTROL SYSTEM ARCHITECTURE

Cross-Reference to Related Application

[0001] This application is a continuation-in-part of provisional application Serial No. 60/262,489, filed 17 January 2001, the disclosure of which is incorporated by reference.

Field of the Invention

[0002] This invention relates to improvements in fiber optics switches using MEMS arrays. More particularly, this invention relates to an optical design, which includes an input alignment array, an input position sensor and a plurality of output position sensors (including both position and angle sensors). This invention also relates to a time multiplexing control system architecture for switching channels and maintaining alignment between an optically connected input and output fiber.

Background of the Invention

[0003] Due to the advantages over electrical signals, such as speed, increased bandwidth and signal quality, the use of fiber optics in communications networks has become common. However, as with electrical signals transmitted over wires, optical signals need to be switched between different optical fibers at appropriate junctions so that such optical signals reach their intended destinations. The conventional way of switching optical signals between fibers is to convert the optical signals to electrical signals, employ conventional electronic switching components to switch the electrical signals, and then reconvert the electrical signals back to optical signals. While effective, this process adds both delay (electronic switching is slower than optical switching) and cost to the switching process.

[0004] To overcome this drawback, photonic switches built with mirrors based on MEMS (Micro Electro Mechanical Systems) technology are being developed.

[0005] International patent application No. PCT/US99/12550, published 23 December 1999, discloses an optical switch, which includes a first array of reflectors (each associated with a separate optical input fiber) and a second array of reflectors (each associated with a separate output fiber). The reflectors are positionable to direct an optical signal from any one of the input fibers to any one of the output fibers. No electronic or other controls are disclosed for positioning the reflectors in the desired orientations, moving them from one orientation to another, or maintaining them in a desired orientation.

[0006] International patent application No. PCT/US99/12334, published 29 December 1999, discloses a mirror based fiber optic switch and control system. The optical control system includes a fiber assembly, a signal separator, a sensor unit, a lens assembly, a stationary mirror, a targeting radiation emitting diode, a moveable mirror assembly with mounted alignment radiation emitting diodes, and a processor. The separator separates the control signals from the communication signals so that the control signals are received by the sensor unit and the communication signals are received by the fiber. The control signals received by the sensor unit provide target identification and alignment information connecting target fibers. The mirror assembly is used to actuate both targeting and alignment adjustments. The mirror surface of the moveable mirror assembly moves in response to commands from the processor to allow for adjustment of the optical path of the communication and control signals. Separate sources and sensors are used for targeting and alignment.

[0007] International patent application No. PCT/US99/21139 discloses what is described as a flexible, modular compact fiber optic switch. Servo control systems are disclosed in this application.

Summary of the Invention

[0008] An optical system for switching a plurality of input communication beams, where each communication beam can be switched from a first output to a second output, and where switching is affected by the use of alignment beams (not the communications beams). This enables the paths to be held even if the associated communication beam is off. The switch includes: *n* communication beam inputs; *n* alignment beam inputs; apparatus for generating *n* alignment beams; apparatus for aligning the communication beams with the alignment beams such that each input communication beam is aligned with a specific alignment beam; an array of *n* input beam directing surfaces, each of which is aligned with a specific communication beam input; an array of *n* output beam directing surfaces; and *n* outputs, each of which is aligned with a specific output beam directing surface. Each of the input beam directing surfaces and each of the output beam directing surfaces is incorporated in a MEMS device. Each MEMS device includes a reflecting surface, apparatus for supporting the reflecting surface for movement about two independent (e.g., substantially orthogonal) axes.

[0009] The switch also incorporates: apparatus for time sequentially energizing the apparatus for generating the alignment beams. This time multiplexing permits the use of a plurality monolithic detectors and a single control system. The first, input detector is positioned between the input beam directing surfaces and the output beam directing surfaces, for sensing the positions of all the alignment beams incident from the input beam directing surfaces. The first detector includes a high bandwidth, high resolution detector, such as a PSD. The first detector also includes a surface for reflecting substantially all communication beam wavelengths, while partially transmitting and partially reflecting the alignment beam wavelengths. This surface has a coating having reflective properties specific to those communication beam wavelengths reflected, and reflective and transmission properties specific to those alignment beam wavelengths which are partially reflected and partially transmitted. Monolithic output position detectors, preferably high bandwidth, high resolution detectors, are also included. One is an angle sensor, the other is a position sensor. Both utilize portions of the alignment beam associated with the beam to be switched.

[0010] The system also includes a controller which is connected to the input beam directing surface, the output beam directing surface, the input position sensor, the angular position sensor and the output position sensor. The controller, the angle position sensor and the output position sensor function in concert to provide the four degrees of control required to properly control the positions of the input beam directing surface and the output beam directing surface. The system further includes apparatus for providing low bandwidth drift compensation, preferably a CCD, and an output alignment beam, which is a single source and which is energized in sequence with the alignment beams.

[0011] The switch incorporates an optical assembly, including: a first beam splitter; a second beam splitter optically coupled to the first beam splitter; and a third beam splitter optically coupled to the second beam splitter. The first beam splitter includes a first coating for reflecting, approximately, 100% of wavelengths used for alignment and up to 10% of wavelengths used for communications. The first coating passing at least 90% of wavelengths used for communication. The optical system further includes *n* outputs which are coupled to the first beam splitter to receive those wavelengths used for communication passed by the first coating. The second beam splitter includes a second coating for reflecting approximately 100% of wavelengths used for communication and passing approximately 100% of wavelengths used for alignment. The third beam splitter includes a third coating for passing, approximately 50% of wavelengths used for alignment and reflecting the balance of said alignment wavelengths. The angle position sensor and output position sensor are secured to this last beam splitter.

[0012] The controller includes means for sending an input command signal to the driver associated with the input beam directing surface aligned with the communication beam to be switched, to change its orientation. The input sensor, which is connected to the controller, sends information signals to the controller on the location of the associated alignment beam on the input position sensor. The controller determines the difference between the input command signal and the information signals received from the input position sensor, and sends a correction signal to the driver. The angle sensor also sends information signals to the controller on the location of the alignment beams on the sensor. In response, the controller sends an output command signal to the output driver associated with the output beam directing surface aligned with the desired output, to change the orientation of this beam output directing surface. The controller also determines the difference between the output command signal and the information signal received from the angle sensor and sends a correction signal to the output drive to move the associated directing surface until the difference is reduced to zero.

[0013] The invention includes a method of selectively aligning an input beam with any one of a plurality of outputs in an optical switch, including the steps of: aligning an input alignment beam with the input beam; aligning the input beam and the alignment beam with an input reflecting means; aligning a separate output reflecting means with each of the outputs and determining, for each possible combination of alignment beam and outputs, the positions of the alignment beam on a surface optically positioned between said input reflecting means and output reflecting means. The method further includes the step of storing the positions on the surface in a memory associated with the optical switch. The determination of the positions includes the step of calculating the positions. The method further includes the step of operating the optial switch to determine a number of actual positions on the surface and using the actually determined positions to calculate all other positions of the alignment beam on the surface. The process is repeated for all alignment beams. Alternately, the method includes the step of operating the optical switch to determine all of the actual positions on the surface.

Brief Description of the Drawings

[0014] Figure 1 is an optical schematic of the optical and MEMS components of the switch of the present invention;

[0015] Figure 2 is a detail of the optical schematic of Figure 1, illustrating the input beam splitter;

[0016] Figure 3 is an additional detail of the optical schematic of Figure 1, *illustrating the optical wedge utilized in the input position sensor.*

[0017] Figure 4 is also an additional detail of the optical schematic of Figure 1, illustrating the prisms and other optical components associated with the output fiber array and the position sensors;

[0018] Figure 5 is a plain schematic view of the MEMS panels (or arrays) incorporated into the present invention;

[0019] Figure 6 is a plain view of an individual mirror assembly incorporated in the MEMS panels;

[0020] Figure 7A-C illustrate the time-optional switching dynamic range requirements of the mirrors incorporated in the MEMS panels;

[0021] Figure 8 is a schematic and functional block diagram of the control system of the optical switch of the present invention;

[0022] Figure 9 is a schematic illustrating the MEMS, optical elements and the sensors of the present invention;

[0023] Figure 10 is a simulation model illustrating the configuration of the servo controller for a single, representative, channel of the present invention, together with a simulation model of the optical switch;

[0024] Figure 11 is a simulation model illustrating the sensor transformation determination incorporated in the servo controller of the present invention;

[0025] Figure 12 is a schematic illustrating the dynamic estimator incorporated in the servo controller of the present invention;

[0026] Figure 13 is a schematic illustrating the controller incorporated in the servo controller of the present invention;

[0027] Figure 14 is a schematic diagram of the servo controller of the present invention as modeled by Simulink®;

[0028] Figure 15 is a schematic illustrating the positioning of the alignment source (associated with the beam to be switched) onto output MEMS, in order to capture such alignment source in the output angle sensor;

[0029] Figure 16 is a schematic illustrating , *inter alia,* the inputs and controls used for the stabilization of the alignment source in the output angle sensor;

[0030] Figure 17 is a schematic illustrating, *inter alia,* the inputs and controls of the servo controller utilized to align the communications beam on the output fiber and control the optical path alignment between the input fiber and the output fiber; and

[0031] Figure 18 is a chart illustrating the interface between the supervisory controller and the servo controller of the present invention.

Description of the Preferred Embodiment

[0032] With reference to Figure 1, the basic optical-MEMS system 11, of the optical switch of the present invention, includes input beam splitter 13, input MEMS panel 15, input position sensor 17, output MEMS panel 19, and output/sensor/beam splitter assembly 21. Beam splitter 13 includes 45° prisms 23 and 25. Prism 23 includes a face 27, to which is bonded input fiber array 29, each fiber of which transmits wavelengths in the range of 1300-1320 *nm* and 1528-1561 *nm.* Prism 25 includes face 31, to which is bonded input alignment source array 33, each of which transmits an alignment beam having wavelengths in the range of 775-795 *nm.* The interface 36 formed by the abutting hypotenuses has a coating which internally at 45° reflects 100% of wavelengths in the range of 775 to 795 *nm*, yet passes wavelengths in the ranges of 1300-1320 *nm* and 1528-1561 *nm*. In the preferred embodiment, array 29 consists of 320 input fibers. Each of the fibers in array 29 injects light into prism 23 through its individual micro collimator lens array (not shown). For optical efficiency, but irrelevant for the controls described below, each such collimator lens focuses its associated input beam approximately midway between MEMS panels 15 and 19. Likewise, array 33 includes 320 individual fibers each of which is associated with a collimating lens (not shown). The opposite ends of each of the fibers is connected to a laser diode (also not shown) supported by the housing (not shown) which supports system 11. As those skilled in the art will appreciate, input fiber array 29 and input alignment source array 33 must be precisely bonded to faces 27 and 31 such that the communication beam of each input fiber is aligned with its assigned individual alignment source (e.g., beam 1 is aligned with alignment source1, beam 150 is aligned with alignment source 150, beam 250 is aligned with alignment source 250, etc.).

[0033] With reference to Figure 3, input position sensor 17 includes an optical wedge 37 having a surface 39 which, in turn, has a coating which reflects, approximately, 100% of the wavelengths in the ranges of 1300-1320 *nm* and 1528-1561 *nm* (so long as the angles of incidence and reflection of such wavelengths are, as illustrated in Figure 3, 45° ± 10° from perpendicular). Although the ±10° range is not critical, some range is necessary to accommodate the range of angles within which the input beams reflect off the individual mirrors 93_I of panel 15. The ±10° range is sufficient to accommodate this angular range of movement. This same coating reflects, approximately, 70% of the wavelengths in the range of 775-795 *nm* (again, so long as the angles of incidence and reflection are within the range of 45° ± 10° from perpendicular) and passes the remaining 30%. This latter portion is used for input position sensing as discussed below.

[0034] With reference to Figure 4, beamsplitter/output/sensor assembly 21 includes prism 41, prism 43, filter 45, glass spacer 47, prism 49, prism 51, intensity regulating filter 53, neutral density filter 55 glass spacer 57, prism 59 and prism 61. To the exposed face 63 of filter 45 is bonded output fiber array

65 which, like input array 29 includes 320 output fibers and a like number of collimating lenses (not shown). The interface 67 between prisms 41 and 43 includes a coating which reflects, approximately, 100% of the wavelengths in the range of 775-759 *nm*. As to the wavelengths in the ranges of 1300-1320 *nm* and 1528-1561 *nm*, 4-10% is reflected at 45°, while the balance is transmitted to the output fibers in array 65. Filter 45 regulates the intensity of the individual beams. There are no reflective coatings on the surfaces of spacer 47 which are bonded to prisms 41 and 49. The interface 69 between prisms 49 and 51 includes a coating which also passes, approximately, 100% of the remaining 775-795 *nm* wavelength. The interface 69 coating also reflects nearly 100% of the wavelengths in the ranges of 1300-1320 *nm* and 1528-1561 *nm*. Glass spacer 57 has no reflective coatings on the surfaces which are bound to prisms 51 and 59. The last coating, applied to interface 71, transmits approximately 50% of the 775-795 *nm* wavelengths, while passing the remainder.

[0035] As is evident from Figure 1, in addition to output array 65, beamsplitter/output/sensor assembly 21 also includes CCD array 73, which is bonded to ND filter 55, output position sensor 75, angle sensor 77, and output alignment source 79.

[0036] As is also evident from Figure 1, the individual mirrors on MEMS panels 15 and 19 create the cross connections between the individual fibers of input array 29 and the individual fibers of output array 65. Mechanically, both MEMS panels 15 and 19 are identical. With reference to Figure 5, though only a representative number are shown, each MEMS panel includes an array of 320 individual MEMS micro steering mirror assemblys 91. Each mirror assembly 91 includes a mirror or reflective surface 93 and a gimbal support 95 which, together with the associated flexure connections (not shown) provides a two axis flexture suspended gimbal mounting system. See Figure 6. Inner rotation is about the y-axis, while outer rotation is about the z-axis. The flexure connections act as frictionless pivets that, theoretically, orthogonalize the gimbal motion. Electrostatic drives (not shown), one per axis, apply force at the flexure connections to rotate mirrors 93 around each of its flexure axes.

[0037] The MEMS assemblies 91 are open loop stable. An applied voltage to one of its electrostatic drives rotates mirror 93 to a fixed angle (ϕ_y, ϕ_z) with some oscillation as the system comes to rest. Closed loop control is not required to position mirrors 93, but it is required to minimize switching time and vibration disturbances, and compensate for variations in the system components and assembly.

[0038] The principal requirements of assemblys 91 are associated with dynamic range, transient response and precision. Each assembly must provide a travel range greater than five degrees to facilitate switching channels at the extremities of the geometry of optical-MEMS system 11. Desired transient response characteristics are derived from the system switching time specification and determine the velocity, acceleration and resonance frequency requirements. Using a time optimal trajectory, assemblys 91 must achieve a minimum of 35 rad/s and 14 k rad/s^2 as shown in Figures 7A, 7B and 7C. The range of resonance frequencies is a controllability issue that drives the sensor and processing demands described below. A positioning accuracy of 0.2^0, with a repeatability of 0.1^0, is sufficient for the open loop functions. While the resolution of the flexures are assumed to be mechanically infinite, they are specified as 25 μrad to support control and calibration.

[0039] To switch channels (i.e., to reroute the information carried on a communication beam on a given input fiber from a first output fiber to a second output fiber) requires the use of the associated alignment laser in array 33, knowledge of the geometry of optical system 11, the position sensors, and the systems electronics. Each input fiber of array 29 is carefully aligned to a specific mirror 93_I of input MEMS panel 15. Thus, fiber 1 of array 29 is always aligned with mirror 93_I 1 of panel 15. Likewise, each mirror 93_O of panel 19 is carefully aligned with a specific output fiber of array 65. Finally, the position of each alignment beam on wedge 37, for each input mirror 93_I on MEMS panel 15 vis-à-vis every output mirror 93_O on MEMS panel 19 is determined as set forth below. All this geometry information is stored in memory in the system electronics described below.

[0040] CCD array 75, which is a focal plane array device, is precisely mechanically registered to the individual fibers of output array 65 during assembly. Since the focal plane array is itself mechanically stable and since it measures that portion of the communication beam which is split off by the coating on interface 67, such measured portion is directly correlated to the position of such communication beam on output array 65. Output position sensor 75 includes a position sensitive device (PSD) coupled to prism 59 by a fiber taper (not shown). Similarly, angle sensor 77 also includes a position sensitive device (PSD) coupled to prism 61 by a fiber taper (also not shown). The PSDs incorporated in sensors 75 and 77 are high bandwidth, high resolution devices that produce a pair of signals related to the x and y position of incident optical energy on the PSD. They are not high accuracy devices and, because they are analog devices, they are subject to drift as a function of both temperature and bias voltage drift. Output position sensor 75 utilizes that portion of the input alignment beam (associated with the communication beam) which is split off by the coating on interface 71. Angle position sensor utilizes that portion of the input alignment beam, which is passed by the coating on interface 71.

[0041] Both CCD array 73 and output position sensor 75 are utilized to align (x, y) the communication beam incident from a particular mirror 93_o with its associated output collimator lens/fiber in array 65. Angle sensor 77 is used to angularly align the communication beam with the desired output collimator lens/fiber to insure low injection loss. Additionally, as explained below, CCD 73 and angle alignment sensor 77 are used to compensate for both temperature and bias voltage drift. As the measurements on the PSD incorporated in sensor 77 are differential, comparing the position of output alignment source 79 with, in turn, each of the input alignment sources, utilizing the time multiplexing features of optical switch 101 relies on the high resolution capability of the PSD. The high bandwidth of this sensor 77 is required to sense the short duration time multiplexed alignment beams. Since this sensor is used for bias/drift/alignment compensation the high bandwidth is not otherwise required.

[0042] The operation of the control system is best understood with reference to Figures 8-17. As illustrated in Figure 8, optical switch 101 includes the optical and MEMS components previously discussed with reference to Figures 1-6. Additionally, switch 101 includes supervisory controller 103, servo controller 105, sensor electronics 107, source controller 109, and CCD processor 111. Input position sensor, in addition to wedge 37, includes a position sensing device (PSD) 113 coupled to wedge 37 by and a fiber taper (not shown). The PSD is, in turn, connected to servo controller 105 via feed back loop 115 and sensor electronics 107. PSD 113 is an analog device of the same type utilized in sensors 75 and 77, which measures the position of each alignment beam on surface 39 associated with both switching and drift. Specifically, PSD 113 is a high bandwidth, high resolution, device that produces a pair of signals related to the x and y position of incident optical energy on the PSD. It is not a high accuracy device and, because it is an analog device, is subject to drift as a function of both temperature and bias voltage drift. Sensor array 73 is connected to CCD processor 111 via connection 117. Output position sensor 75 is connected to servo controller 105 via feedback loop 119 and sensor electronics 107. Angle sensor 77 is also connected to servo controller 105, via feedback loop 121 and sensor electronics 107. Sensor electronics 107 does signal processing for all three PSDs, including converting the analog signals from the PSDs to digital signals.

[0043] During the calibration of switch 101 the positions (sometimes referred to as the "offsets") of each of the 320 alignment beams on surface 39 of wedge 37 to effect optical alignment with teach of the 320 output-MEMS mirrors 93_O (i.e., 320 x 320 possible combinations) are determined. The first step in this calibration process is to calculate the positions from the geometry of the system (e.g. the spatial location of each MEMS mirror 93, the angels through which each MEMS mirror 93 rotates, the distances between each input MEMS mirror 93_I and the surface of surface 93 for each output MEMS mirror 93_O). Secondly, the correctness of a few randomly selected offsets is validated by testing to anchor the previously calculated offsets using actual measurements from the sensors of system 101. The errors between analytical data and the corresponding calculations are used to correct the switching commands for each input MEMS mirror 93_I. Representative positions of the 320^2 actual positions on surface 39 are illustrated at 121 in Figure 9. Representative discrete positions for reach of the 320^2 offsets on the face of CCD sensor 73 are illustrated at 123. Similarly, representative discrete positions for each of the 320 offsets on the surface of output position sensor 75 are illustrated at 125. As is also illustrated in Figure 9, at 127 the discrete angle for each alignment input source, basically a zero offset, is illustrated.

[0044] Servo controller 105 performs a number of functions: (1) it processes data from sensors 75, 77 and 113, and from the sensor data determines the operating configuration of optical-MEMS system 11 (including the system mode) for each beam path; (2) transforms linear sensor space to angular MEMS space; (3) performs both the open loop and closed loop control of each individual MEMS mirror 93_I, 93_O; (4) compensates for optical path errors and misalignment; and (5) stabilizes MEMS dynamics during switching. Servo controller 105, which is best understood with reference to Figures 10-14, includes state logic/transform 131, input MEMS dynamics estimator 133, input controller 135, output MEMS dynamics estimator 137, and output controller 139. It also includes algorithms for use in conjunction with effecting the foregoing functions.

[0045] The state logic/transform 131, schematically illustrated in Figures 10 and 11, performs several functions, including the logic (i.e., sequencing of steps) necessary to switch a communication beam from one output fiber to another output fiber. It manages the inputs, including both input commands and processed CCD data from supervisory controller 103, and inputs from the various PSDs to perform switching operations. This sequencing is described below. The transform portion of state logic/transform 131 transforms sensor space, which is linear, into MEMS space, which is angular. The position of each MEMS mirror 93 is determined by ϕ_Z, ϕ_Y. The invertible optical sensitivity matrix M, Figure 11, describes the relationship between the angle position of each of MEMS mirrors 93 and measurements from the PSDs of sensors 75, 77 and 17. Matrix M uses, for instance, data obtained during the calibration of optical-MEMS system 11. Inputs include the position of each alignment beam (associated with the communication beam to be switched), the angles (ϕ_{z1}, ϕ_{y1}) of input MEMS mirror 93_I, the angles (ϕ_{z2}, ϕ_{y2}) of the output MEMS mirrors 93_o, and position information from sensors 75, 77 and 113. Outputs include the alignment position on the sensors, which is the measured positions (Δy_2, Δz_2, $\Delta\phi_y$, and $\Delta\phi_z$) of the beams on the PSDs of sensors 75 and 77. It is this measured position data that is sent to MEMS dynamic estimators 133 and 137. See Figures 10 and 14. With further reference to Figure 10: the Alignment Source(s) Position represents the positions of each of the alignment sources of array 33; Optical Transform models where the alignment beams travel in switch 101; Sensor(s) Position represents the physical positions of the sensors in the simulation model; Misalignment represents the static misalignment between the alignment beams and the communication beams (i.e., bias); and Noise represents the uncertainty inherent in all measurements.

[0046] The MEMS dynamics estimators 133 and 137 and controllers 135 and 139 are mathematical entities that reside in programmable logic devices (PLDs) that are a part of the electronics of servo controller 105. The input data, output signal, and operation of these devices are shown in Figures 12, 13 and 14. The specific gains and other parameters (e.g., inertia, damping, spring constant) are specific functions of the mechanical performance of the MEMs and the system geometry, and are determined as a part of the system calibration process. With reference to Figure 13, the error integral gain (K_1), the position feedback gain (K_P), the rate feedback gain (K_R), and the error feedback gain (K_E) are defined as follows:

$$K_1 = \omega_2^{\,2} / (K_{act}\, \omega_1^{\,2}) * (5/.005) / (2\pi) \quad \text{(for switch time = 5 ms)}$$

$$K_P = (\omega_2^{\,2} - \omega_1^{2}) / (K_{act}\, \omega_1^{\,2})$$

$$K_R = (2\omega_2 - 2\zeta_m\, \omega_1) / (K_{act}\, \omega_1^{\,2})$$

$$K_E = \omega_2^{\,2} / (K_{act}\, \omega_1^{\,2})$$

wherein damping = ζ_m; resonance = ω_1, ω_2; actuator scale factor = K_{act}

[0047] Switching is initiated by a system command to supervisory controller 103 to steer the input mirror 93_I associated with the input fiber (and, hence, communication beam) to be switched to the output mirror 93_O associated with the selected output fiber. This requires the use of the offsets discussed above and the alignment beam from array 33 which is associated with the input beam to be switched. As previously stated, during assembly of beam splitter 13, array 29 and array 33, each individual collimator lens/fiber in array 33 is carefully aligned with its corresponding input collimator lens/fiber in array 29. Each of the associated individual lasers is, via source controller 109, sequentially activated every 800 *n*sec. All and output alignment source 79 (a laser diode) are sequenced in, approximately, 250 µsec. As explained below, this rapid sequencing provides time multiplexed discrete measurements of each optical path.

[0048] The first step in the switching process is to position the alignment beam (associated with the communication beam to be switched) on the selected output MEMS mirror 93_o, in order to capture the alignment source beam in angel sensor 77. See Figure 15. This is initiated by an open lop command from supervisory controller 103 to input MEMS dynamic estimator 133 (as illustrated in Figure 10) which, via controller 135, sends a command to the individual MEMS driver (associated with the mirror 93_I (1) and the input collimator lens/fiber (1) whose beam is to be switched) to rotate the selected mirror 93_I to point the alignment beam to an absolute position on surface 39 of wedge 37 and on MEMS panel 19 (i.e., the specific mirror 93_O associated with the output fiber to be switched to). Position information from PSD 113, via closed (feed back) loop 115 corrects for any misalignment of input MEMS mirror 91_I and voltage variations, and provides stabilization of the input mirror's dynamics during switching. PSD 113 monitors the position of the alignment beam and provides, via sensor electronics 107, digital signals reporting the beam's location. The difference between this signal and the input position command signal (i.e., where to go) is an error signal (one for each degree of freedom) processed by transform 131, estimator 133 and controller 135.

Controller 135 causes corrected voltage signals to be applied to the input MEMS mirror 91_I being rotated. When the error signal to transform 131 is zero, the voltage applied to the MEMS device 91_I is held constant.

[0049] The next step in the switching process, which is carried on simultaneously with the input MEMS alignment discussed above to minimize switching time, is to stabilize (i.e., reduce the offset to zero) the alignment beam in angle sensor 77. See Figure 16. Sensor 77 measures the angle of the beam reflected off of the output MEMS mirror 93_O (and coating 67) and sends a signal, via closed feedback loop 121 and sensor electronics 107, to servo controller 105 to zero the alignment angle errors. As is evident from Figure 16, when the error signals (i.e., the difference between the output angle command (from supervisory controller 103) and the signal from sensor 77 (for each of the two degrees of freedom) is zero, the voltage applied to the output MEMS driver 91 is held constant. The closed loop feedback from sensor 77 corrects for any output MEMS misalignment and voltage variations, and provides stabilization of the output MEMS dynamics during switching.

[0050] The third state in the switching process is to provide alignment of the communication beam being switched on the output fiber the beam is being switched to. As those skilled in the art will appreciate, this requires that the communication beam be precisely positioned on the output collimator lenses of array 65 in both position and angle. With reference to Figure 17, output position sensor 75 and angle sensor 77 measure the optical path alignment. As before, the signal from sensor 77 is sent to servo controller 105 via loop 121 and sensor electronics 107, where it is compared with the angle command. The error signal is set to state logic/transform 131. Similarly, a signal (that portion split off by the coating on interface 71) is sent from sensor 75, via loop 119 and sensor electronics 107, to servo controller 105. This signal is compared with the output position command signal and an error signal is sent to state logic/transform 131. The signals are then sent to both estimators 133,137, controllers 135, 139. Signals are then sent to the individual MEMS used in the switching to, as necessary, maintain (if no position change is required) or change (if a position change is required) voltage. The feedback continues until both error signals are driven to zero.

[0051] Output alignment source 79, which is connected to source controller 109 via connection 123, is used to provide low frequency drift correction for angle sensor 77. The output alignment source 79 provides an angular reference location on sensor 77. See Figure 17. The source 79 is aligned with the collimator of the output beams in array 65 so that if a communications beam is parallel with the beam from output alignment source 79, it will strike the collimator at the appropriate incidence angle. Thus, the position of each input alignment beam on sensor 77 is compared with that of the beam from 79 and adjustments are made via the servo controller 103 electronics to bring them into alignment. Output alignment source 79 is also pulsed, as are the alignment sources, so that the time multiplexed position readout on 77 can be uniquely associated with a particular source.

[0052] CCD 73 is used to measure the output alignment of the communication beams and to provide low frequency correction for sensor drift. With reference to Figure 17, this function is identified as “drift correction.” CCD processor 111 and supervisory controller 103 are the physical elements which perform this function. Sensor drift can result from thermal changes, electrical drift or the passage of time. The correction process involves comparing, for each communication beam, the signal from CCD array 73 with the signal from the PSD of output position sensor 75. At low frequency, CCD 73 corrects the signal from the PSD. However, at high frequency, the signal from the PSD is not adjusted by the signal from CCD 73

[0053] The above described process for the switching and maintaining the alignment of a particular information beam is representative of all 320 communication beams and the associated 320 alignment laser diodes in array 33. The sequencing of each individual laser diode connected to array 33 permits the use of a single set of the monolithic position sensors described above and a single supervisory controller 103 and servo controller 105. Each laser diode coupled to array 33 is sequentially blinked for 800 *n*sec. This time interval permits the sensors to measure the entire path of the alignment beam blinked on. Output alignment source 79 is also blinked in sequence (but not simultaneously) with the input alignment laser diodes. All 321 alignment beams are sequentially blinked approximately every 250 Φsec. The above described process is sometimes referred to as time multiplexing (i.e., the use of $n + 1$ reference beams in a timed sequence fashion to allow $n + 1$ measurements with a single set of sensors. The use of PSDs permit this rapid sequencing. Such high speed sampling allows for the command of the MEMS mirrors at relatively high rates, providing both higher bandwidth disturbance rejection and rapid switching.

[0054] Whereas the drawings and accompanying description have shown and described the preferred embodiment of the present invention, it should be apparent to those skilled in the art that various changes may be made in the form of the invention without affecting the scope thereof.

We claim:

1. An optical system for switching a plurality of input communication beams, wherein each communication beam can be switched from a first output to a second output, said optical system including:

(a) a plurality of communication beam inputs;

(b) a plurality of alignment beam inputs;

(c) an array of input beam directing surfaces, each said input beam directing surface of said array positioned to receive a communication beam from a specific communication beam input and an alignment beam from a specific alignment beam input;

(e) an array of output beam directing surfaces;

(f) a plurality of communication beam outputs, each of said outputs being aligned with a specific output beam directing surface; and

(g) an input position sensor, positioned optically between said array of input beam directing surfaces and said array if output beam directing surfaces, arranged so as to sense the positions of said alignment beams incident from said array of input beam directing surfaces.

2. The system of claim 1, wherein each of said input beam directing surfaces and each of said output beam directing surfaces is a MEMS device, each said MEMS device including a reflective surface supported for movement about two independent axes.

3. The system of claim 1, wherein said input position sensor includes a high bandwidth, high resolution position sensor.

4. The system of claim 3, wherein said high bandwidth, high resolution position sensor is monolithic.

5. The system of claim 4, further including an alignment beam source adapted to sequentially energize the respective alignment beams.

6. The system of claim 1, wherein said input position sensor includes an optical element that reflects substantially all communication beam wavelengths while partially transmitting and partially reflecting wavelengths of said alignment beams.

7. The system of claim 6, wherein said optical element includes a coating having reflective properties specific to those communication beam wavelengths reflected, and reflective and transmission properties specific to those alignment beam wavelengths which are partially reflected and partially transmitted.

8. The system of claim 1, further including an output position sensor.

9. The system of claim 8, wherein said output position sensor includes an angle sensor.

10. The system of claim 9, wherein said angle sensor includes a high bandwidth, high resolution angle sensor.

11. The system of claim 10, wherein said high bandwidth, high resolution angle sensor is monolithic.

12. The system of claim 8, when said output position sensor also includes a position sensor.

13. The system of claim 12, wherein said position sensor includes a high bandwidth, high resolution sensor.

14. The system of claim 13, wherein both of said high bandwidth, high resolution sensors are monolithic.

15. The system of claim 14, further including an alignment beam source adapted to sequentially energize the respective alignment beams.

16. The system of claim 12, further including a controller connected to said array of input beam directing surfaces, said array of output beam directing surfaces, said angular position sensor and said position sensor so as to allow said controller, said angle position sensor, and said position sensor together functioning to provide four degrees of control to control the positions of said input beam directing surfaces and said output beam directing surfaces.

17. The system of claim 8, further including a low bandwidth drift compensator.

18. The system of claim 17, wherein said low bandwidth drift compensator includes a CCD array.

19. The system of claim 8, further including an output aligner.

20. The system of claim 19, wherein said output aligner is a single source.

21. The system of claim 20, further including an alignment beam source adapted to sequentially energize the respective alignment beams.

22. In an optical switch having n inputs and n outputs and optical means for connecting each of said inputs to each of said outputs (n2 possible combinations), a method of connecting the beam carried on any one of said inputs with any one of said outputs with only a single controller means, said method including the steps of:

(a) aligning a separate alignment source with the input beam of each of said inputs; and

(b) sequentially energizing each said alignment source.

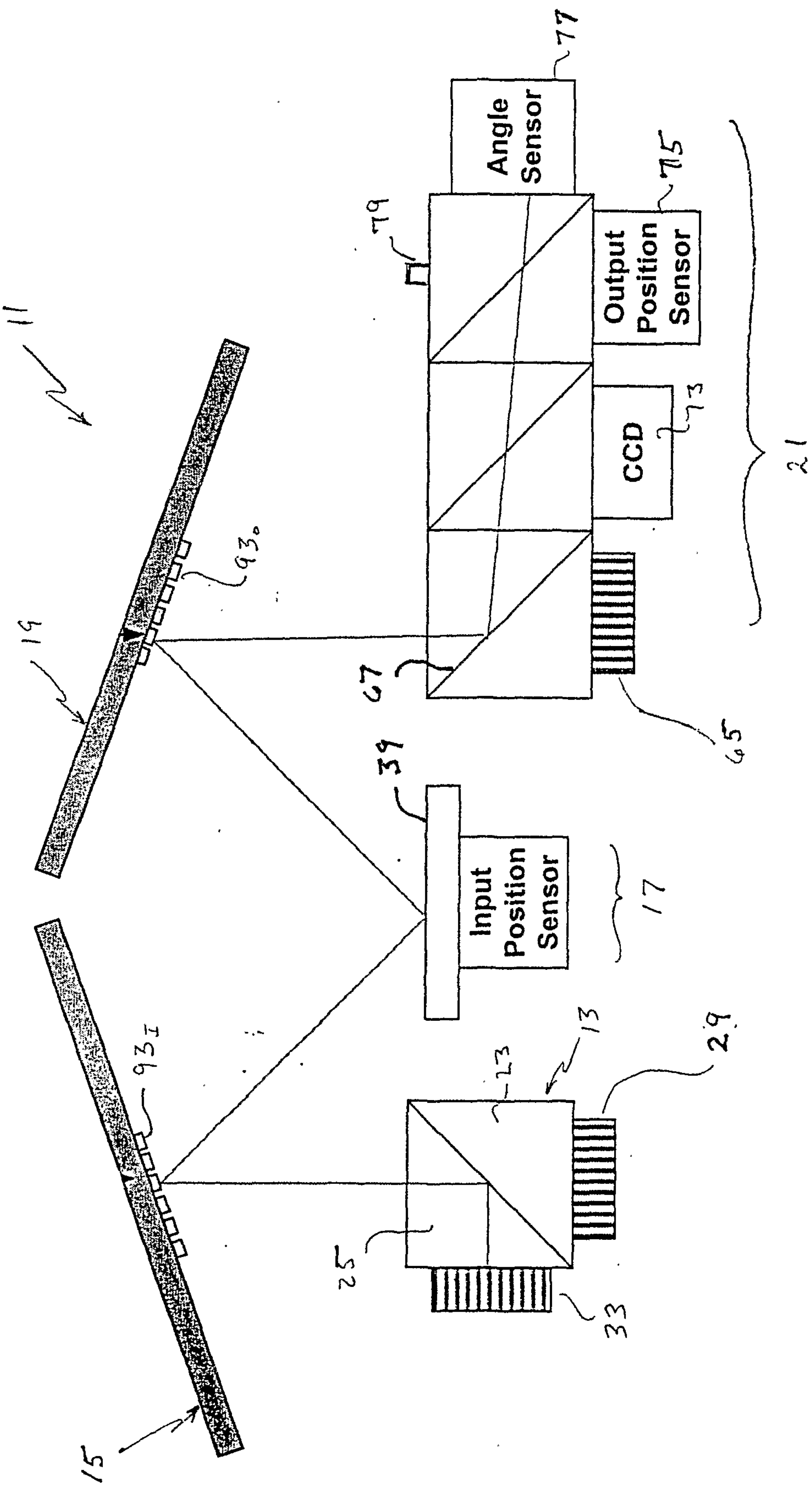

11
19
93o
93I
15
39
Input Position Sensor
17
13
23
25
29
33
67
65
Angle Sensor
77
79
Output Position Sensor
75
CCD
73
21

FIGURE 1

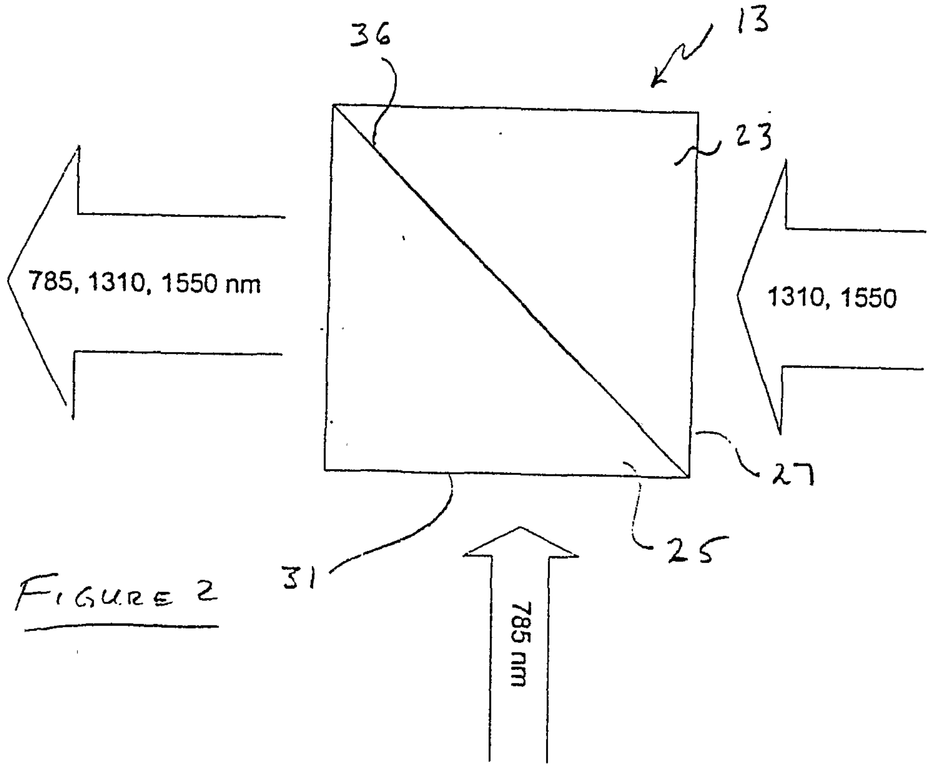


FIGURE 2

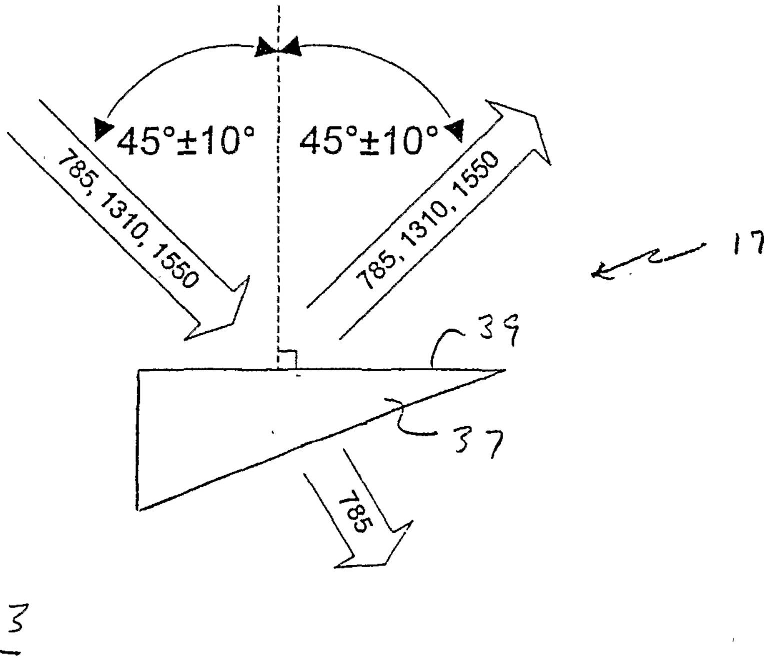


FIGURE 3

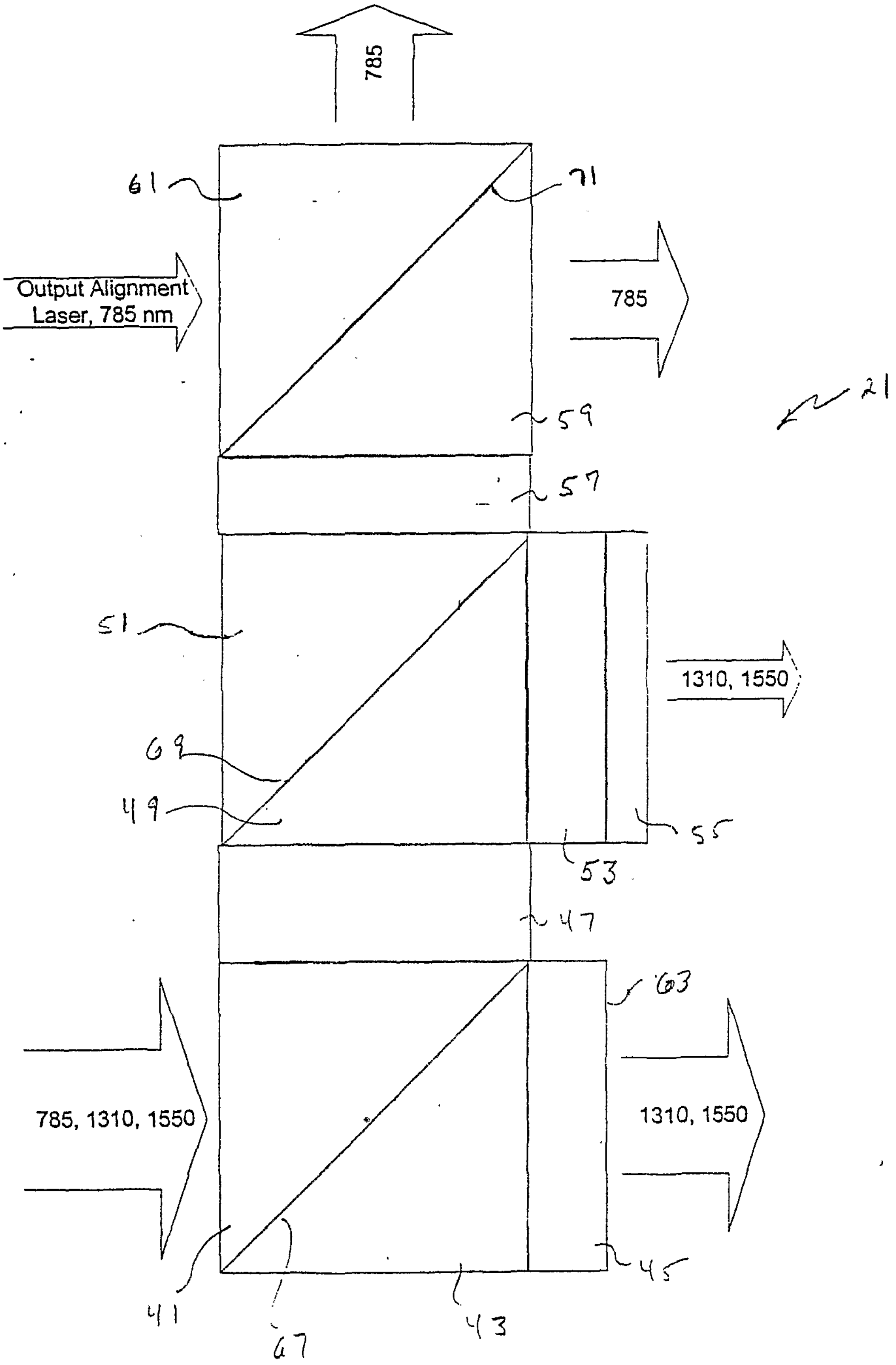

785
61
71
Output Alignment Laser, 785 nm
785
21
59
57
51
1310, 1550
69
49
55
53
47
63
785, 1310, 1550
1310, 1550
41
67
43
45

Figure 4

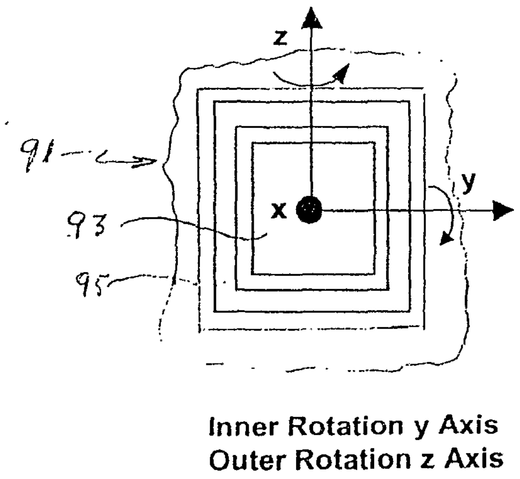


FIGURE 6

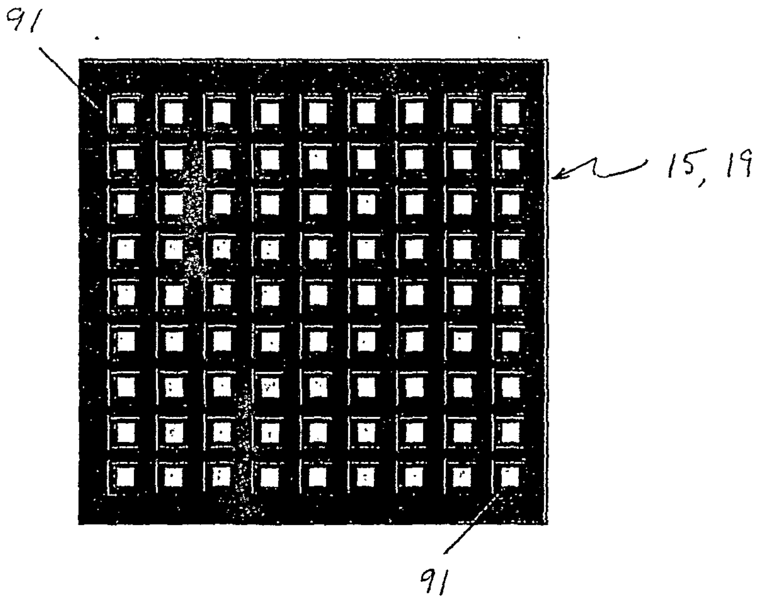


FIGURE 5

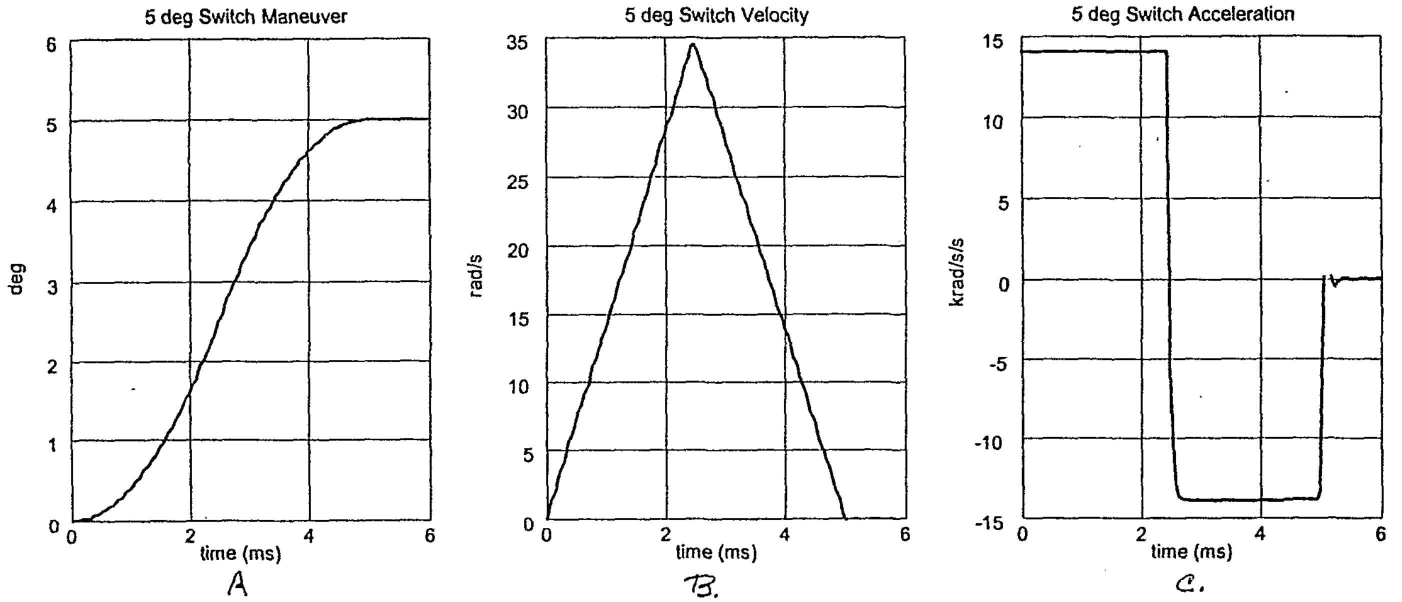


Figure 7 MEMS Time-Optimal Switching Dynamic Range Requirements

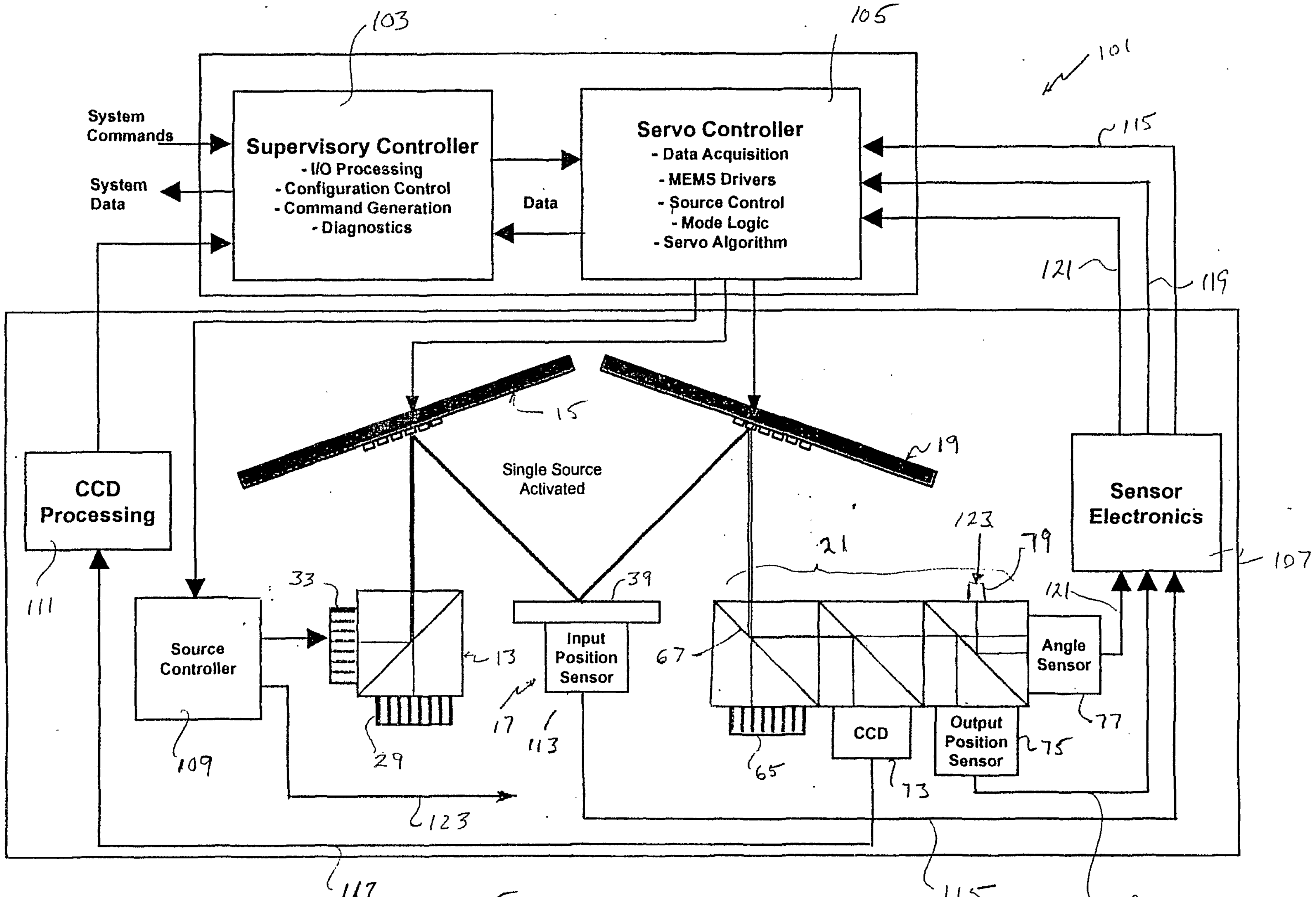

103
105
101
System Commands
System Data
Supervisory Controller
- I/O Processing
- Configuration Control
- Command Generation
- Diagnostics
Data
Servo Controller
- Data Acquisition
- MEMS Drivers
- Source Control
- Mode Logic
- Servo Algorithm
115
121
119
15
19
Single Source Activated
CCD Processing
111
Sensor Electronics
107
123
79
21
33
39
Source Controller
109
13
Input Position Sensor
17
113
29
67
65
Angle Sensor
121
77
CCD
73
Output Position Sensor
75
123
117
115
119

Figure 8

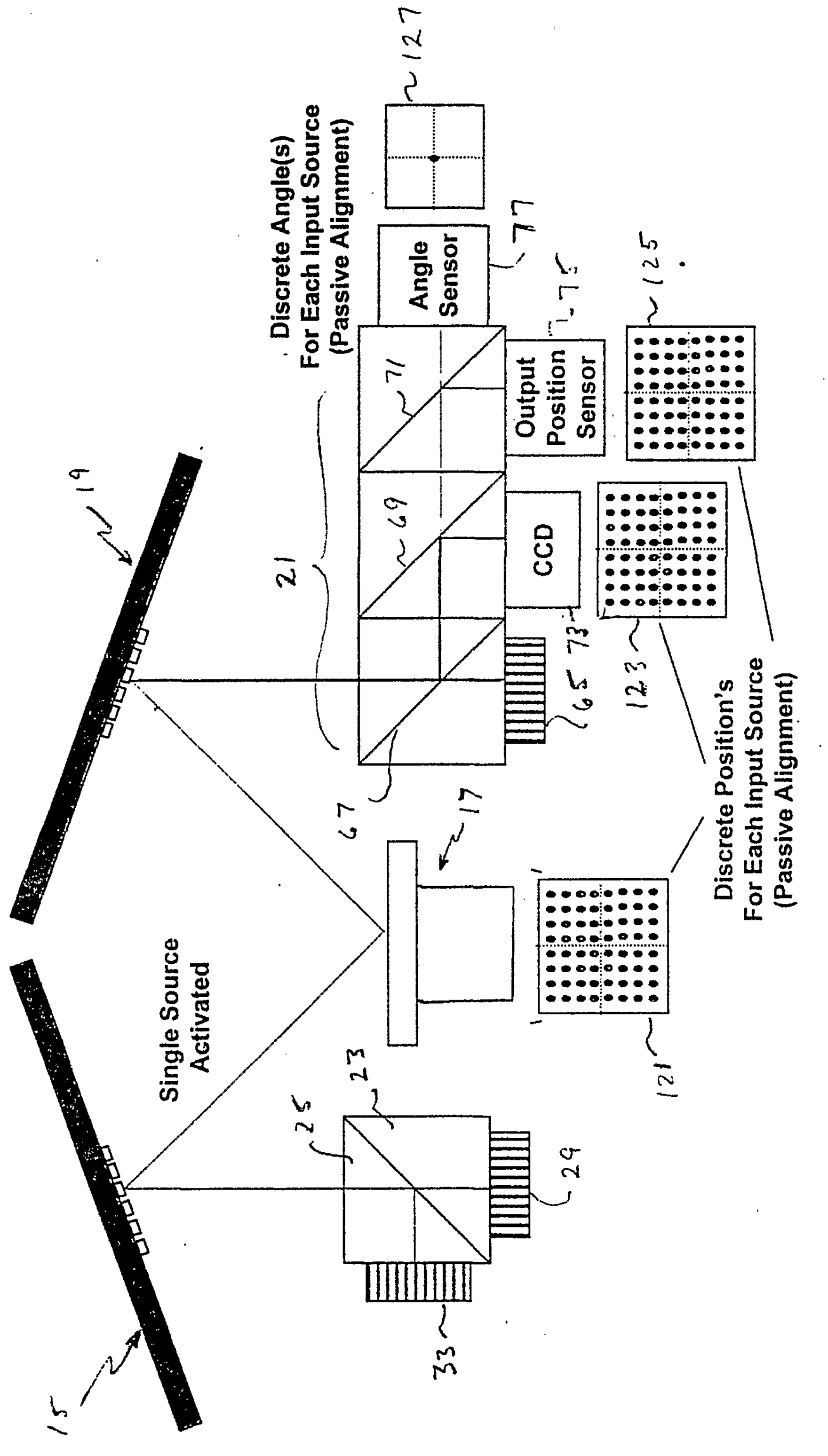

Single Source Activated
Discrete Angle(s) For Each Input Source (Passive Alignment)
Angle Sensor
Output Position Sensor
CCD
Discrete Position's For Each Input Source (Passive Alignment)
15
19
17
21
23
25
29
33
65
67
69
71
73
75
77
121
123
125
127

Figure 9

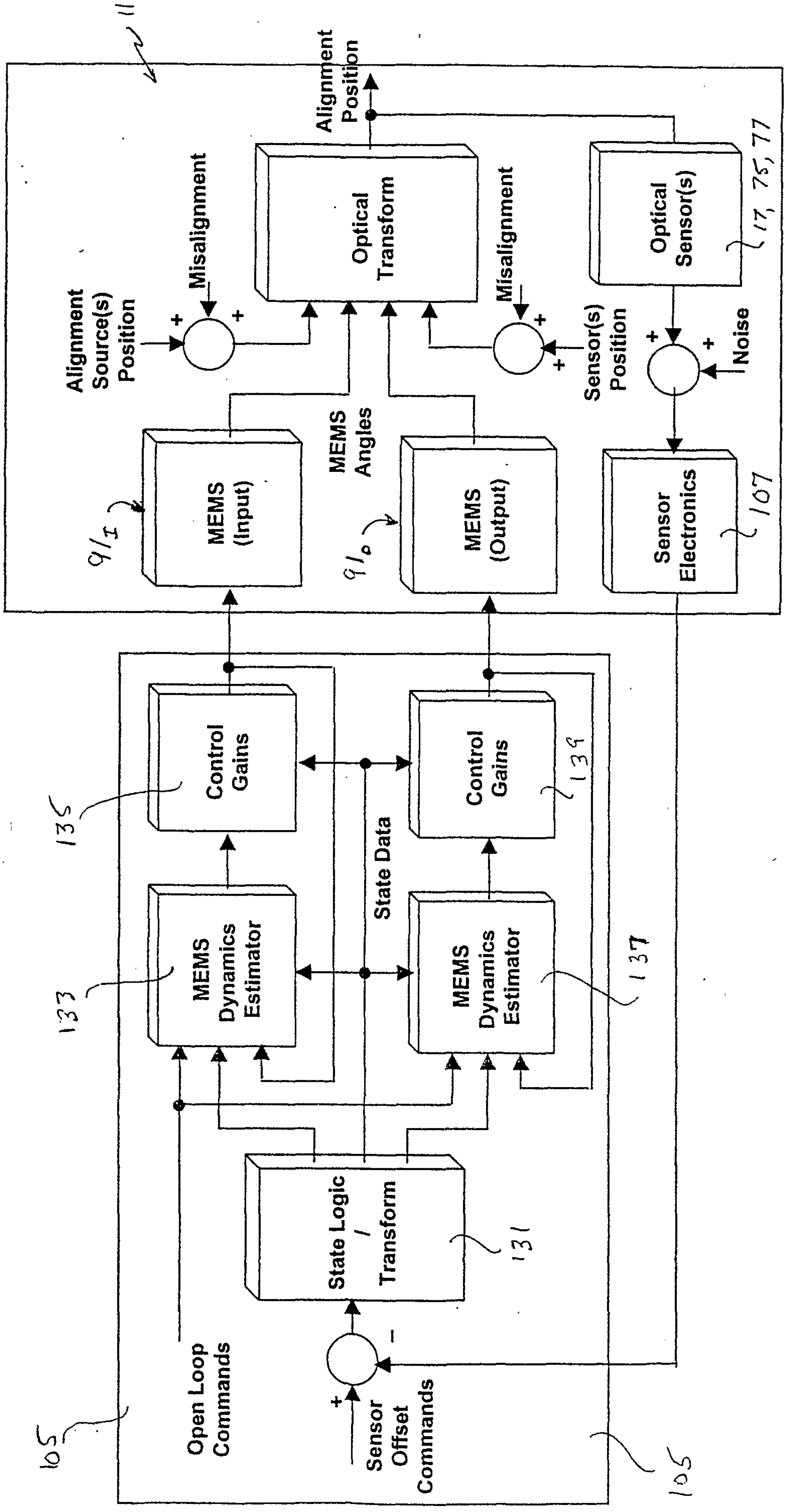
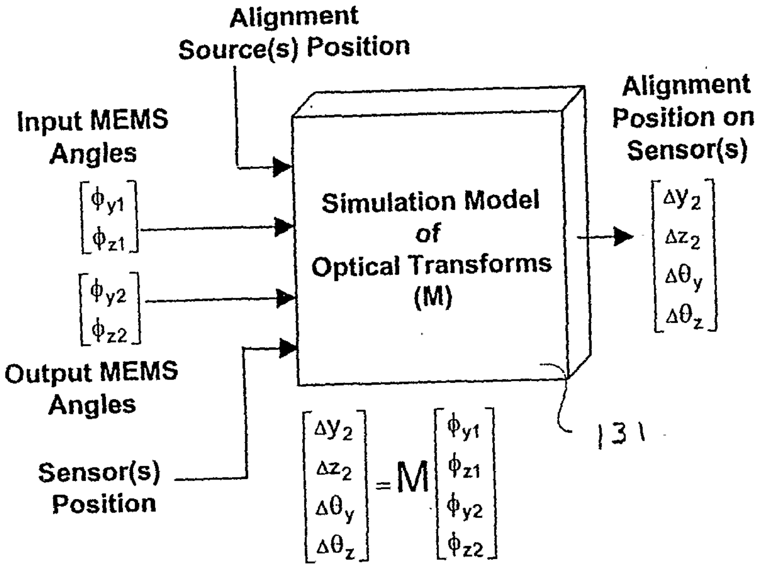

11
Alignment Position
Alignment Source(s) Position
Misalignment
+
+
Optical Transform
Misalignment
+
+
Sensor(s) Position
Optical Sensor(s)
17, 75, 77
+
+
Noise
MEMS (Input)
91I
MEMS Angles
MEMS (Output)
91o
Sensor Electronics
107
Control Gains
135
Control Gains
139
State Data
MEMS Dynamics Estimator
133
MEMS Dynamics Estimator
137
State Logic / Transform
131
Open Loop Commands
+
-
Sensor Offset Commands
105
105

Figure 10



$$\begin{bmatrix}\phi_{y1}\\ \phi_{z1}\end{bmatrix} \quad \begin{bmatrix}\phi_{y2}\\ \phi_{z2}\end{bmatrix} \quad \begin{bmatrix}\Delta y_2\\ \Delta z_2\\ \Delta\theta_y\\ \Delta\theta_z\end{bmatrix}$$

$$\begin{bmatrix}\Delta y_2\\ \Delta z_2\\ \Delta\theta_y\\ \Delta\theta_z\end{bmatrix} = M\begin{bmatrix}\phi_{y1}\\ \phi_{z1}\\ \phi_{y2}\\ \phi_{z2}\end{bmatrix}$$

Figure 11

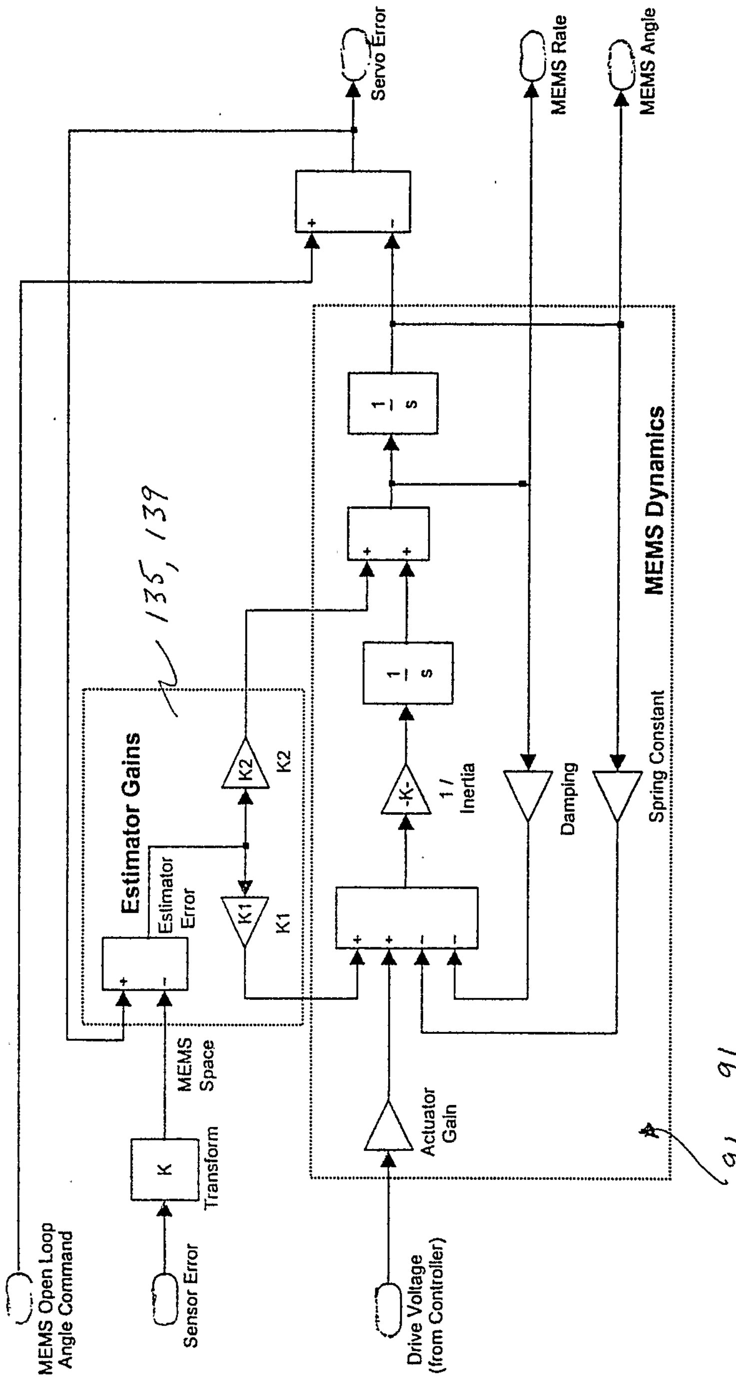


FIGURE 12

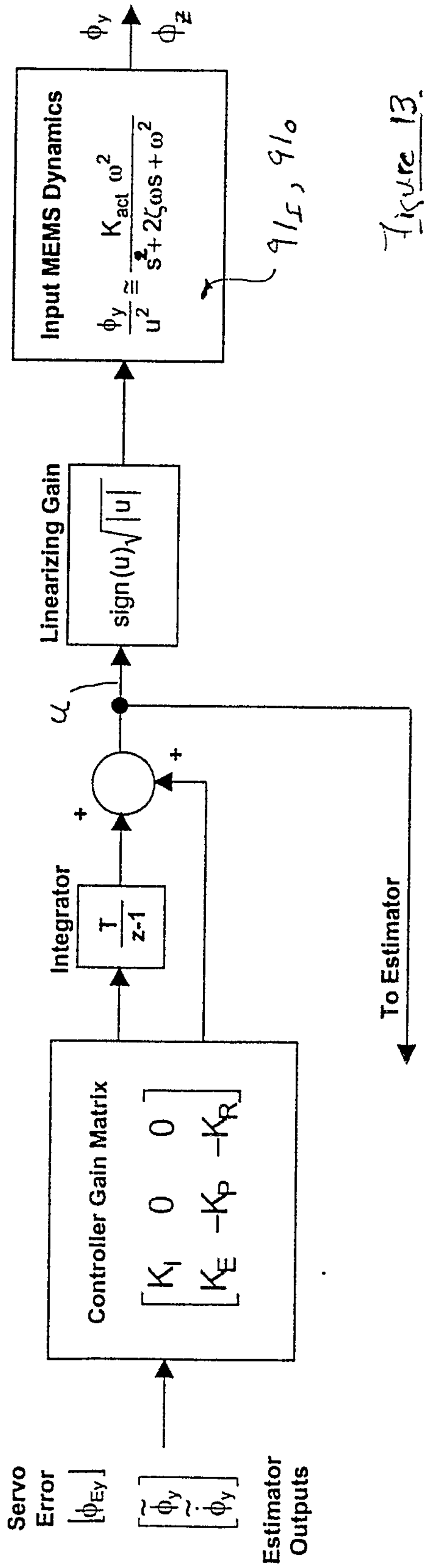


Figure 13.

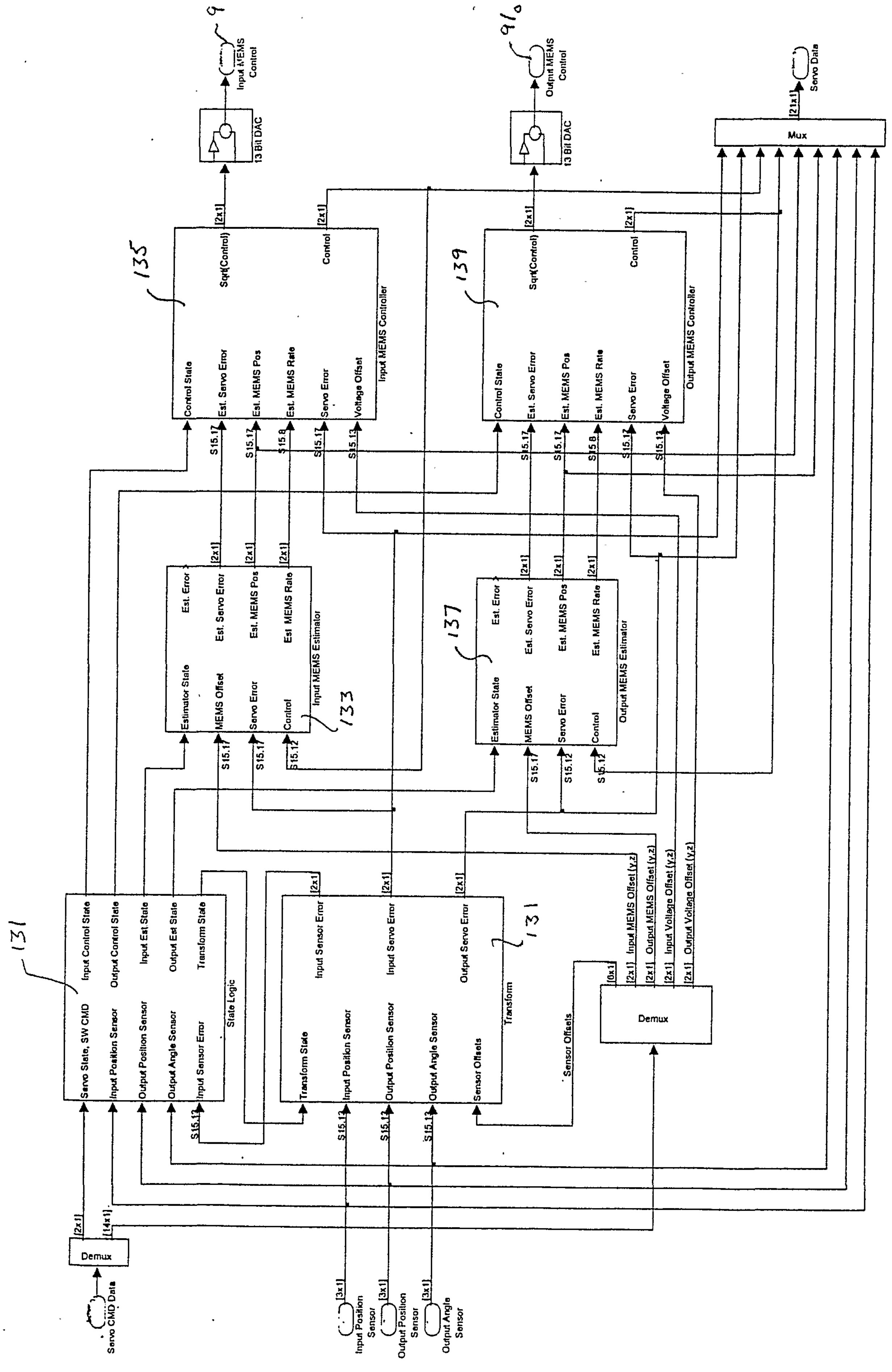

91I
Input MEMS Control
13 Bit DAC
91o
Output MEMS Control
13 Bit DAC
Servo Data
[21x1]
Mux
135
Sqrt(Control)
Control
[2x1]
[2x1]
Control State
Est. Servo Error
Est. MEMS Pos
Est. MEMS Rate
Servo Error
Voltage Offset
Input MEMS Controller
S15.17
S15.17
S15.8
S15.17
S15.13
139
Sqrt(Control)
Control
[2x1]
[2x1]
Control State
Est. Servo Error
Est. MEMS Pos
Est. MEMS Rate
Servo Error
Voltage Offset
Output MEMS Controller
S15.17
S15.17
S15.8
S15.17
S15.13
[2x1]
[2x1]
[2x1]
Estimator State
MEMS Offset
Servo Error
Control
Est. Error
Est. Servo Error
Est. MEMS Pos
Est. MEMS Rate
Input MEMS Estimator
133
S15.17
S15.17
S15.12
137
[2x1]
[2x1]
[2x1]
Estimator State
MEMS Offset
Servo Error
Control
Est. Error
Est. Servo Error
Est. MEMS Pos
Est. MEMS Rate
Output MEMS Estimator
S15.17
S15.12
S15.12
131
Servo State, SW CMD
Input Position Sensor
Output Position Sensor
Output Angle Sensor
Input Sensor Error
Input Control State
Output Control State
Input Est State
Output Est State
Transform State
State Logic
S15.12
131
Transform State
Input Position Sensor
Output Position Sensor
Output Angle Sensor
Sensor Offsets
Input Sensor Error
Input Servo Error
Output Servo Error
Transform
[2x1]
[2x1]
[2x1]
S15.12
S15.12
S15.13
Sensor Offsets
Demux
[0x1]
[2x1]
[2x1]
[2x1]
[2x1]
Input MEMS Offset (y,z)
Output MEMS Offset (y,z)
Input Voltage Offset (y,z)
Output Voltage Offset (y,z)
Demux
[2x1]
[14x1]
Servo CMD Data
[3x1]
Input Position Sensor
[3x1]
Output Position Sensor
[3x1]
Output Angle Sensor

Figure 14

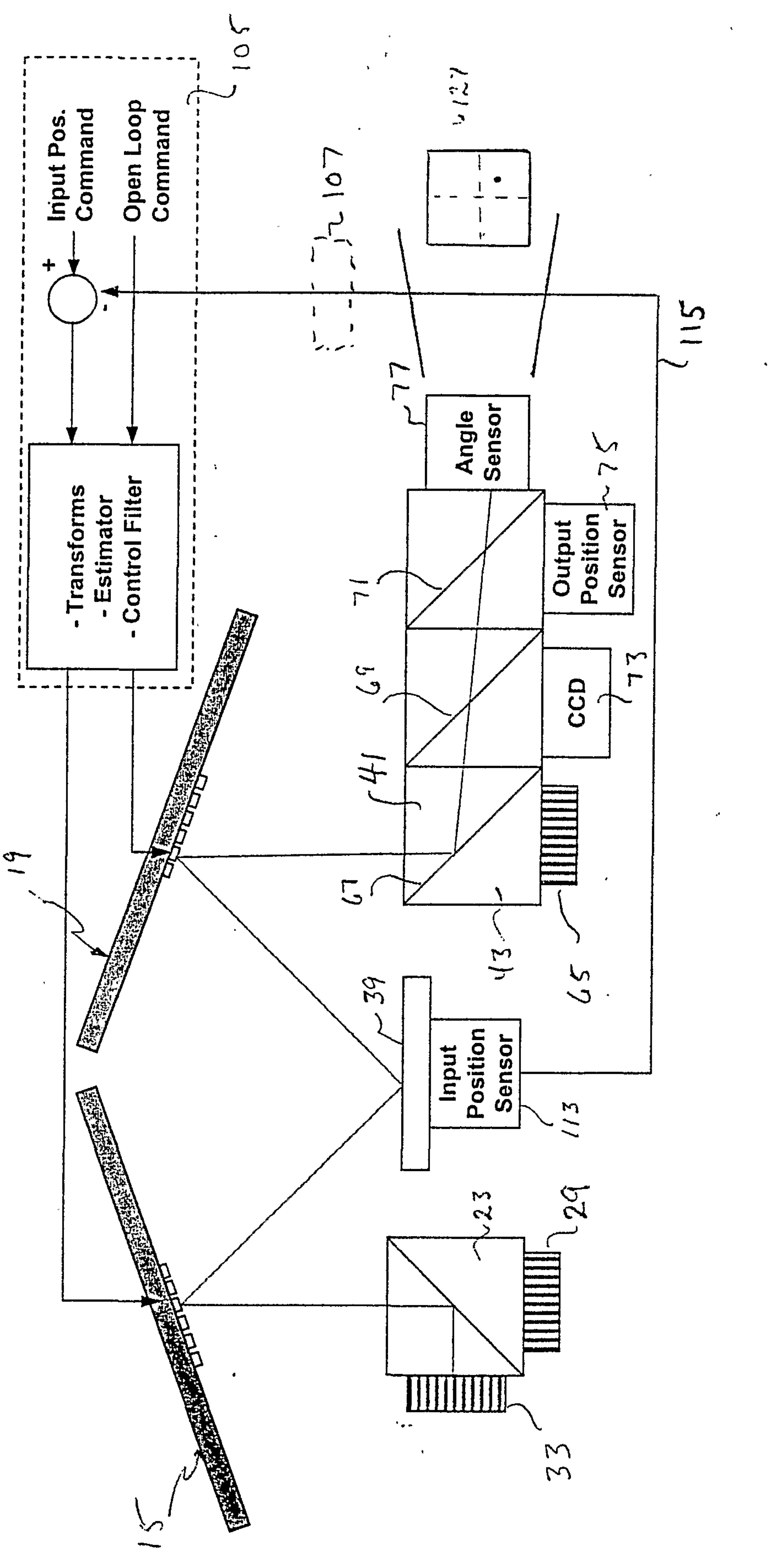

105
Input Pos. Command
+
-
Open Loop Command
- Transforms
- Estimator
- Control Filter
107
127
Angle Sensor
77
Output Position Sensor
75
CCD
73
71
69
41
67
43
65
115
19
39
Input Position Sensor
113
15
23
29
33

FIGURE 15

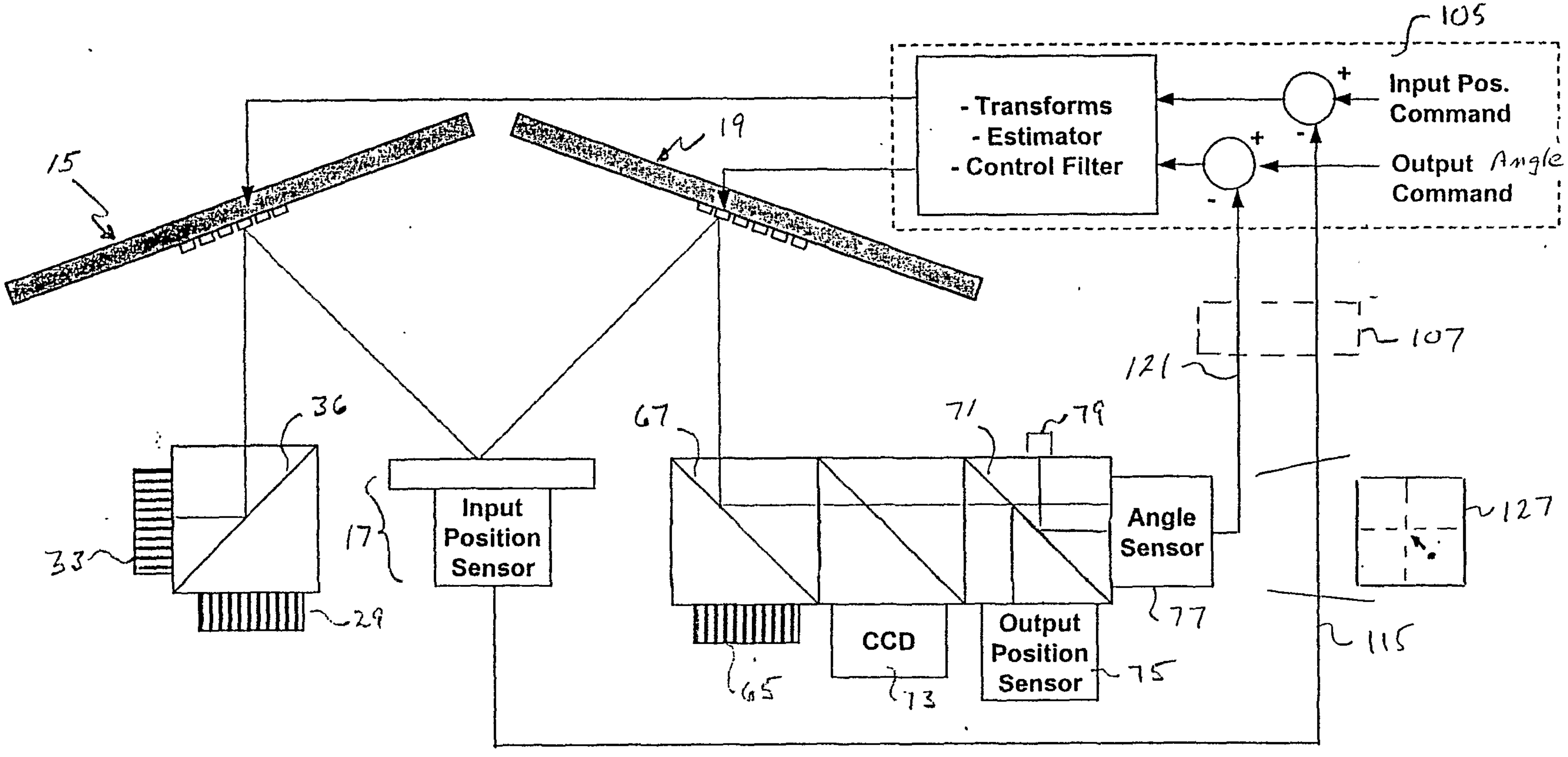

105
Input Pos.
Command
Output Angle
Command
+
-
+
-
- Transforms
- Estimator
- Control Filter
15
19
107
121
36
67
71
79
127
33
17
Input
Position
Sensor
Angle
Sensor
29
77
115
65
CCD
73
Output
Position
Sensor
75

FIGURE 16

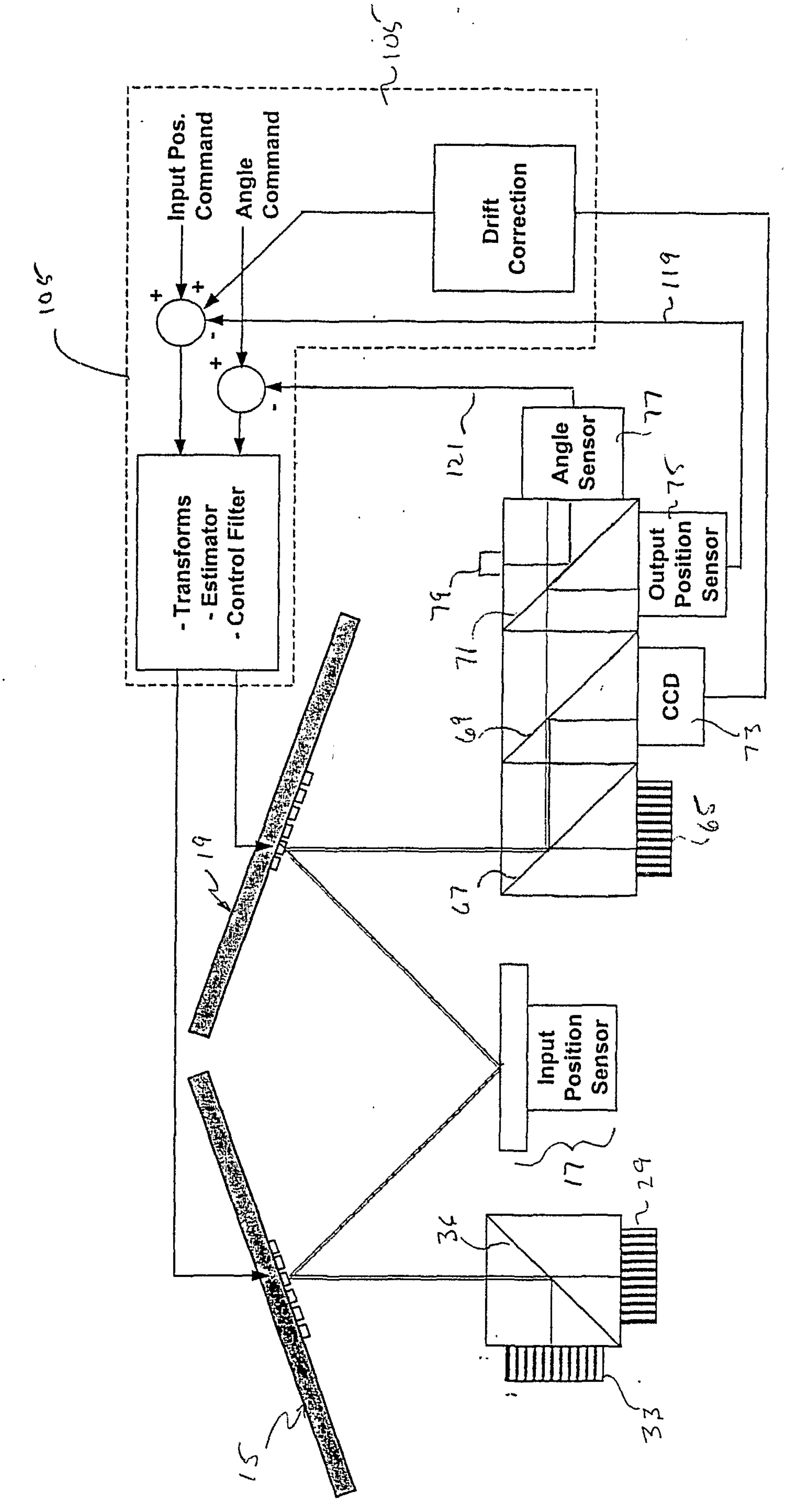
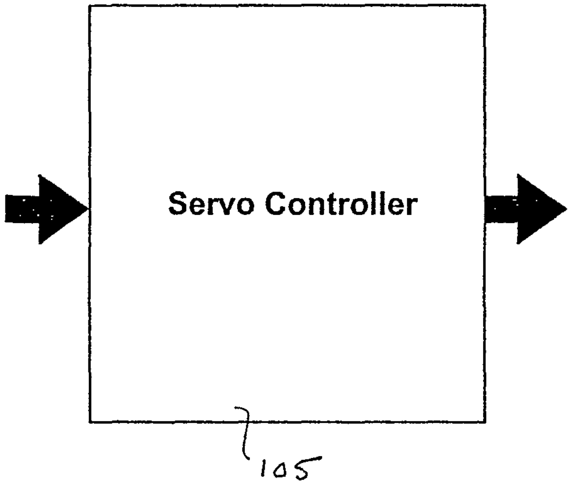

105
105
Input Pos. Command
Angle Command
+
+
-
+
-
Drift Correction
119
121
- Transforms
- Estimator
- Control Filter
Angle Sensor
77
75
Output Position Sensor
79
71
69
CCD
73
65
67
19
Input Position Sensor
17
29
36
33
15

FIGURE 17

Inputs (From Supervisor)

1. Servo ID (Input / Output MEMS)
2. Servo State Command (1x)
    Reset
    Direct Voltage Control
    Open Loop Control
    Low Bandwidth Control
    High Bandwidth Control
    IMA Test
    OMA Test
3. Sensor Offset (6x)
    2 Axis Input Position Offset (v)
    2 Axis Output Position Offset (v)
    2 Axis Output Angle Offset (v)
4. MEMS Offset (4x)
    2 Axis Input and Output Offset (rad)
5. Voltage Offset (4x)
    2 Axis Input and Output Voltage (v)



Outputs (To Supervisor)

1. Servo ID (Input / Output MEMS)
2. Servo State (1x)
3. Servo Errors (4x)
    2 Axis Input and Output Error (rad)
4. Control Outputs (4x)
    2 Axis Input and Output Command (v)
5. MEMS Position Estimates (4x)
    2 Axis Input and Output Command (rad)
6. Input Position Sensor (2x)
    2 Axis Position Measurement (v)
7. Output Position Sensor (2x)
    2 Axis Position Measurement (v)
8. Output Angle Sensor (2x)
    2 Axis Angle Measurement (v)

FIGURE 18