TELESCOPING ROBOT ARMS

by

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BUTLER ANALYSES

This tells a tale about a challenge in modeling a highly articulated structure with colinear beam elements in preparation for an eigenvalue analysis. Many is the time that you have heard a client say, "I just want a simple beam model to give me some preliminary answers." Sometimes the words simple and beam are contradictory. The completed model looks simple when plotted, but the ingredients that went into the beam to represent the equivalent structure were highly complicated. This paper gives a good example of a non-simple simple-beam model.

Figure 1 shows a robot consisting of 3 pairs of crossed positioning arms that move a platform with respect to a base. Mounted on the platform is a similar mechanical system giving fine control positioning to a tool-piece. Figure 2 is a close-up of one of the 6 main telescoping arms. A survey of one arm's operation will start at the base where a spider operating through bearings in two perpendicular directions allows the arm to rotate freely in 2 directions while preserving the axial and torsional transmissions. The block beyond the spider has a drive motor cantilevered from the close end and has a shaft bearing gland cantilevered from the far end. The drive shaft extends from the overhung bearing in the motor armature into a coupling that connects the motor rotor to a stub where it is given alignment by the pair of bearings in the block housing. Beyond the block the shaft is grooved in continuous spirals that engage a ball nut. This grooved shaft is called the lead screw. The ball nut is at the head of a hollow shaft into which the lead screw can travel for pulling the platform down and vice versa. The connection to the platform is made through a bracket and trunion arrangement which again allows freedom of rotation about 2 axes, while preserving the axial transmissions. Figures 3 and 4 show the NASTRAN plot of the model in views giving explosions parallel to the drive shaft on the side then explosions parallel to the trunion shaft on the bottom.

Examining the schematic or the exploded plots the reader can see that in two places there are 3 beams operating inside of one another and at several other places 2 beams are colocated.

The aspects of this model that are worth discussing are how some of these multiple connections were handled. Only 3 of the many problems will be reviewed. Focus will be directed toward the spider joint first which is shown in figure 5. The problem is to put grid points at the end of the yoke; at the hub of the spider; and at the middle of the strut between tongues; then find bars, or rods, or scalars to represent the properties of these parts between these points . The attack on modeling begins with bending in the X-Y plane as defined in figure 6. The spider rotates in yoke bearings about the z axis, causing the bending in the X-Y plane to be discontinuous. This implies that the bending of the yoke in the X-Y plane is independent of the bending of the tongue in the X-Y plane when viewed from the grid point in the spider hub. Bending of the yoke contributes to translational displacements in the y direction at the spider hub. Also, bending of the tongue and spider contribute to translational displacements in y at the spider hub. Translational displacements in y at the spider hub are continuous. At first blush it looks fairly straight-forward to model the yoke and spider and tongue by using two bars connecting at a common point in the spider hub and applying pin flags to the ends to inhibit the transfer of moments about z. Pause and reflect on inertia properties. Inertias are properties of grid points not elements. The Izz component of inertia at the spider hub for the web is quite distinct from the Izz component of inertia at the spider hub for the tongue. If these individual values were both assigned to the same grid point, they would be summed and the rotational acceleration about the z axis would load connecting members at the hub by an amount proportional to the sum of the inertias. This is not the proper representation for the discontinuity that exists here. The individual inertias must be kept distinct.

Consequently, two individual points must be assigned to the hub location. The yoke connects to one of the points and the tongue connects to the other point. Only the yoke elastic and mass properties about the z axis are assigned to the yoke hub point. But, both the spider and the tongue elastic and mass properties are assigned to the tongue hub point. Continuity in the y hub displacement between the 2 end points is enforced by applying a multi-point constraint between their y d.o.f.'s.

The pattern of logic for modeling the bending in the X-Z plane is similar to that used above for bending in the X-Y plane. The end result is that individual hub points are needed. The two points used for modeling X-Y bending can serve for X-Z bending. However, here the spider properties combine with the yoke instead of the tongue. Continuity in the hub z displacements is enforced by applying a multi-point constraint between their z d.o.f.'s.

If slop in the ball bearings is ignored in the yoke and the tongue, the spider maintains continuity in axial and torsional displacements from yoke to tongue. Two options are available for modeling hub displacements and properties in and about x. Option A is to connect via the two points used in bending for axial and torsion then constrain x translational d.o.f.'s and the x rotational d.o.f.'s together. Option B calls for a third point to be defined. The argument for a 3rd hub point is that it avoids the singularity that arises in setting up an MPC in torsion due to a zero separation distance between points. Another argument supporting a 3rd point is that there is no compelling requirement of the physics to connect the bending d.o.f.'s to the torsional d.o.f.'s, because linear theory admits no coupling between them. It is correct to combine elastic and mass properties in and about x at the hub so a single grid point will serve.

In summary, the spider joint is modeled by
(1) colocating 3 G.P.'s at the spider hub;
(2) connecting the yoke bar to one hub point, assigning only yoke elastic and mass properties to it for rotations about z, assigning both spider and yoke properties to it for rotations about y;
(3) conncecting the tongue bar to a second hub point, assigning both spider and tongue properties to it for rotations about z, assigning only tongue properties to it for rotations about y;
(4) constraining the y d.o.f.'s together and the z d.o.f.'s together between yoke and tongue hub points to ensure translational continuity while maintaining rotational discontinuity.
(5) connecting a yoke conrod and a tongue conrod together at a third hub point, for modeling continuous axial and torsional actions through the spider.
(6) putting single point constraints on the axial and torsional d.o.f's of the yoke and tongue hub points to inhibit participation of the bars in these freedoms.

Another interesting topic was the torsional coupling of the lead screw shaft with the armature housing through the motor field. With no field excitation in the armature the lead screw shaft is free in torsion at the rotor end. But this is not the eigenvalue condition that was needed for control frequency investigations. Therefore, the spring constant for the armature field/rotor poles was needed. The motor has a torque rating of 135,400 oz.in. Assume that the motor has an induction slip of 15% (1/7 of a turn). This implies that the rotational displacement of the rotor with respect to the stator field is 2 Pi/7. The torsional spring constant can now be computed as torque developed under a given rotational displacement.

C = [(135,400 oz.in.)/16 oz. per lb.] / (2 Pi/7) = 9428 in.#/Ra.

Half of this value was applied to each of the two bearings. Scalar springs were the elastic elements used for this torsional field spring.

Another uncommon operation to model was the so-called screw ratio. The ball nut rating produced a travel in the negative axial direction of 0.2 inches for each full rotation of the lead screw. This was represented by multi-point constraints between rotation of the lead screw at GP 36 and the travel of the ball nut at GP 41 and at GP 37 to GP 42.

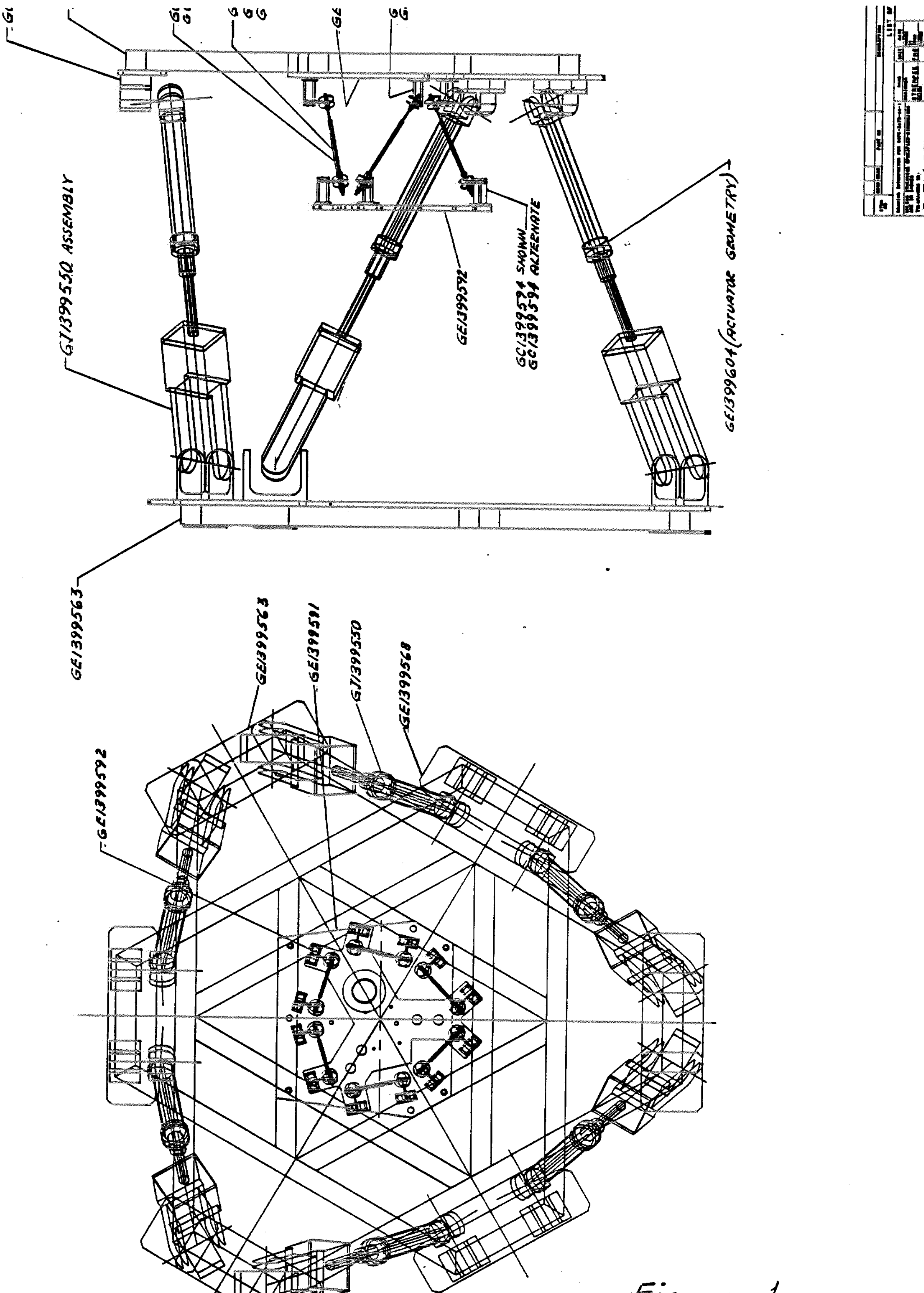
Ux (nut)/θx (screw) = 0.2 / 2 Pi. ==> θx = 10 Pi Ux.

This fixed relationship did not alter the fact that there was also an axial spring rate between the ball nut and screw. No details will be given here, but the point is raised, because there is a tendency to overlook this axial spring rate because of the attention to the screw rate.

Look at exploded plots of the model. Multi-point constraints are designated with capital M. Scalar relationships are designated with capital E. Notice that multipoint constraints were used in a number of places. The spider point between GP's 12 & 21 has already been discussed. Separate GP's were used for the stator and rotor at the 2 bearings, because bending was uncoupled and because torsion was coupled magnetically through a scalar, so MPC's were used to constrain transverse translations together at the bearing GP's 26 to 31 and 22 to 32. Separate GP's were used for the overhung bearings and the shaft stub, because bending, torsion and axial actions were uncoupled. MPC's were used to constrain transverse translations together at the bearing GP's 25 to 33 and 24 to 34. Separate GP's were used for the lead screw and the ball nut, because bending was uncoupled and screw action was linked by an MPC between rotation and translation. Therefore MPC's were used to constrain translations together at the forward and after bearings of the ball nut GP's 41 to 36 and 42 to 37.

Considerations at the trunion end were similar to those at the spider end escept that shafts were at right angles to each other. Four colocated GP's were used to separate out the bending discontinuities from the translational continuities. MPC's were applied in 2 pairs between the four points. More care needed to be exercised here than at the spider, because two coordinate systems were involved.

One last observation. All features of NASTRAN that were used in this analysis were available in Level 5.0 in May of 1968. This example illustrates what a fine job Dick MacNeal did in setting up the applied mechanics features in NASTRAN. I set up a pretty comprehensive set of specifications for the original NASTRAN program, but in translating these specifications to reality, Dick MacNeal performed according to the highest standards of excellence. My specifications did not embrace pin flags for the BAR element, but Dick would not attach his name to a BAR without it. Multi-point constraints were not in the original specifications, but Dick dug into his bag of handy tricks that he used in solving problems and incorporated them into the original version as a matter of pride of workmanship. These are but two small, but intensely useful measures, of Dick MacNeal's crafting of NASTRAN's solution capability. I must admit that I often come upon suprise bonuses or discover unexpected thoroughness when I study the Theoretical Manual. Thank you, Dick. Will we ever know the whole story of your generosity?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GE1399592
GC1399594 SHOWN
GC1399594 ALTERNATE
GE1399604 (ACTUATOR GEOMETRY)
GE1399563
GE1399563
GE1399591
GJ1399550
GE1399568
GE1399592

Figure 1

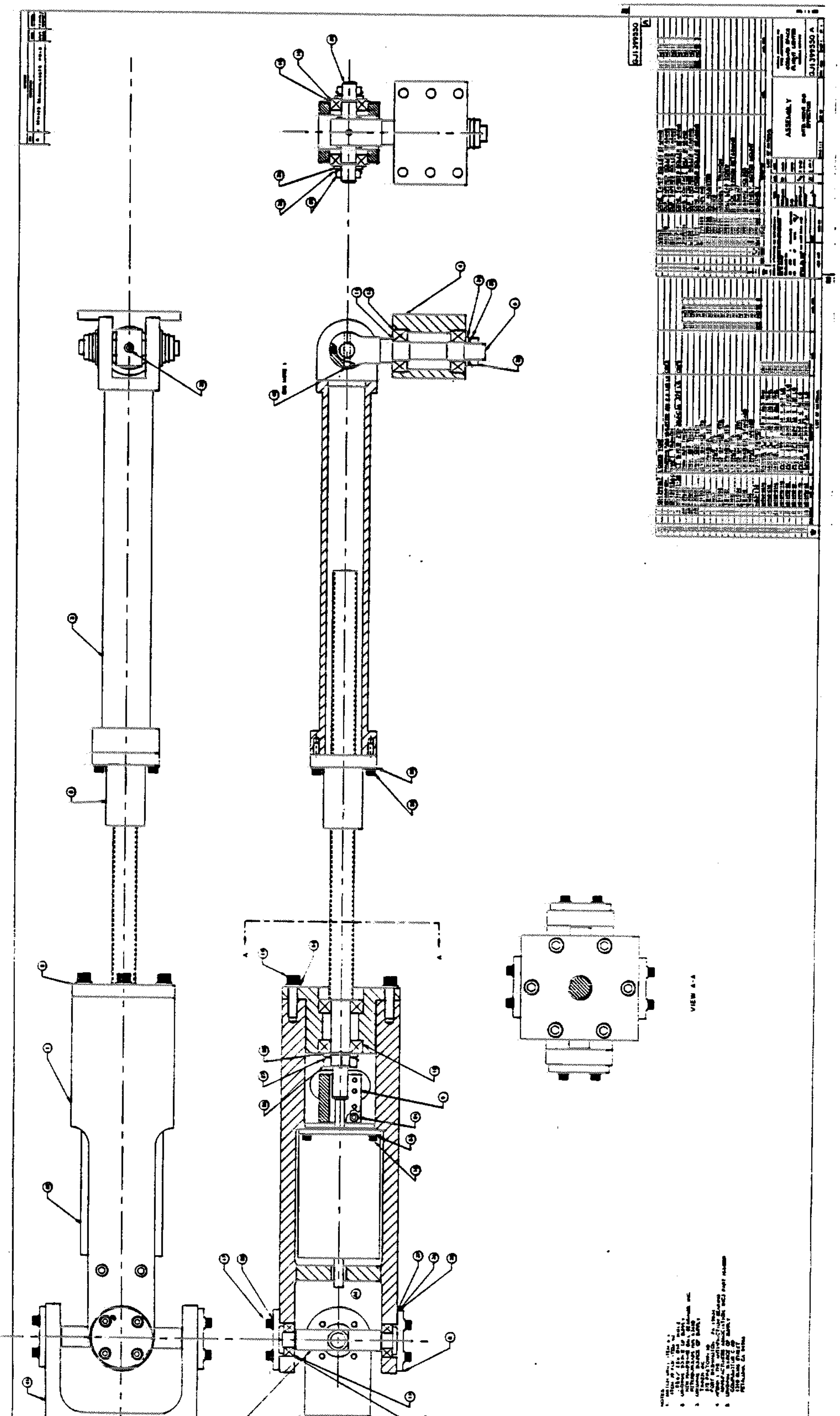

Figure 2

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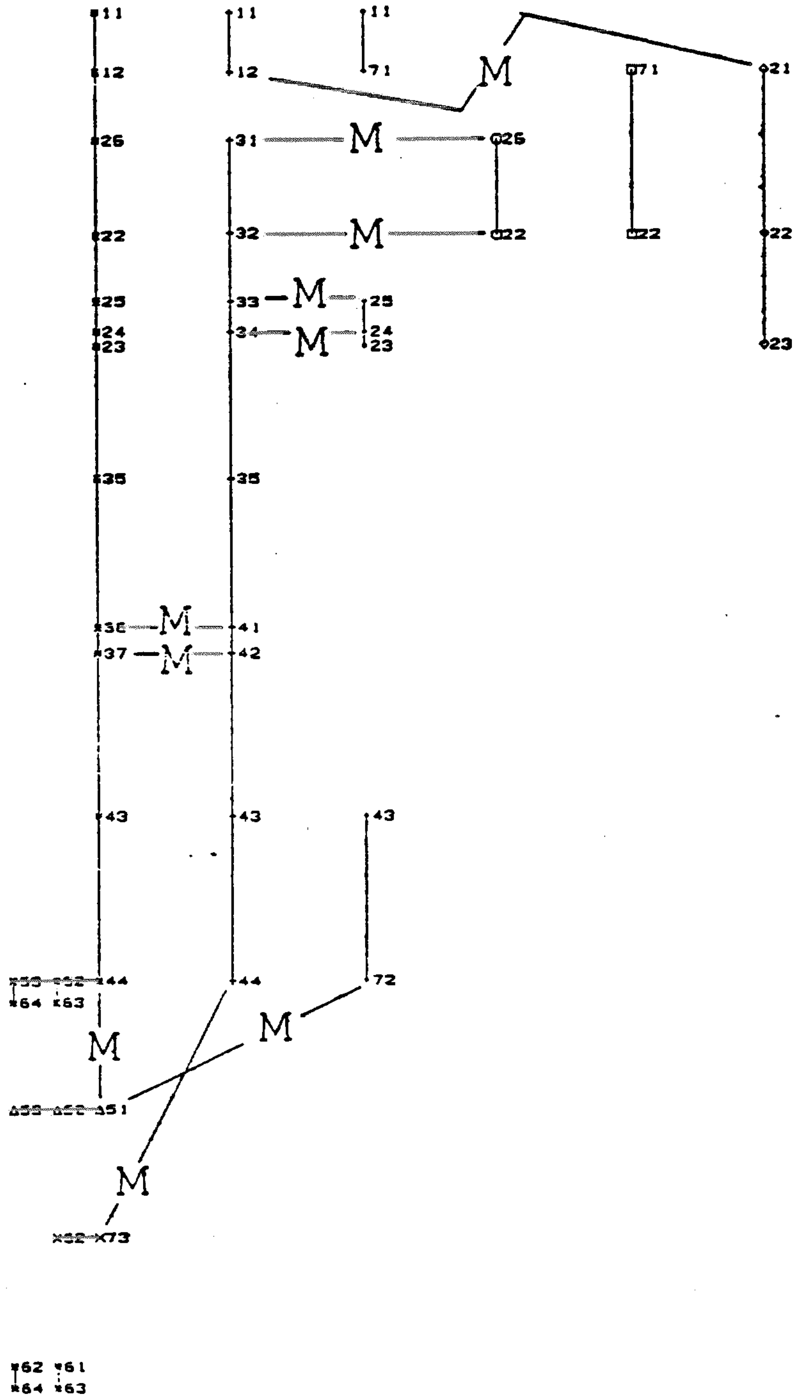

Figure 3

GSFC EXPERIMENTAL INTELLIGENT END EFFECTOR
PURELY BAR MODEL. ALL MASSES BY CONM2.

EXPLODED VIEW

UNDEFORMED SHAPE

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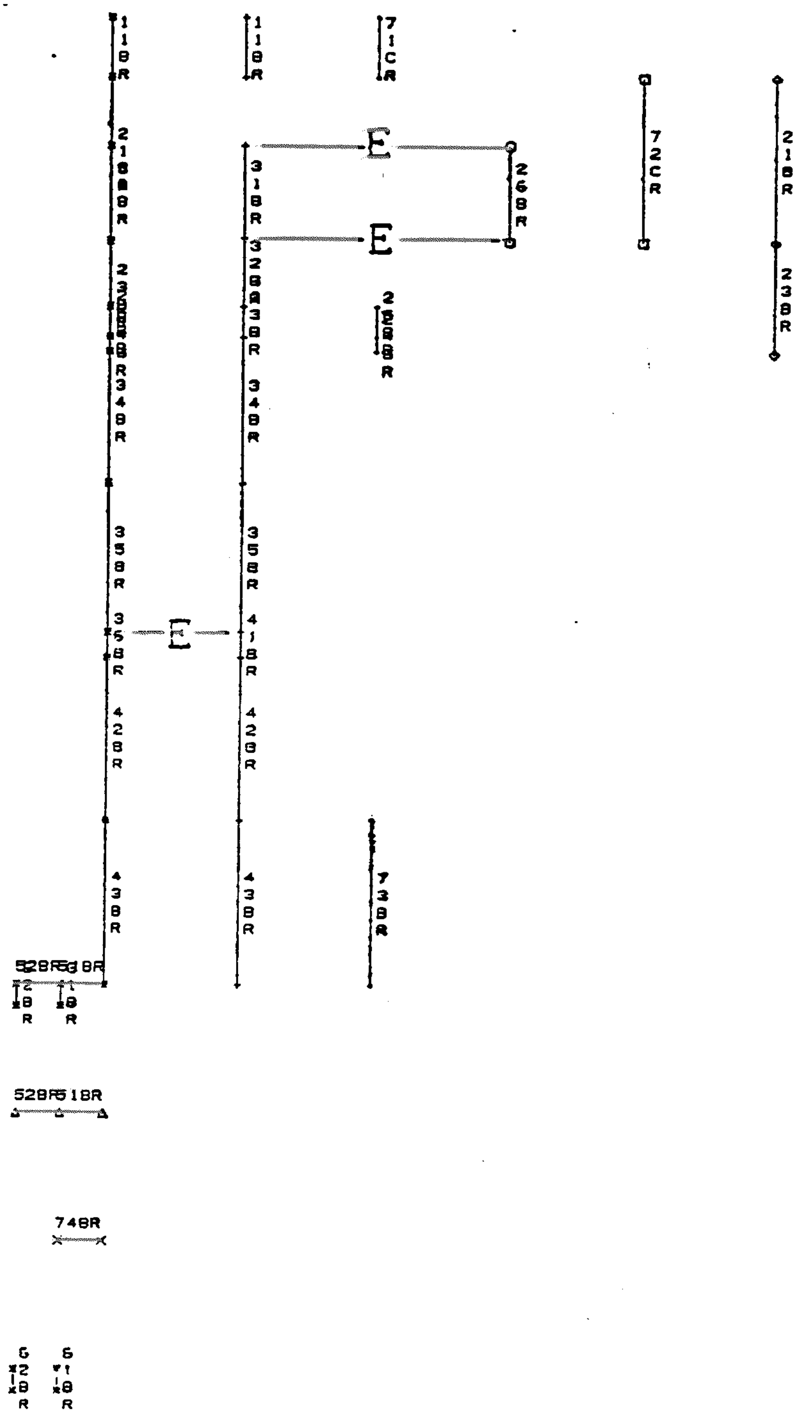

Figure 4

GSFC EXPERIMENTAL INTELLIGENT END EFFECTOR
PURELY BAR MODEL. ALL MASSES BY CONM2.

UNDEFORMED SHAPE

EXPLODED VIEW

SPIDER LINK

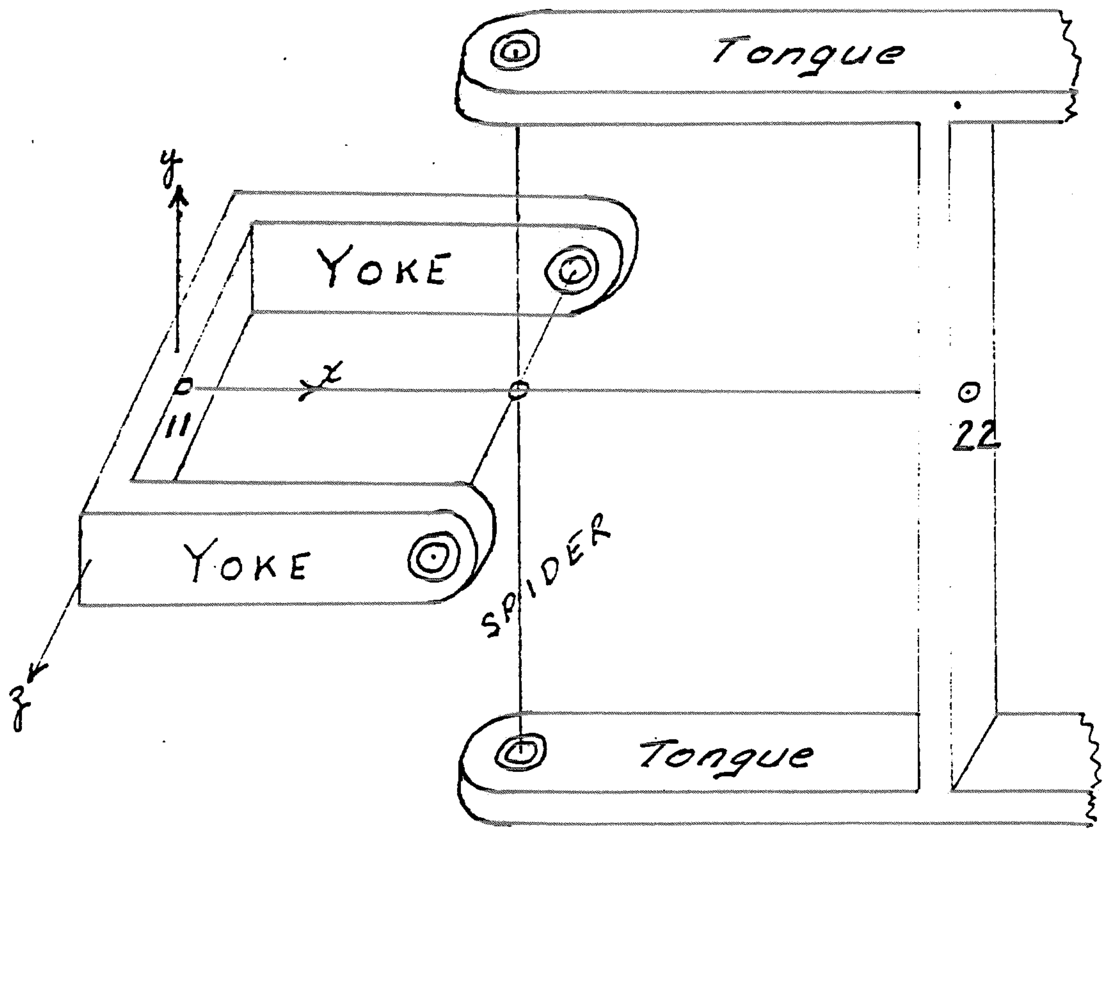

Figure 5