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(54) MANIPULATOR

(71) We, INTERNATIONAL BUSINESS MACHINES CORPORATION, a Corporation organized and existing under the laws of the State of New York in the United States of America, of Armonk, New York 10504, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to a manipulator having a pair of gripper fingers and a drive mechanism to drive the gripper fingers.

According to the present invention there is provided a manipulator having a pair of gripper fingers, a drive mechanism to drive the gripper fingers, a pair of sensor assemblies, each gripper finger being coupled to the drive mechanism through a respective one of the sensor assemblies, there being in each sensor assembly a plurality of force sensors disposed in series between the drive mechanism and the respective finger and adapted to sense moments about a plurality of orthogonal axes resulting from forces applied to the respective finger, there being for each force sensor in one of the sensor assemblies a corresponding force sensor in the other of the sensor assemblies to sense a moment about a parallel orthogonal axis, the disposition of the force sensors of the one sensor assembly relative to their respective finger being different from the disposition of the corresponding force sensors of the other sensor assembly relative to their respective finger, whereby like forces applied to both fingers result in different moments being applied to corresponding force sensors in the pair of sensor assemblies.

The invention will now be described by way of example with reference to the accompanying drawings in which:—

Figure 1A shows a perspective view of a computer-controlled manipulator in accordance with this invention,

Figure 1B shows a finger drive mechanism for fingers and associated sensor assemblies of the manipulator shown in Figure 1A,

Figure 2 shows a perspective view of the gripper fingers and associated sensor assemblies of manipulator shown in Figure 1A,

Figure 3 shows the effect of forces applied to the right finger of Figure 2,

Figure 4 shows the effect of forces applied to the left finger of Figure 2,

Figure 5 shows the gripper fingers of Figure 2 holding a power screw driver adjacent to a work table or fixture,

Figure 6 shows a plan view of a portion of the manipulator of Figure 1 and a power screw driver,

Figure 7 shows a flow chart describing movement of the fingers in Figure 7 until they touch the screw driver of Figure 6,

Figure 8 shows a front elevation of the fingers of Figure 1 oriented vertically above a post holding several washers,

Figure 9 shows a plan view a portion of the manipulator of Figure 1 with the screw driver of Figure 6 between the opened fingers,

Figure 10 shows a flow chart describing the operation of the manipulator in the position of Figure 10 to pick up the screw driver,

Figure 11 shows graphically the output from a force sensor module of one of the sensor assemblies shown in Figure 2, and,

Figure 12 shows a flow chart describing how to determine the contact force between an object and a work table.

Figure 1A shows a manipulator controlled by a central processing unit (CPU) 44 having three mutually perpendicular X, Y and Z arm segments 38, 40 and 42 for providing x, y and z direction of motion of the gripper. Segments 38, 40 and 42 are slidably connected together by holder 39, 41 and 43 to provide an articulated three-part manipulator arm. At the outboard end of the arm segment 38 is shown a gripper 45 connected to X arm segment 38 by roll shaft 46 wrist 47, and finger drive mechanism 48. The X arm segment 38 is slidable in holder 39 affixed to the end of Y arm segment 40. Holder 39 carries a linear motor 50 affixed thereto including actuators adapted for operating upon a parabolic displacement cam 53 in accordance with United States Patent No. 3,848,515. Rack 108 drives a potentiometer 114 by its associated pinion.

Potentiometer 114 operates to send messages indicating X arm position data to CPU 44 indicating the position of arm 38. Y arm segment 40 is slidable along the Y axis in holder 41 with a similar drive motor 51 secured thereto to operate upon cam 54. Potentiometer 116 is driven by its pinion riding on rack teeth 110, as segment 40 moves by to signal Y arm position data to CPU 44. Z arm segment 42 does not move up and down along the z axis, but instead, holder 43 is rigidly and permanently secured to holder 41 and holder 43 has motor 52 secured thereto to operate upon cam 55 to raise and lower the rest of the arm including segments 38 and 40, etc. on arm segment 42. Z axis position is sensed by potentiometer 118 and rack teeth 112. The entire structure is rotatable about the center of arm segment 42 which is mounted upon a rotatable disc which is driven by a rotary drive inside cylinder 56. Potentiometer 57 driven by rack teeth 107 senses arm rotation. Still another rotary drive turns roll shaft 46, as do motors for the yaw, and pitch axes 58 and 59 of wrist 47. The finger drive mechanism 48 moves fingers 10 and 11 of gripper 45 which can be opened or closed (moved together and apart) by means of the mechanism shown in Fig. 1B.

As shown in Fig. 1B, the motor 74 is operatively connected by means of gears 76 to a pair of gear racks 80 for driving the finger driver blocks 23 and 24 either toward or away from each other in unison. Gear racks 80 move longitudinally to the left and right as shown by the arrows in Fig. 1B. A potentiometer 78 has its shaft teeth in operative engagement with motor gears 76 so that the motor shaft angular position is reflected in the output of the potentiometer 78 on line 86. This output on line 86 is therefore directly related to the separation of the finger driver blocks 23 and 24.

Referring to Fig. 2, the gripper 45 consists of two fingers 10 and 11. A three-degree-of-freedom force sensor assembly 12 is connected to the inboard end of the right finger 10. Another three-degree-of-freedom force sensor assembly 13 is connected to the inboard end of the left finger 11.

The sensor assembly 12 is composed of three I-beam sensor modules 14, 15, 16 and sensor 13 is composed of similar modules 17, 18, 19. Each sensor module takes the form of a generally I-shaped beam having two pairs of strain gauges mounted one pair on each face of the web thereof. The beam has end portions or blocks to adapt the force sensor at an angle of 90° to the next force sensor. The outputs of the pairs of strain gauges are applied in a Wheatstone bridge circuit so that each force sensor is sensitive to forces applied perpendicular to the web thereof and to moments applied about an axis extending through the web.

The four strain gauges of each module are electrically connected in a Wheatstone bridge circuit with the opposite connected elements in the circuit being comprised of the pair of strain gauges on the same surface of the module web. The sensor modules are enabled to sense forces in respective x, y and z axes and for sensing moments about the x, y and z axes, thereby providing six degrees of freedom in sensing. The general arrangement and electrical connection of the sensor modules is more fully described in our UK Patent No. 1,489,040.

It will be noted from Figure 2 that for each sensor module in the sensor assembly 12 there is a corresponding sensor module in the other sensor assembly 13. Thus sensor module 14 has a web disposed to be sensitive to a moment about the z axis resulting from forces applied to the right finger 10. The module 14 corresponds to the sensor module 18 which is also sensitive to a moment about the z axis resulting from forces applied to the left finger 11. Similarly the sensor module 15, sensitive to moments about the y axis, corresponds to the sensor module 17 also

sensitive to moments about the y axis. Finally the sensor module 16, sensitive to moments about the y axis, corresponds to the sensor module 19 sensitive to moments about the x axis. Although none of the sensor modules is sensitive to moments about the x axis it will be shown that the modules are sensitive to forces applied to the fingers in the z axis and it will be shown how moments about the z axis can be computed from the forces applied to the fingers 10 and 11. It will further be noted that the disposition of the series of sensor modules 14, 15 and 16 relative to the finger 10 is different from the disposition of the modules 17, 18 and 19 relative to the finger 11. Therefore like forces applied to the two fingers 10 and 11 will result in different moments being applied to corresponding sensor modules in the sensor assemblies 12 and 13. In the particular arrangement shown, the order of the sensor modules in the sensor assembly 12 is different from the order of the corresponding sensor modules in the sensor assembly 13.

Right Finger

In Figure 3, the right finger 10 is connected at its inner end to sensor module 14, A, having a vertical web or blade as diagrammatically shown with a rectangular surface extending up and down. Module 14, A, is connected to block 21, which connects to sensor module 15, B, which has a horizontal web or blade with its rectangular surface extending from side to side. Module 15, B, is connected to elbow-block 22 which is connected to module 16, C, which has a vertical web or blade extending normal to the planes of the blades of modules 14 and 15 with its rectangular surface extending from side to side. Module 16, C, is connected to driver block 23 attached to finger drive mechanism 48. If the right finger is not holding an object, a force vector \vec{F}_R applied at an arbitrary point R on the right finger 10 can be approximately resolved into three components vectors, F_{XR} , F_{YR} and F_{ZR} is shown in Figure 3. At point A in Figure 3, sensor 14 measures only the moment in the direction of the moment M_A . The output of force sensor 14 output at point A can be related to the external force vector \vec{F}_R by

$$M_A = -F_{XR} \cdot (Y_R - Y_A) + F_{YR} \cdot (X_R - X_A) \quad (1)$$

where Y_R and Y_A are the Y coordinates of points R and A and X_R and X_A are the X coordinates of those points. In a similar manner, the sensor output at points B and C for sensors 15 and 16, respectively provide

$$M_B = F_{XR} \cdot (Z_R - Z_B) - F_{ZR} \cdot (X_R - X_B) \quad (2)$$

$$M_C = F_{XR} \cdot (Z_R - Z_C) - F_{ZR} \cdot (X_R - X_C) \quad (3)$$

Equations (1), (2) and (3) can be written in a matrix form

$$\begin{bmatrix} M_A \\ M_B \\ M_C \end{bmatrix} = \begin{bmatrix} -(Y_R - Y_A) & (X_R - X_A) & 0 \\ (Z_R - Z_B) & 0 & -(X_R - X_B) \\ (Z_R - Z_C) & 0 & -(X_R - X_C) \end{bmatrix} \cdot \begin{bmatrix} F_{XR} \\ F_{YR} \\ F_{ZR} \end{bmatrix} \quad (4)$$

Left Finger

As shown in Fig. 4, the left finger 11 is connected at its inner end to sensor module 17, D, having a horizontal web or blade extending laterally. Module 17, D is connected to block 26 which is connected to module 18, E, having a vertical web or blade extending up and down along axis of finger 11. An elbow block has a horizontal leg 27 and a vertical leg 20 which is far longer than the vertical extent of elbow block 22 of the right finger 10. Module 19, G, connects leg 20 to driver block 24 attached to the other end of the finger drive mechanism 48. Module 19, G, has a vertical web or blade extending up and down across the linkage normal to the axis

of finger 11 in a plane parallel to that of module 16 and normal to those of modules 17, D, and 18, E. Thus module 19, G, has a substantial offset from module 16, C.

For the left finger 11, a three-degree-of-freedom force sensor is also mounted on the inner end of the finger. However, the sensor location is different from the corresponding sensor location for the right finger. An intentional offset distance has been provided by leg 20 extending above elbow 21 about one or two inches. Again, a force vector, F_L , applied at point L on the left finger can be approximately resolved into three components, F_{LX} , F_{LY} and F_{LZ} as shown in Fig. 4. Note the coordinates for point L in Fig. 4 may be different from those of point R in Fig. 3. The force sensor outputs at points D, E and G on sensors 17, 18, and 19, respectively can be related to the force vector applied at the finger by

$$\begin{bmatrix} M_D \\ M_E \\ M_G \end{bmatrix} = \begin{bmatrix} (Z_L - \bar{Z}_D) & 0 & -(X_L - X_D) & F_{LX} \\ -(Y_L - Y_E) & (X_L - X_E) & 0 & F_{LY} \\ (X_L - X_G) & 0 & -(X_L - X_G) & F_{LZ} \end{bmatrix} \quad (5)$$

Having described the arrangement of the manipulator of Figures 1A and 1B and the effect of forces on the left and right fingers in the x, y and z axes, some applications of the manipulator will now be described.

Referring to Figure 5, the pair of parallel fingers 10, 11 are holding an object, e.g. a screw driver 28. The contact force between the screw driver 28 and a work table 29 can always be transferred to a force vector \bar{F}_H applied at the centre of gravity (point H) of the object 28, being held by fingers 10, 11. The point H has coordinates X_H , Y_H and Z_H . The force vector consists of six components, F_{XH} , F_{YH} and F_{ZH} and three moments M_{XH} , M_{YH} and M_{ZH} . Assume the contact point between the object (e.g. screw driver) and the right finger 10 is point R. The contact point between the object and the left finger 11 is point L. Taking the object as a free body, the force equilibrium equations for this object are

$$F_{XH} = F_{XR} + F_{XL} \quad (6A)$$

$$F_{YH} = F_{YR} + F_{YL} \quad (6B)$$

$$F_{ZH} = F_{ZR} + F_{ZL} \quad (6C)$$

$$M_{XH} = F_{ZR} \cdot (Y_R - Y_H) + F_{ZL} \cdot (Y_L - Y_H) + F_{YR} \cdot (Z_R - Z_H) - F_{YL} \cdot (Z_L - Z_H) \quad (6D)$$

$$M_{YH} = (-F_{ZR}) \cdot (X_R - X_H) + (-F_{ZL}) \cdot (X_L - X_H) + (F_{XR}) \cdot (Z_R - Z_H) + (F_{XL}) \cdot (Z_L - Z_H) \quad (6E)$$

$$M_{ZH} = (-F_{XR}) \cdot (Y_R - Y_H) + (-F_{XL}) \cdot (Y_L - Y_H) + (F_{YR}) \cdot (X_R - X_H) + (F_{YL}) \cdot (X_L - X_H) \quad (6F)$$

In general, there would also be a moment at the contact points between the finger and the object. However the gripping surface has a moment isolator surface 88 composed of an elastomer on the gripping surfaces of fingers 10 and 11, so that only a force can be translated to the finger.

Eqs. (6A to 6F) can be written in the matrix form as

$$\begin{bmatrix} F_{XH} \\ F_{YH} \\ F_{ZH} \\ M_{XH} \\ M_{YH} \\ M_{ZH} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ \hline 0 & (z_R - z_H) & (y_R - y_H) & 0 & (z_L - z_H) & (y_L - y_H) \\ (z_L - z_H) & 0 & (x_R - x_H) & (z_R - z_H) & 0 & -(x_L - x_H) \\ -(y_R - y_H) & (x_R - x_H) & 0 & -(y_L - y_H) & (x_L - x_H) & 0 \end{bmatrix} \cdot \begin{bmatrix} F_{XR} \\ F_{YR} \\ F_{ZR} \\ F_{XL} \\ F_{YL} \\ F_{ZL} \end{bmatrix}$$

or

$$\bar{F}_H = \tilde{A} \cdot \bar{F}_{RL} \quad (7)$$

Eqs. (4) and (5) can be combined as

$$\begin{bmatrix} F_{XR} \\ F_{YR} \\ F_{ZR} \\ F_{XL} \\ F_{YL} \\ F_{ZL} \end{bmatrix} = \begin{bmatrix} -(y_R - y_A) & (x_R - x_A) & 0 \\ (z_R - z_B) & 0 & -(x_R - x_B) \\ (z_R - z_C) & 0 & -(x_R - x_C) \\ (z_L - z_D) & 0 & -(x_L - x_D) \\ 0 & -(y_L - y_E) & (x_L - x_E) \\ (x_L - x_G) & 0 & (x_L - x_G) \end{bmatrix} \cdot \begin{bmatrix} M_A \\ M_B \\ M_C \\ M_D \\ M_E \\ M_G \end{bmatrix}$$

or

$$\bar{F}_{RL} = \tilde{B} \cdot \bar{F}_m \quad (8)$$

combining eqs. (7) and (8), we obtain

$$\bar{F}_H = \tilde{A} \cdot \bar{F}_{RL} = \tilde{A} \cdot \tilde{B} \cdot \bar{F}_m = \tilde{H} \cdot \bar{F}_m \quad (9)$$

Eq. (9) provides the general relation between the measurement vector, \bar{F}_m , (output of the six sensors) and the force vector applied at the object being held at the finger, \bar{F}_H . If one has the measurement output from the six sensors, one can estimate the force vector applied to the fingers but one cannot directly estimate the general force vector applied at the object held by the fingers. This is because the sensor output is also a function of the following additional parameters:

- (1) weight of the object being held by the finger (1 unknown)
- (2) parts position and orientation of the object (6 unknowns)
- (3) length between contact points of an object held by the fingers (1 unknown)
- (4) contact force and moment between the finger and the object (6 unknowns).

In order to eliminate these additional unknowns a sequence of operations may be performed as follows:—

Item 1: Search for an Object with One Finger

Referring to Figure 6, the orientation of the centre line of a post in the form of a screw driver 28 must be known. For example in Figure 6, the centre line of the

screw driver 28 coincides with the Z axis. The chord length or diameter t_1 of the screw driver 28 is stored in the computer, the exact location of the screw driver is unknown. The flow chart for a computer program for automatically determining the location of the screw driver is shown in Figure 7.

5 Referring to Figures 6 and 7, the Y motor 51 moves until the finger 10 touches the screw driver 28. At the instant when finger 10 touches screw driver 28, the force sensor output ΔM_A exceeds a prescribed value E, and the Y arm segment position at that instant is registered by potentiometer 116. The relative position between the finger surface and Y arm segment is measured by the Y arm segment position sensing potentiometer 114 at point M in Fig. 6. The exact position of the screw driver can be computed by

$$Y_w = Y_M + Y_f - \frac{t_1}{2} \quad (10)$$

15 In a similar manner, the manipulator system can locate a washer 40 on washer post 41 as shown in Fig. 8. In this case, the prior information is the thickness of the washer, t_2 , and the direction of the center line of the washer post.

Item 2: Pick Up an Object with a Controlled Gripping Force

20 Referring to Fig. 6 once the approximate position of the object 28 (e.g. a screw driver) has been determined, the manipulator system can move to a position as shown in Fig. 9. By simultaneously operating the Y motor 51 and the finger motors as shown by the flow chart in Fig. 10, the finger 10 contacts the screw driver e.g. point Q in Fig. 9. The Y coordinate of the contact point Q is

$$Y_Q = Y_M + Y_{MQ} + d_Q \quad (11)$$

25 where Y_M and Y_{MQ} are the positions of Y arm segment 40 and the finger motor system respectively and they can be measured by potentiometer 116 and 78 respectively. Value d_Q is the deflection of the finger which will be described later. After the finger 10 contacts one side of the object 28 (screw driver), the motor 74 for the fingers 10 and 11 and the Y motor system are moved simultaneously (Fig. 10) until both the right and left fingers 10 and 11 contact the object 28 (e.g., screw driver) at points Q and H as shown in Fig. 9 with the position of left finger 11 shown in phantom. The Y coordinate of point H is

$$Y_H = Y_M - Y_{MH} - d_H \quad (12)$$

35 where Y_{MH} is the left finger motor position and d_H is the finger deflection at point H. If the geometry of the object is simple, e.g. a screw driver 28 as shown in Fig. 9, the X coordinates of the contact points Q and H must be the same, (i.e. $X_Q = X_H$). The gripping force between the object 28 and the fingers 10 and 11 can be related to the sensor output as

$$M_A = (-F_Q) \cdot (X_Q - X_A) \quad (13)$$

$$M_E = (F_H) \cdot (X_H - X_E) = (-F_Q) \cdot (X_H - X_E) = (-F_Q) \cdot (X_Q - X_E) \quad (14)$$

40 The coordinates X_A and X_E of the sensor elements A and E have been measured previously. Therefore, the gripping force and the contact position between the finger and the object being held by the finger can be determined from eqs. (13) and (14) from

$$(-F_Q) = \frac{M_E - M_A}{X_A - X_E} \quad (15)$$

$$45 \quad X_Q = X_A + \frac{(M_A)(X_A - X_E)}{(M_E - M_A)} \quad (16) \quad 45$$

From eqs. 15 and 16, a controlled gripping force can be applied to the manipulator system to pick up an object. The flow chart is shown in Fig. 10. If the gripping force and the contact position are known, the deformation of the finger can be

accurately determined from the structural beam equation and the screw driver diameter or chord length, t_s , can be accurately determined from eqs. 11 and 12. It should be noted that the sensor system consists of three orthogonal thin beams and the deformation of the fingers 10 and 11 can be accurately calculated.

5 Item 3: Weighing an Object 5

The force sensor system can be employed to measure the weight of an object. Referring to Fig. 5, at a specific position, where the Z coordinate coincides with the gravitation force, sensors B, C, D and G are all sensitive to the weight of the object being held by the fingers. Therefore, the weight of the object can be determined by

$$10 \quad W_H = \frac{M_C - M_B}{X_C - X_B} + \frac{M_G - M_D}{X_G - X_D} \quad (17) \quad 10$$

where M_C , M_B , M_G , and M_D are the sensor output of sensors C, B, G and D respectively.

15 Item 4: Locating the Center of Gravity of an Object at the Manipulator's Hand 15

Once the weight of the object has been obtained the location of the center gravity of the object can also be determined. Referring to Fig. 5, at the specific position where the Z axis coordinate coincides with the gravitational force, the weight vector W_H may be divided into two components, W_{HR} and W_{HL} . W_{HR} is the weight that will apply to the right finger 10 and W_{HL} is the weight that will apply to the left finger 11. From the sensor output from sensors B and C 14 and 16, one can determine the value of W_{HR} and the X coordinate of point H. From sensor outputs of sensors 17 and 19, D and G, one can compute the value of W_{HL} and the X coordinate of point H. In other words, the X coordinate of the center gravity (point H) can be either determined from right finger sensors or left finger sensors. This provides criteria which are useful when checking the accuracy of the sensor system. 25

In a similar manner, one can move the finger systems such that the Y or Z coordinate coincides with the gravitational force to determine the Y and Z coordinates of the center of gravity of the object (e.g. point H in Fig. 5).

30 Item 5: Sensor Output Due to the Weight of the Object at any Orientation 30

During the assembly process, the manipulator system can be rotated to any orientation. Therefore, the sensor outputs due to the weight of the object will vary at different orientations. Following the procedure presented in steps 3 and 4, one can determine the weight and the center of gravity of the object being held by the manipulator fingers. Referring to Fig. 1A, the absolute orientation of the finger system can be computed from the output voltage of the potentiometers at the pitch, yaw and roll motors and the vector, \bar{W}_H , due to the weight of the object can be obtained. The sensor output can be computed from eq. (18) 35

$$\bar{F}_M = [\hat{H}]^{-1} \bar{W}_H$$

where $[\hat{H}]$ is defined in eq. (9). \bar{F}_M is a vector consisting of six sensor outputs (also defined in eq. (9)). 40

45 Item 6: Selection of the Zero Reference Point for the Sensor Output and System Applications 45

A typical force sensor output is shown in Fig. 11 (solid line). If the temperature has been changed, then the zero reference point will be shifted from point O_1 to point O_2 . The zero reference point will also be shifted if the orientation of the finger system has been changed. Referring to Fig. 5, if the orientation of the finger system has been rotated, the force vector W_H due to the dead weight of the object being held by the finger will be shifted from the solid line W_H to a dotted line W_H in Fig. 5. The dead weight of the blocks between adjacent sensors, (e.g. block K between sensor A and B) will also change the absolute voltage output of the sensor system. Therefore, the sensor output must compensate for the weight effect presented in step 5. An alternate calibration technique which has been implemented in this manipulator system is based on the value of the slope as shown in Figure 6. Then e.g. (9) can be modified as 50

$$55 \quad (\Delta \bar{F}_M) = (\Delta Q) \cdot (\Delta \bar{F}_H) \quad (19) \quad 55$$

Where $(\Delta \bar{F}_H)$ is the incremental force vector applied at the object being held by the finger and $(\Delta \bar{F}_M)$ is the incremental sensor output vector.

Once the (ΔQ) matrix has been obtained, it can be stored in the computer system and will be used to determine the contact force between the object (e.g. a screw in Figure 5) and a work table. This technique is shown in Figure 13.

With reference to Figures 3, 4 and 5 it is assumed that only forces (e.g. F_{XR} , F_{YR} , F_{ZR} , F_{XL} , F_{YL} and F_{ZL}) will be applied to the finger. However, the same procedure will also be applied to the system where moments will also be applied to the finger. Additional equations must be set up to include the compliance of gripping surfaces.

It has been shown how to measure a large number of parameters including 1) gripping force, 2) a six-degree-of-freedom force vector applied at the object being held by the manipulator, 3) weight of the object, 4) centre of gravity of the object, 5) approximated location and orientation of an object on a work table. Using this system, one can perform a task such as a complex typewriter subassembly task.

This sensor system interfaces with the computer system in order to

- a. determine the weight of an object held by the finger,
- b. pick up an object with a controlled force,
- c. search for a post,
- d. locate an object with one finger, and
- e. locate an object with two fingers.

The system can give an analog signal to measure the X, Y and Z force applied at a wand system which is mounted at the finger not shown.

WHAT WE CLAIM IS:—

1. A manipulator having a pair of gripper fingers, a drive mechanism to drive the gripper fingers, a pair of sensor assemblies, each gripper finger being coupled to the drive mechanism through a respective one of the sensor assemblies, there being in each sensor assembly a plurality of force sensors disposed in series between the drive mechanism and the respective finger and adapted to sense moments about a plurality of orthogonal axes resulting from forces applied to the respective finger, there being for each force sensor in one of the sensor assemblies a corresponding force sensor in the other of the sensor assemblies to sense a moment about a parallel orthogonal axis, the disposition of the force sensors of the one sensor assembly relative to their respective finger being different from the disposition of the corresponding force sensors of the other sensor assembly relative to their respective finger, whereby like forces applied to both fingers result in different moments being applied to corresponding force sensors in the pair of sensor assemblies.

2. A manipulator according to Claim 1 wherein the order in which the force sensors are disposed in the one sensor assembly is different from the order in which the corresponding force sensors in the other sensor assembly are disposed.

3. A manipulator according to Claim 1 or 2 wherein each sensor assembly includes an elbow block rigidly interconnecting a first of the force sensors in the series thereof to the remaining force sensors in the series, the elbow block of the one sensor assembly being of different length from the elbow block of the other sensor assembly.

4. A manipulator according to Claim 1, 2 or 3 wherein each force sensor comprises a generally I-shaped beam having strain gauges mounted on the web thereof and the beam has end portions to adapt each force sensor at an angle of 90° to the next in the series.

5. A manipulator according to any one of the preceding claims wherein there are three force sensors in each sensor assembly.

6. A manipulator substantially as hereinbefore described with reference to and as shown in Figures 1A, 1B and 2 of the accompanying drawings.

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FIG. 2

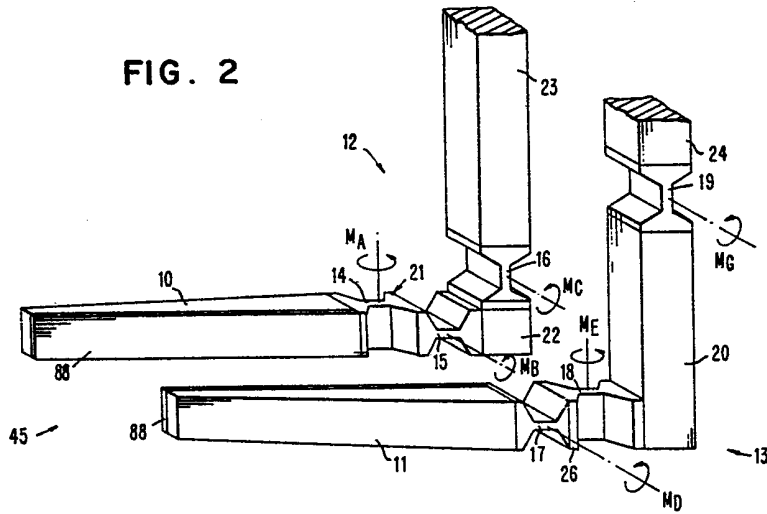
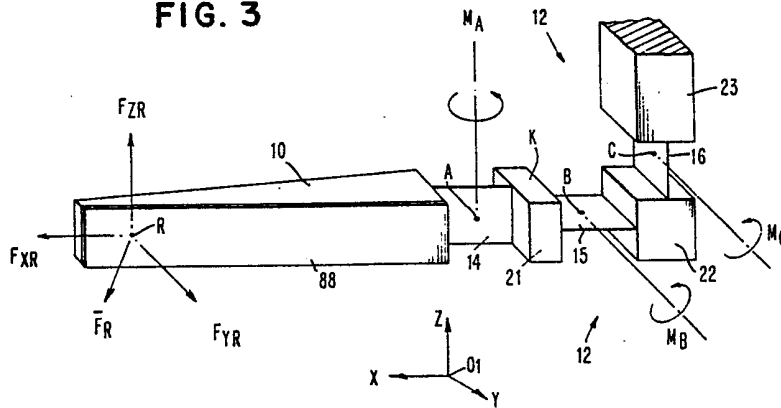


FIG. 3



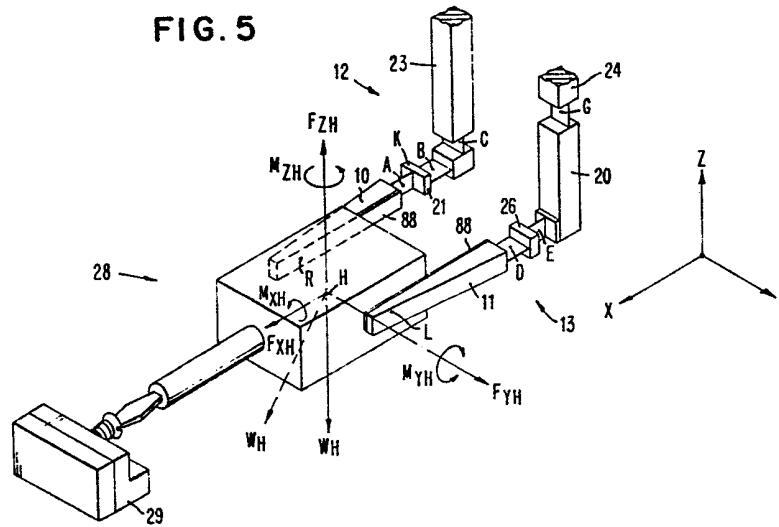
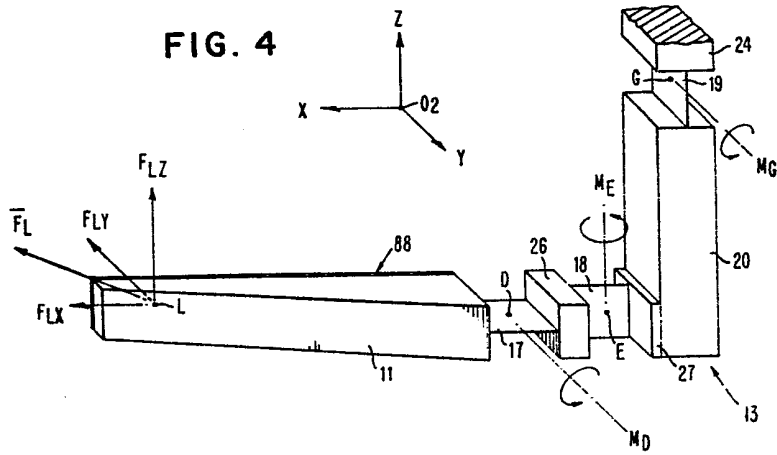


FIG. 6

