ACCURATE POSITIONING OF LONG, FLEXIBLE ARM'S*

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ABSTRACT

An articulated robotic manipulator (ARM) system is being designed for space applications. It will be physically lightweight, slender, and flexible compared to typical ground-based robot systems. When manipulating unknown masses with long flexible segments, it is difficult, using standard means, to accurately determine the position of the end tips of these ARM's. The problem is how to quickly and accurately position long, flexible ARM's.

This presentation summarizes the work being done on a concept utilizing an infinitely stiff laser beam for position reference. The laser beam is projected along the segments of the ARM, and the position is sensed by the beam rider modules (BRM) mounted on the distal ends of the segments. The BRM concept is the heart of the system. It utilizes a combination of lateral displacements, and rotational and distance measurement sensors. These determine the relative position of the two ends of the segments with respect to each other in six degrees of freedom. The BRM measurement devices contain microprocessor controlled data acquisition and active positioning components. We use an indirect adaptive controller which senses this information to accurately control the position of the ARM.

The goal of the project is to design a space rated sensor, control, and manipulator assembly. This ARM will have a 10-m reach and will be capable of positioning payloads of up to 100 kg with millimeteric accuracy.

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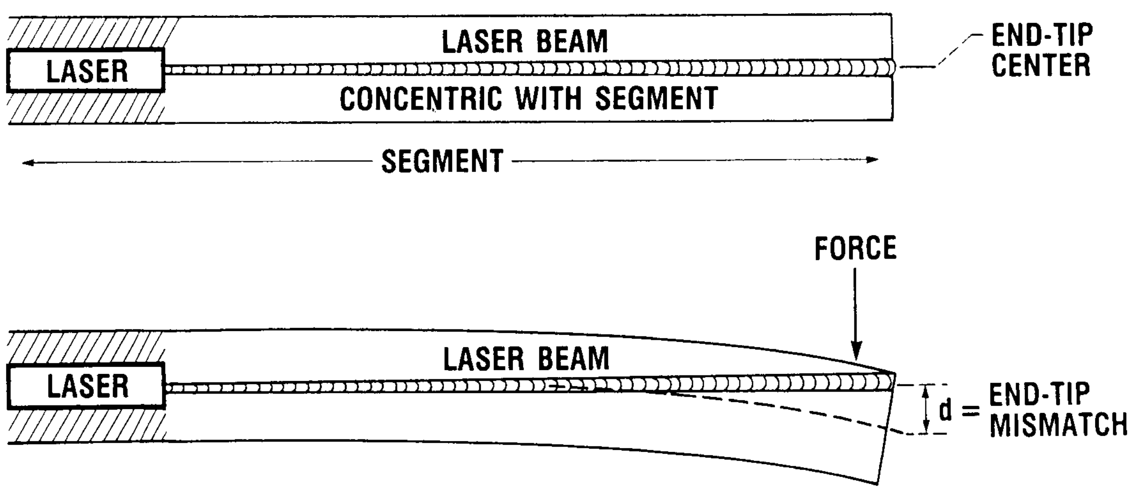
OVERVIEW

LASER BEAM RIGID BODY POSITIONING CONCEPT

There are numerous uses for articulated robotic manipulators (ARM's) with long reaches and large load carrying capacities. The difficulty is that any material beam with length L will bend when a perpendicular force is applied at the end. This will displace the end tip by an amount d from its expected position.

When manipulating an ARM, there are two ways of dealing with this problem. The first is to make the beam so stiff that, for the forces involved, the value d is less than the positioning accuracy required. Therefore, d can be ignored. The difficulty with this approach is that a massive beam is required to obtain this rigidity. The second approach is to calculate the value of d for any particular displacement force. In general, such calculations are difficult and dependent upon the value of the payload mass. This method works best when the payload is kept constant.

We circumvent these problems by using a perfectly straight, infinitely rigid laser light reference beam. We measure in real time the displacement vector d between the segment end tip and the laser reference beam.



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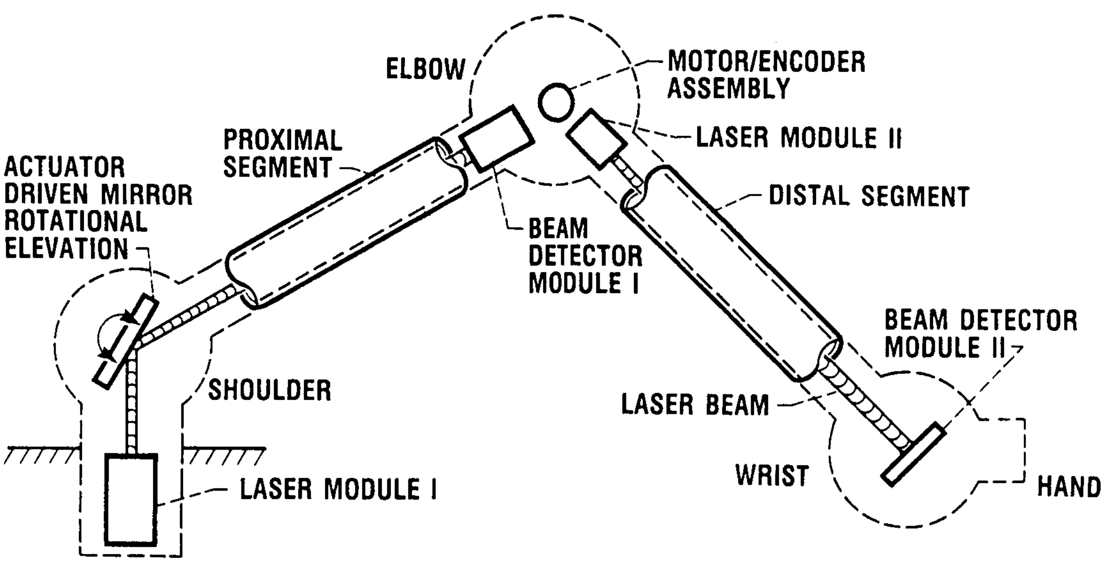
ARM CONFIGURATION

From this concept we have designed a two-segment ARM. The shoulder articulation rotates and elevates. Concentric with the shoulder is a beam positioning unit which moves simularly. Both of these are independently attached to the base reference point. BRM1 provides the vector position of the elbow with respect to the base reference point.

The rotation of the elbow articulation is monitored by a high-resolution encoder. This information is used to define the elbow laser reference point for the second segment. BRM2 provides the vector position of the wrist with respect to the elbow reference point.

A series of vector coordinate transformations is used to provide the position of the wrist end tip with respect to the base reference point. Thus, we are able to accurately specify the wrist end-tip position in real time.



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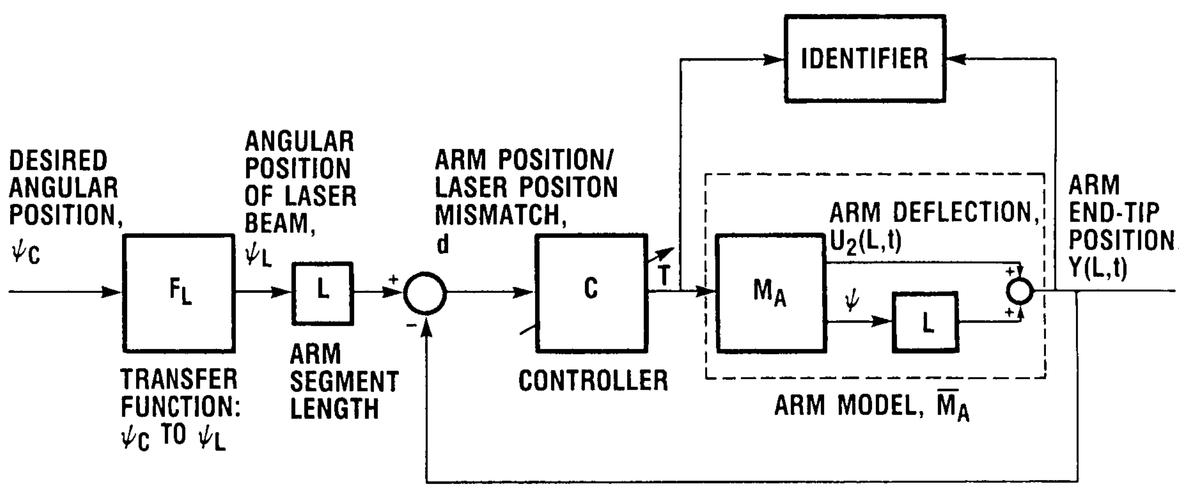
INDIRECT ADAPTIVE CONTROL SCHEME

The end-tip position information serves two functions. The first function is to dynamically control the behavior of the ARM. An indirect adaptive controller is used to monitor the end-tip positions. Using the d vector information, it stimulates the actuators which force the ARM to behave in a predictable manner. The second function is to define points in the work envelopes such that the ARM can move the payload from one position to another. Such movement can be either point to point or along a predefined path.



CONTROL INPUT: TORQUE T APPLIED TO BASE OF ARM

OUTPUTS TO BE CONTROLLED: 1. POSITION OF ARM END TIP
2. DEFLECTION OF ARM END TIP

- **LASER MEASURES ARM DEFLECTION AT END TIP**
- **TORQUE MEASURED (KNOWN) AT ARM BASE**
- **THESE TWO MEASUREMENTS USED TO FINE TUNE ARM MODEL WHICH IS USED TO FINE TUNE ARM CONTROLLER**

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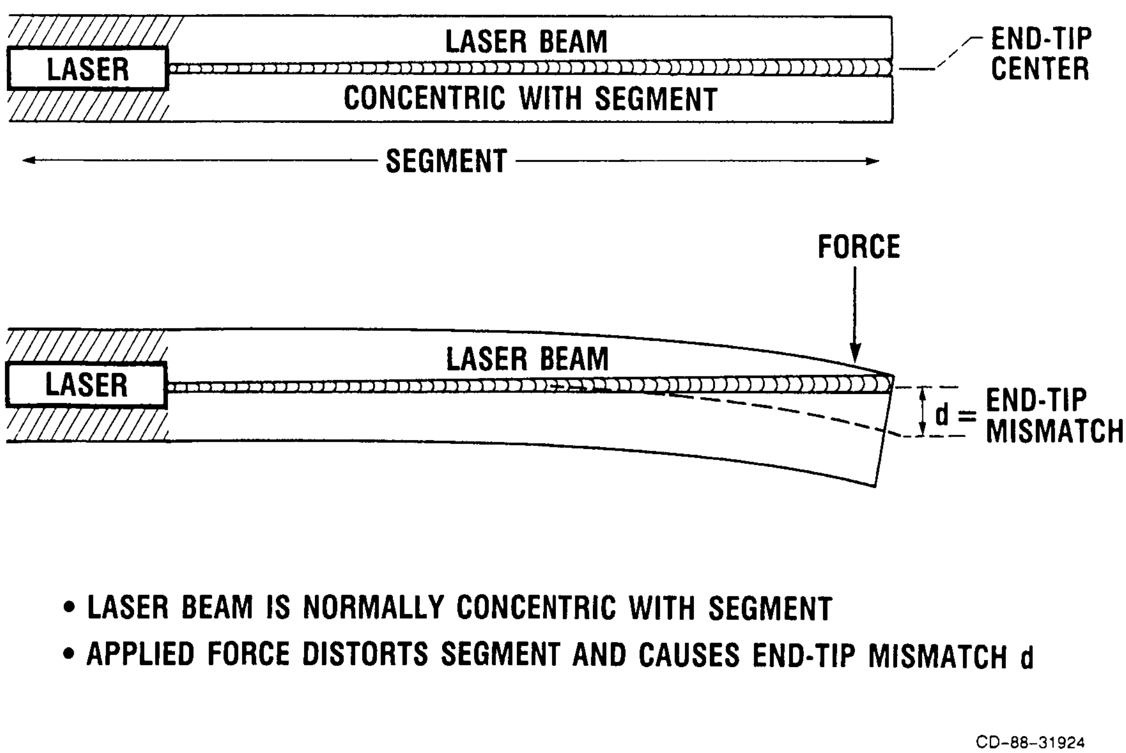
POSTER PRESENTATION

LASER BEAM RIGID BODY POSITIONING CONCEPT

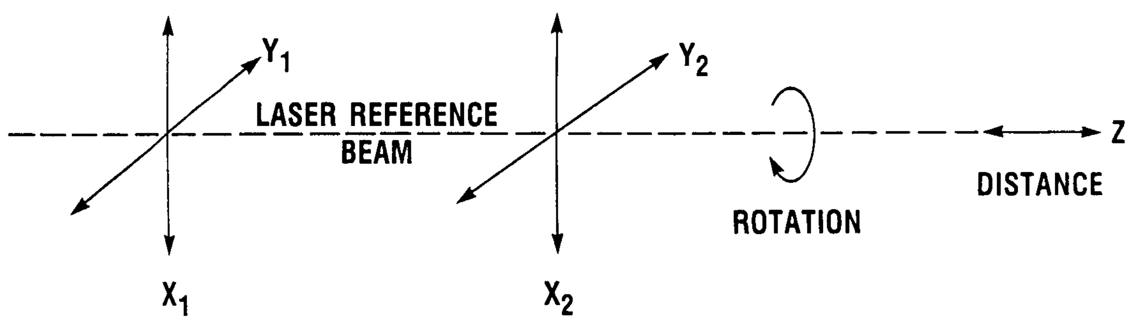
Assume a physical cantilever segment of length L. A force F perpendicular to the central axis of the segment will cause a displacement d. The magnitude of d is proportional to F and to the "stiffness" of the segment. Typically, robotic manipulators use short stiff segments to minimize d, preferably to a point where it can be neglected during operation. A long segment can be defined as a segment which has a value of d that becomes significant during normal operation and, therefore, cannot be neglected. Since, in general, the prediction or calculation of d is difficult, accurate positioning of long, flexible segments in real time is difficult. Our concept utilizes the fact that a light beam is perfectly rigid. Thus, the light beam serves as an axis of absolute reference. The value d is the distance between the light beam and the segment's distal end-tip position. Since, by using our methods, we can measure this value in "real time," accurate positioning of long, flexible segments becomes feasible.

Real time is the sampling frequency required to observe the effects of induced modal contributions. Currently, we are conducting experiments to determine the validity of our modal analytical model. Preliminary calculations indicate that contributions beyond the first three modes are negligible.



BEAM RIDER MODULE DEFINES SIX DEGREES OF FREEDOM

A two-segment ARM configuration maximizes the work space envelope. To accurately position the wrist end-tip platform of such an ARM in space requires the definition of six degrees of freedom. Although a variety of coordinate systems will meet this criterion, the one we choose is based upon our laser reference beam. A first point is determined by the values X_1, Y_1, and Z. A second point along the beam is defined by X_2 and Y_2. The angular value of rotation, about the Z-axis, defines the sixth degree of freedom. Together these values are used to uniquely specify the positions of the beam rider module (BRM) on the laser reference beam. It is the purpose of the BRM to determine the mismatch between the laser reference beam and the segment end tip, the vector d. This value is then used to accurately position the ARM.



- **FIVE LINEAR DEGREES OF FREEDOM**
- **ONE ROTATIONAL DEGREE OF FREEDOM**

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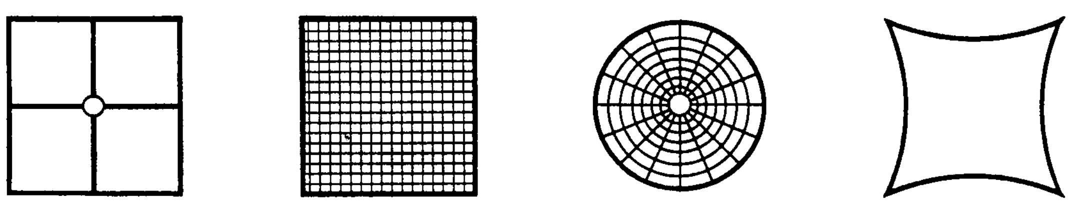
X-Y DETECTOR CONFIGURATIONS

Four planar detectors were selected for evaluations. The first is the quadrant detector, with and without a central orifice. In operation, analog circuitry is used to detect beam movement; the detector is physically translated such that the laser reference beam is kept centered in the quadrant. The amount of translation correlates to the X or Y values of the coordinate system. The second is the rectangular matrix detector. Digital circuitry is used to process the detector information and provide an X-Y coordinate of the beam spot. Significant amounts of digital signal processor (DSP) is required for this configuration; it was determined that this detector would be feasible only at very low (30 Hz) frequencies. The third is the annular matrix. This schema requires significant DSP, as does the rectangular matrix, and is not, generally, commercially available. Fourth is the lateral effects diode. This detector uses analog circuitry to rapidly provide an X and Y value. It appears to have sufficient resolution for our purposes. The major drawbacks are its high cost and its lack of linearity.



QUADRANT DETECTOR ANALOG 2×2	**RECTANGULAR MATRIX DIGITAL** 500×500	**ANNULAR MATRIX DIGITAL** 200×200	**LATERAL EFFECTS ANALOG** 2000×2000

- **DIFFERENT DETECTORS HAVE DIFFERENT RESOLUTIONS**
- **DETECTORS REQUIRE ANALOG OR DIGITAL PROCESSING**

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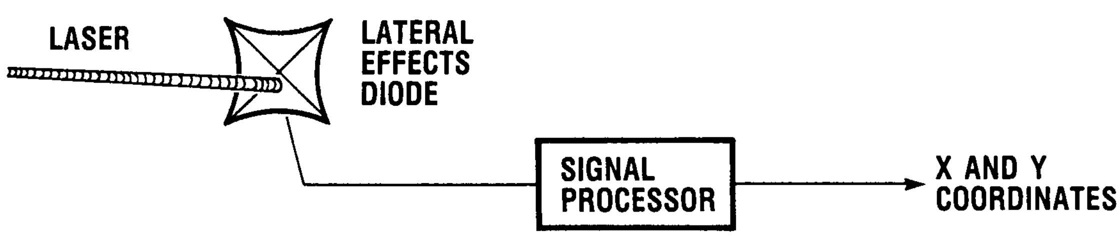
LATERAL EFFECTS DIODE

The output of the lateral effects diode is run through a multistage analog signal processor. The first stage isolates the diode from the processor. Ideally, only the magnitude of the charge produced by the light beam is sampled. This is because any current flow decreases the resolution of the detector. Resolutions are on the order of 1 part in 2000 of the length of the detectors. The outputs from the four edges are added, subtracted, and divided in such a manner that $\pm X$ and $\pm Y$ locations of the beam are represented by the output voltages from the processor. The frequency response of the system is limited by capacitance factors, which depend upon the size of the diode. Responses on the order of hundreds of kilohertz should be possible.



- **SIGNAL FROM LATERAL EFFECTS DIODE CONVERTED TO X AND Y COORDINATES**
- **THIS INFORMATION USED BY INDIRECT ADAPTIVE CONTROLLER TO POSITION ARM**

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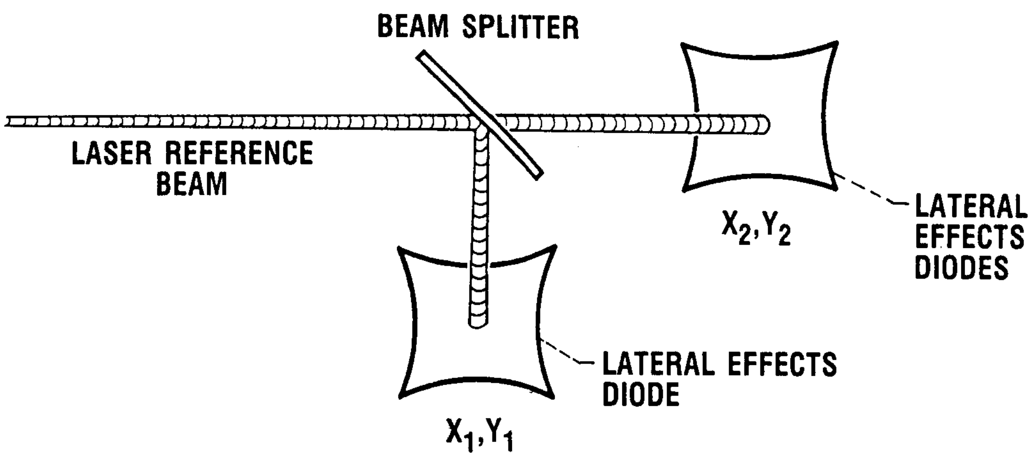
NONMOVING, FOUR-DEGREE-OF-FREEDOM DEFINING SCHEMA

A BRM using the lateral effect (LE) diodes would use a beam splitter to partition the beam's energy between detectors. Variation on this scheme can be used to define further degrees of freedom. For example, using a retroflector in the location of LE diode 2 would result in a laser beam retracing the path of the original beam for use with a laser interferometer. The reflected portion of this beam would be used to excite LE diode 2 and, therefore, provide information on coordinates X_2 and Y_2.



- **DETECTOR ASSEMBLIES ATTACHED TO SEGMENT**
- **DEFLECTION OF SEGMENT CAUSES CHANGE IN POSITION OF LASER BEAM ON DIODE**

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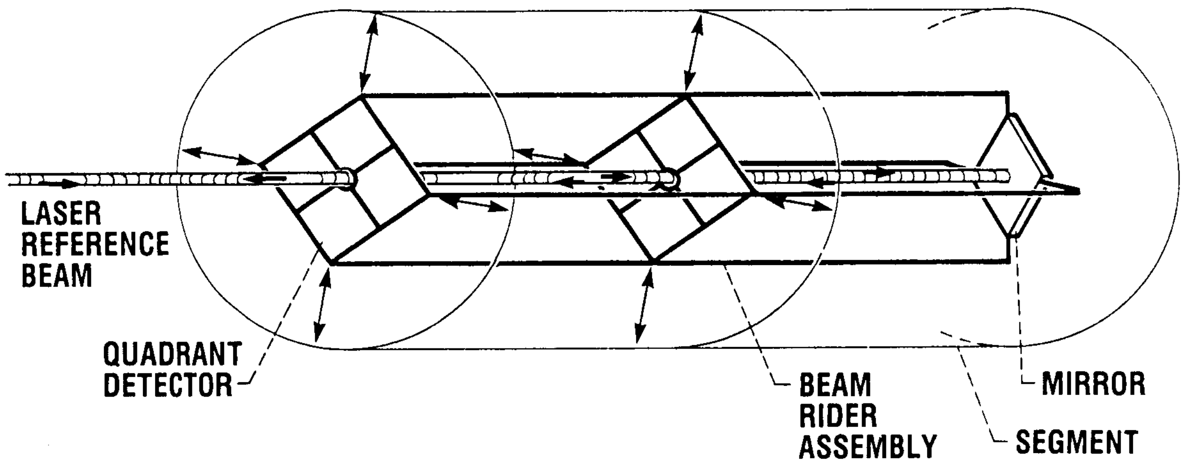
ACTIVE POSITIONING QUADRANT DETECTOR

A BRM can be made by using a pair of quadrant detectors and a retroflector. The BR assembly fits within the segment and is translated in the X_1,Y_1 and X_2,Y_2 directions. The beam is retroflected back down the tube. When the segment is displaced, the beam moves from the detector centers. The unbalanced output signal produced is used in a feedback loop to drive a motor and reposition the diodes. The detector and associated circuitry is analog and therefore has a high frequency response. The difficulty is in the design of a motor with matching high frequency response characteristics.



- BEAM RIDER ASSEMBLY FITS INSIDE SEGMENT
- ASSEMBLY HOLDS QUADRANT DETECTORS AND MIRRORS ASSEMBLY
- LINEAR MOTORS BETWEEN ASSEMBLY AND SEGMENT POSITION ASSEMBLY TO REMAIN COLINEAR WITH LASER REFERENCE BEAM

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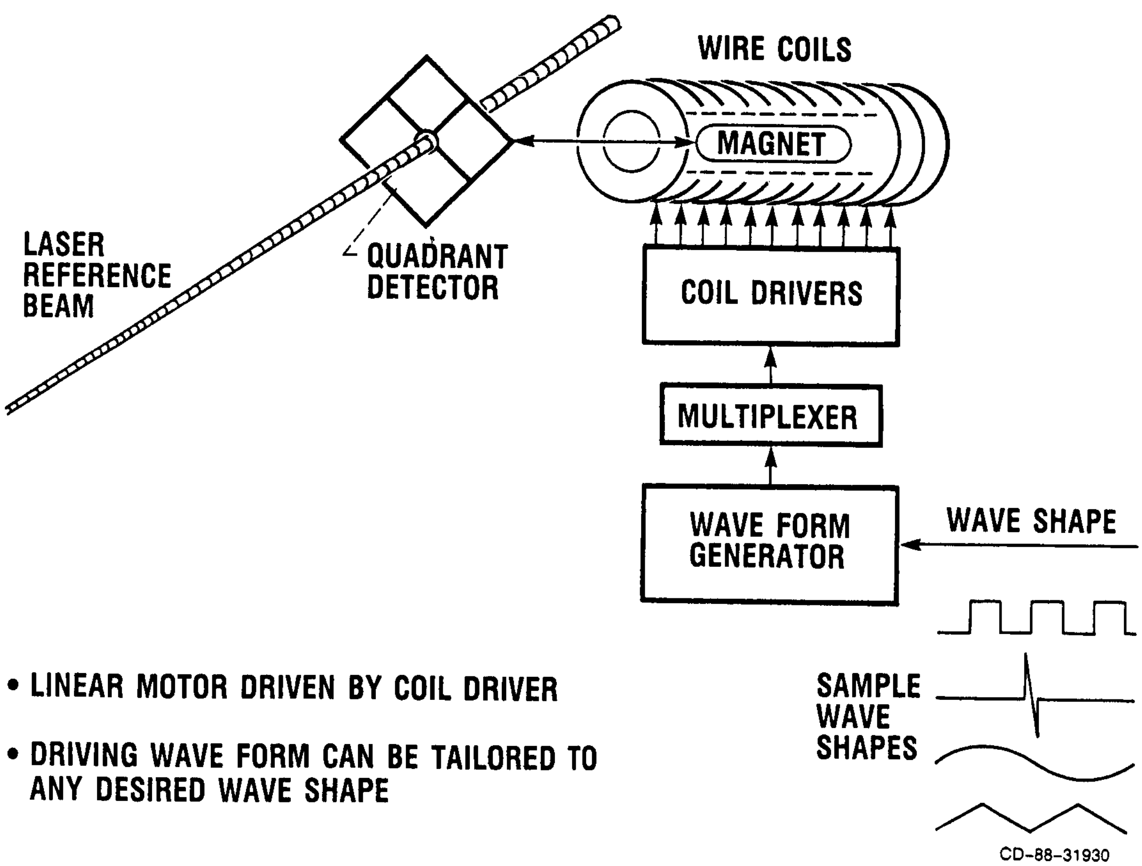
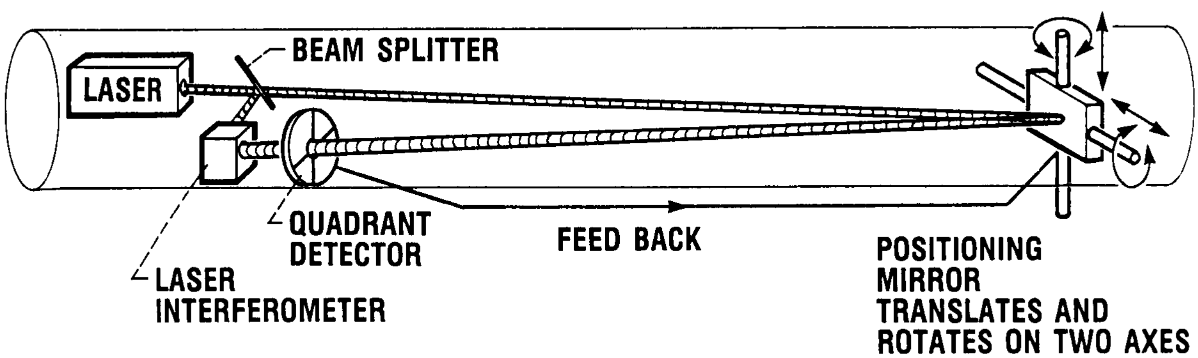
ACTIVE POSITIONING LINEAR MOTOR

A linear actuator, such as a voice coil, was determined to be a good candidate for the BRM because of its high frequency response. The major drawback of the voice coil actuator is that it has insufficient linear travel. To extend the travel, we designed an actuator which has serial sets of coils. Sequential or simultaneous excitations of the coils provide the desired linear travel. The coil driver can drive 256 coils with a positive or negative current. The value of the current in each coil is set by a multiplexing unit which addresses each coil uniquely by using an 8-bit code. The drive value is stored until reset. The wave from generator determines which value is placed on which address line. The wave form can be generated by a computer and represents a standing wave. The most appropriate standing wave to promote the desired movement is generated and sent to the linear actuator. The centering of the quadrant detector terminates the movement.



DISTANCE MEASURING EQUIPMENT - LASER INTERFEROMETER

A laser interferometer is being used as our distance measuring equipment. However, because this instrument measures incremental rather than absolute distance, an initialization is required prior to operation. During operation the incident reference beam and the return beam enter the interferometer. The interference fringes produced by changes in distance are counted and used to indicate the distance traveled. Alternative schemes using time of flight and resonant cavity length mode measurement are also under consideration.



- QUADRANT DETECTOR SENDS FEEDBACK TO POSITIONING MIRROR TO ASSURE CORRECT POSITIONING OF BEAM ON INTERFEROMETER
- LASER INTERFEROMETER DETERMINES TOTAL DISTANCE TRAVELED BY LASER
- RESULT IS ACCURATE DETECTION OF ANY CHANGE IN LENGTH OF ARM DUE TO APPLIED LOAD OR OTHER EFFECTS

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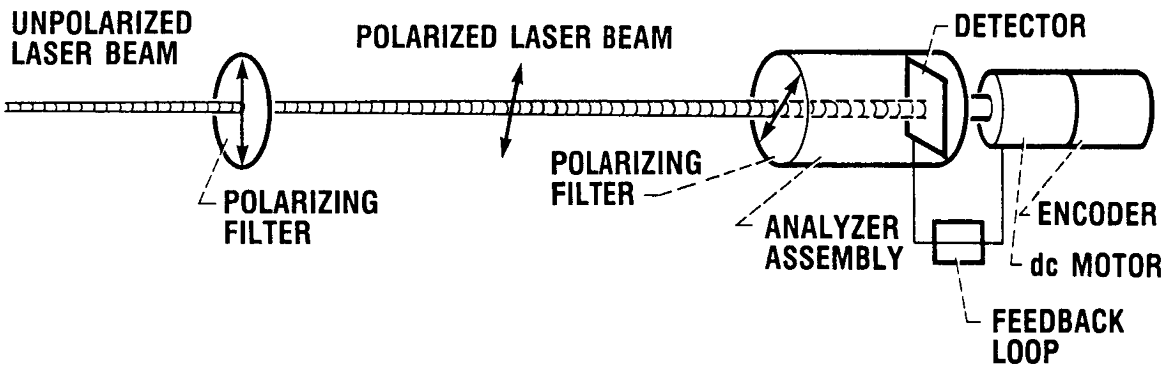
ROTATIONAL MEASURING EQUIPMENT - BEAM POLARIZATION

The rotational measurement equipment (RME) will make use of the polarized laser beam. An analyzer on the distal portion of the segment is used to analyze the beam. As an analyzer rotates around the reference beam towards 90°, the magnitude of the transmitted beam is reduced towards extinction. The RME module uses a detector to monitor beam intensity. The detector and analyzer are mounted on a motor encoder unit. The motor is controlled by detector output in such a manner that it rotates to provide maximum output. The required amount of rotation is measured by the encoder. This value can then be used for positioning the ARM.



- ARM ROTATION DETECTED USING POLARIZING FILTERS
- dc MOTOR ROTATES ANALYZER ASSEMBLY UNTIL DETECTOR READS MAXIMUM INTENSITY

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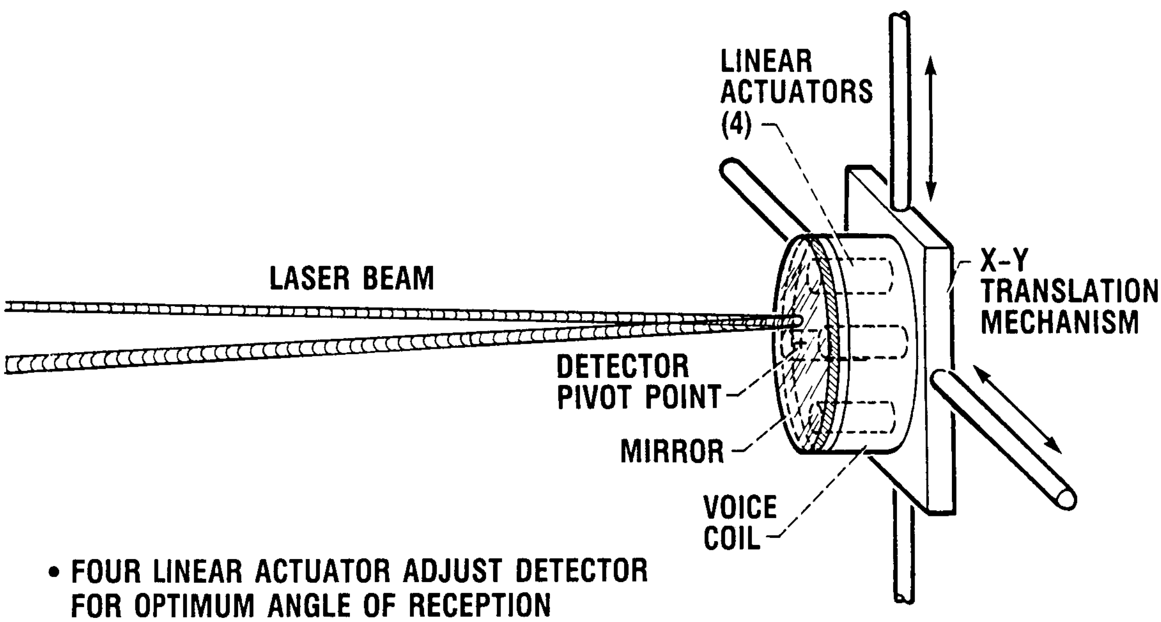
ACTIVE BEAM RETROFLECTOR ASSEMBLY

The use of a conventional interferometer setup requires the reflection of the incident beam back to the interferometer. If only a linear movement along the Z-axis is allowed, a corner cube or retroflector may be used. However, because in our application lateral displacement of the distal segment is possible, an active positioning device is required to keep the reflected laser beam aimed at the interferometer. A quadrant detector with a central orifice is placed in front of the interferometer. The output of the detector is used to drive the mirror mover angularly and correctly center the beam. When the angular movement exceeds a limit value, the mirror is translated. This arrangement allows the use of this schema for large values of d.



- **FOUR LINEAR ACTUATOR ADJUST DETECTOR FOR OPTIMUM ANGLE OF RECEPTION**
- **ENTIRE MIRROR POSITIONING MECHANISM MAY TRANSLATE IN X AND Y DIRECTIONS**

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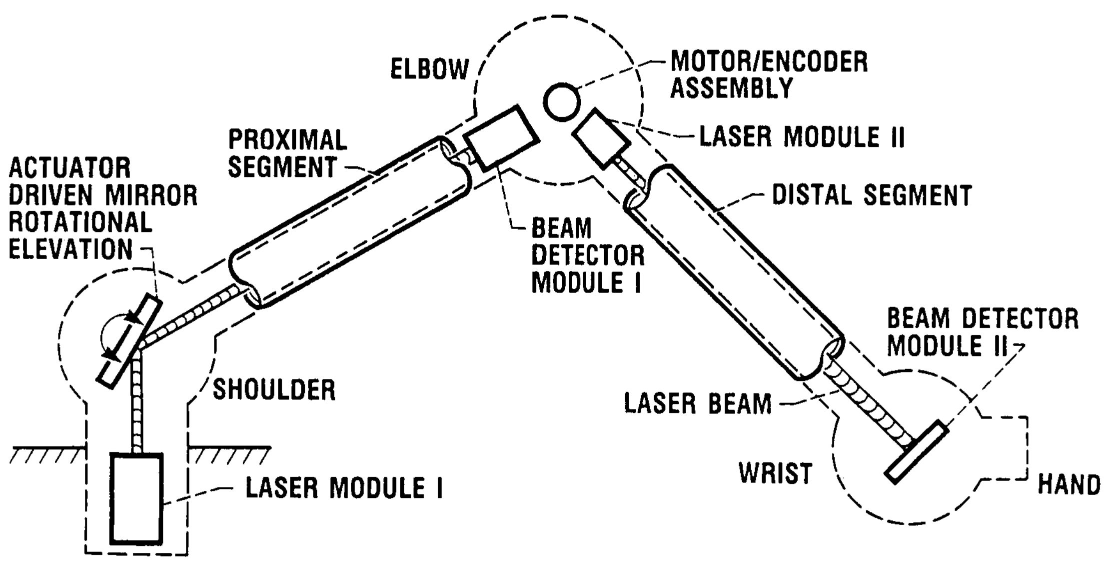
ARM CONFIGURATION

The ARM consists of two articulations, two segments, and a wrist platform. The shoulder articulation rotates about two axes and is connected to the elbow by the proximal segment. The elbow rotates on one axis and is connected to the wrist by the distal segment. The hand, manipulator, or end effectors mount on the wrist platform. Because of temperature changes, the segments in our current design will change length as materials expand or contract. Our concepts are compatible with future designs which would use extensible segments.



FEATURES:
- **LASER BEAM IS "INFINITE STIFFNESS" REFERENCE FOR FLEXIBLE STRUCTURE**
- **DETECTORS AND MIRROR DRIVES UNDER MICROPROCESSOR CONTROL TO TRACK ARM DEFLECTIONS**

IMPACT:
- **LOCATION OF END ARM IS KNOWN WITHIN 1 mm AT 10 m RADIUS**
- **POSITION, VELOCITY, ACCELERATION, AND FORCE OUTPUTS FOR ARM CONTROL AND REAL-TIME TRAJECTORY MANAGEMENT**

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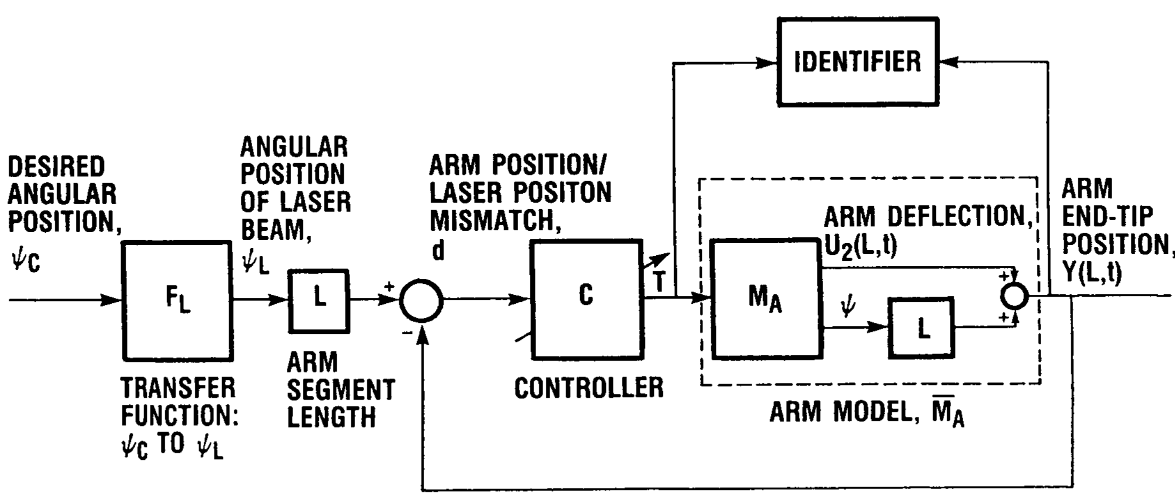
INDIRECT ADAPTIVE CONTROL SCHEME

In order to design a controller for a system, one must have an accurate model of the system. In the case of the ARM, we assume that its model consists of a finite number of linear, ordinary differential equations. The driving term, or input, to this model is torque applied to the base of the ARM, and the response, or output, is the end-tip position of the ARM. We will employ an identifier to determine the number of modes which must be included in the model and the model parameters (e.g., damping coefficients) required. The identifier takes input (torque) and output (end-tip position) measurements and uses those to estimate the values of the coefficients in the differential equations which compose the model. From the model the actual controller is constructed. The controller variables become functions of the identifier's ARM parameter estimates; as the identifier obtains better estimates of the ARM's parameters the controller becomes more finely tuned to the ARM. Any changes in the ARM's characteristics (e.g., a change in arm segment material compliance due to heating or cooling) will be sensed by the identifier. The identifier then changes the corresponding variables in the in-line controller. This provides continuous smooth operation of the overall system. An identifier linked to an in-line controller is referred to as an indirect adaptive control scheme.



CONTROL INPUT: TORQUE T APPLIED TO BASE OF ARM

OUTPUTS TO BE CONTROLLED: 1. POSITION OF ARM END TIP
2. DEFLECTION OF ARM END TIP

- **LASER MEASURES ARM DEFLECTION AT END TIP**
- **TORQUE MEASURED (KNOWN) AT ARM BASE**
- **THESE TWO MEASUREMENTS USED TO FINE TUNE ARM MODEL WHICH IS USED TO FINE TUNE ARM CONTROLLER**

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