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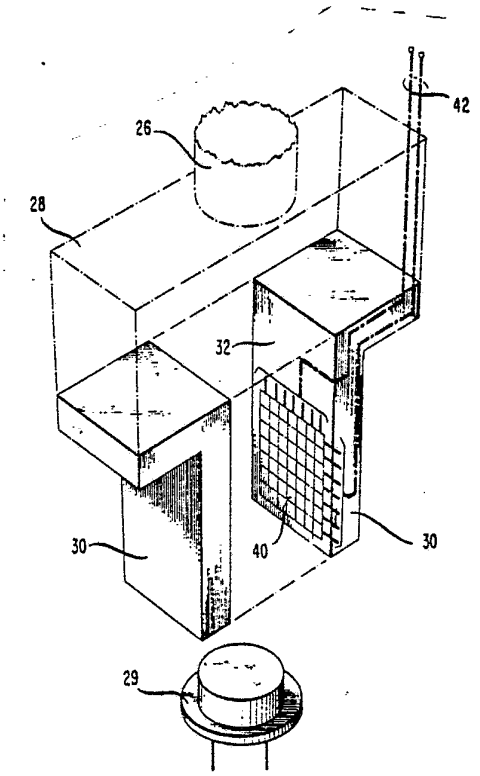
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(54) Title: TACTILE SENSOR ARRAY

(57) Abstract

A movable part of a robot, such as the fingers of the robot hand, are provided with an array (40) of tactile elements mounted on a substrate (48). Each element includes a magnetic dipole (44) embedded in a compliant medium (46) on one side of the substrate and a magnetic sensor (49) on the other side of the substrate. The dipole and sensor are in parallel planes. A force or torque deforms the compliant medium and displaces the magnetic dipoles with respect to the sensor. The sensor detects the change in magnetic field and produces an electrical signal which is used to control the robot. Magnetoresistive sensors are preferred. The disclosed sensors are capable of sensing both torque and tangential forces.



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TACTILE SENSOR ARRAY

Background of the Invention

This invention relates to tactile sensor arrays particularly useful in robotic systems.

By tactile sensing is meant sensing patterns of touching; i.e., sensing of forces over an area of contact.

Many types of tactile sensors array have been proposed. See, for example, an article by D. Hillis, International Journal of Robotics, Vol. 1, p. 33 (1982). A common limitation of all these devices is the lack of torque sensing and, in most cases, also tangential force sensing. Such sensing is provided in certain ones of arrays according to this invention. Another limitation of known sensors is their fragility and susceptibility to damage. More rugged sensors are provided by the invention.

Summary of the Invention

A tactile sensor includes an array of tactile elements each of which includes a magnetic dipole embedded in a compliant medium disposed adjacent to a magnetic sensor. Forces applied against the compliant medium deform it and displace the magnetic dipole therein with respect to the sensor. The sensor detects the change in magnetic field caused by the relative movement and produces an electrical signal.

Brief Description of the Drawing

FIG. 1 is an enlarged isometric view of a robot gripper including a tactile sensor array;

FIG. 2 is a top view of a tactile sensor array;

FIG. 3 is a side view of an array showing typical system interconnections between the sensors thereof, a signal processor, a servo circuit, and the robot;

FIG. 4 is an enlarged view of two tactile elements of the array of FIG. 3 showing one element compressed by a normal force F;

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FIG. 5 is a top view of a tactile element containing four magnetoresistive sensors for sensing torque or tangential forces;

FIG. 6 shows how the element of FIG. 5 is provided with a randomizing magnetic field to reduce hysteresis effects; and

FIGS. 7 and 8 are schematics showing alternative embodiments of the compliant medium/dipole arrangement in accordance with our invention.

Detailed Description

With reference now to FIG. 1, there is shown a known type pneumatic or servo-driven robot hand commonly termed a gripper including a palm member 28 which rotates about the axis of a mounting post 26. A pair of fingers 30 are slidably mounted on the palm member 28.

In accordance with one embodiment of this invention, at least one, and preferably both, of the facing surfaces 32 of the fingers 30 is provided with a tactile array 40 of sensors which are described in more detail in conjunction with FIGS. 2-6. The signals generated by array 40 in response to forces applied thereto in handling object 29 are coupled via cables 42 to a suitable processor (e.g., processor 50 of FIG. 3).

In a manufacturing process, object 29 might be, for example, a package or header for a semiconductor component. Since the object may be delicate, the gripper should be able to pick it up without crushing it (hence normal force should be sensed), without dropping it or allowing it to slip (hence tangential force should be sensed), and without allowing it to rotate (hence torque should be sensed). To achieve these ends, the tactile array is designed as follows.

The array 40 shown in FIG. 2 is typically a matrix arrangement of tactile elements 42. For purposes of illustration, a square array having seven elements on a side is depicted. Each element includes a magnetic dipole 44, and all the dipoles are oriented essentially

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parallel to and coplanar with one another. As can be seen in FIG. 3, each dipole 44 is embedded in a body 46 (e.g., a cube) of a compliant medium. The bodies 46 are arranged adjacent to one another on one side of an electrically insulative substrate 48 to form the array. In addition, each element includes a magnetic sensor 49 on the other side of the substrate. Alternatively, the sensors 49 may be embedded in substrate 48 or may be formed on top of it, provided that electrical contact to them can still be made. The dipoles 44 in the compliant medium and the elongated dimension of the sensors 49 are aligned with one another and are oriented in parallel planes. Each sensor 49 is connected to a signal processor which, in turn, supplies an output, indicative of a force applied to the array, to a servo circuit 52. The latter controls, in known fashion, various movements of the robot of which the gripper is a part.

Illustratively, each element of the 7x7 array shown in FIG. 2 measures 2x2 mm. The combination of this level of resolution and number of elements is adequate for general robotic applications. Also, the array is quite rugged and not easily damaged in such applications.

The mechanism of operation is illustrated in FIG. 4 which shows two adjacent tactile elements 42a and 42b. Element 42b, on the right, is subject to a normal force F. This force deforms the compliant medium 46b (shown here schematically) and displaces the magnetic dipole 44b toward the sensor 49b. The sensor 49b detects the change in magnetic field and produces an electrical signal, which is fed to signal processor 50 external to the array.

The tactile array need not be mounted on a robot; it could be mounted, for example, on a table top and the object could be carried by a robot to the array. In this way, signal processor 50 can be used to quantify the force applied by the object or to identify the shape of the object.

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The available semiconductor magnetic sensors which are easily fabricated in arrays are based either on the magnetoresistive or on the Hall effect. Simple Hall effect sensors can detect a dipole translation (as shown in FIG. 4) but not a dipole rotation in the plane parallel to the substrate 48. Thus, Hall sensors cannot be easily arranged to detect a torque applied in this plane. Magnetoresistive elements, on the other hand, can be easily arranged on the substrate to detect both translation and rotation, and hence are preferred.

FIGS. 5 and 6 show one embodiment of a tactile element 42 in which four magnetoresistive sensors 49a-d are arranged on the substrate so as to detect translation (normal forces), and rotation (torque), as well as tangential forces. The arrow 44 represents the dipole which is embedded in the medium above the substrate. The size of each sensor (exaggerated in the figures) is about 100 μm long by 2 μm wide by 0.05 μm thick. The angle between each adjacent sensor is 90^{o}; i.e., the sensors lie along adjacent edges of a square and the dipole 44 lies along a diagonal of the square. The sensors are made, for example, of permalloy which is a ferromagnetic alloy comprising 19% Fe and 81% Ni. The resistivity of permalloy is 17 μ ohm/cm. However, because the material is magneto-resistive, the resistance along the major axis of the sensor is a function of the magnetic field parallel to it. Relative changes up to 3.5% are possible, depending on the intensity of the field. Differences between the detected resistances of the four sensors allow reconstruction of the degree of translation and rotation of the dipole.

For example, a clockwise torque about the z-axis causes the head and tail of dipole 44 to rotate toward sensor 49a and sensor 49c, respectively. The dipole rotation generates in opposite sensors 49a and 49c equal signals which, however, are greater than the signals from opposite sensors 49b and 49d. The size of the signals is related to the magnitude of the torque whereas the pair of

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sensors having the larger signals identifies the direction of the torque. On the other hand, a tangential force in the y-direction displaces dipole 44 toward sensors 49a and 49b and away from sensors 49c and 49b. Again, the size of the signals is related to the magnitude of the force whereas the pair of sensors having larger signals identifies the direction of the force. Similarly, tangential forces in the x-direction are detected. Finally, normal forces (translation in the z-direction) are detected as previously described with reference to FIG. 5.

Of course, a force in an arbitrary direction may include torque components as well as vector components in one or more of the x, y, z directions. These components may be simultaneously monitored and/or measured and, for example, compared using a suitable computer system to reference values in order to perform desired robotic functions.

If magnetic hysteresis due to the domain structure of the permalloy material is a concern, it can be reduced by a randomizing magnetic field built into the substrate 48 as shown in FIG. 6. Existing magnetic bubble memory technology, as described by A. H. Eschenfelder, Magnetic Bubble Technology, Springer-Verlag (1980), provides all the features of the magnetic sensing part of the tactile elements. Permalloy magnetoresistors of the size indicated above, deposited on an iron garnet substrate which randomizes the domains, can be used for this purpose. Alternatively, a reset magnet located beneath the substrate can be used to reset to zero or a fixed value the magnetic field after each tactile event. However, if the hysteresis effect can be quantified, it can also be compensated for in the software used in a computer or processor which performs the force calculations and controls the robot.

A major advantage of this sensing technique is the small size of the magnetoresistors. On a 2x2 mm square it is easy to accommodate many sensors. For illustrative purposes, we have described the use of four sensors which

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makes it possible to detect four degrees of freedom of dipole motion; i.e., displacement in the x, y, and z directions and torque about the z-axis. The maximum number of degrees of freedom for the dipole is five. In our configuration we do not sense the pitch about the perpendicular. Because of the smallness of the sensors, it is possible to make electrical connections to each element via contact pads (not shown) around the perimeter of the chip. Using a standard form of matrix addressing, each element is accessed by 4 columns and 4 rows of parallel wires, which can be distributed as 14 leads per side of the tactile array (one per mm).

Illustratively, the magnetic dipoles 44 are fabricated of vicalloy (a Co, V, Fe alloy) or chromindur (a Cr, Fe, Co alloy) which have high field intensities (H_c = 214 and 380 Oe, respectively) and are available in thin sheet form (about 25 Mm thick). As is well known in the magnetic bubble art, they can also be patterned and spray-etched in an acid solution. In fact, magnetic cards with arrays of vicalloy dipoles, 1x1 mm, separated by 1-2 mm are commercially available. On this scale of separation the magnetic fields of the dipoles do not interfere.

Finally, the compliant medium 46 can be tailored to the particular force sensitivity required, typically 1-100 g/mm^2 for robotic applications. In this work we have used Sylgard™ (a trademark of Dow Corning Corporation of Midland, Michigan) which is a solventless silicon resin polymer. Sylgard flows easily before curing and bonds to the substrate well. After curing, the polymer has good elastic and thermal properties. As with the other components of our tactile array, the design is not material specific and can therefore be optimized for the desired characteristics.

In another embodiment of the invention, the compliant layer is formed as a composite (FIG. 7) where each dipole 44 is embedded in a small block 45 of one type

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of material, and the array of blocks is embedded in another material 46. In addition, as shown in FIG. 8, the compliant material can be formed as two layers 46 and 47 so that, as the surface layer 47 becomes worn during operation, it can be replaced easily without disturbing the dipoles in underlying layer 46. Other arrangements are possible.

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Claims

1. A tactile sensor characterized as comprising, an array of tactile elements each of which compries a compliant medium (46), means forming a magnetic dipole (44) in said medium, and a magnetic sensor (49) adjacent said dipole, whereby a force applied against said compliant medium causes displacent of the dipole therein relative to said magnetic sensor.

2. The tactile sensor of claim 1 wherein said magnetic sensors comprise magnetoresistive sensors.

3. The tactile sensor of claim 2 wherein in each of said elements said magnetoresistive sensor and said magnetic dipole are aligned with one another and lie in planes parallel to one another.

4. The tactile sensor of claims 1, 2 or 3 wherein said compliant medium is formed on one surface of a substrate (48) and said magnetic sensors are formed on the opposite surface of said substrate.

5. The tactile sensor of claims 1, 2 or 3 wherein said compliant medium comprises a first layer (46) adjacent said substrate and in which said dipoles are located and a second replaceable layer (47), which is contacted by said object.

6. The tactile sensor of claims 1, 2 or 3 wherein said compliant medium includes embedded therein a plurality of bodies each of which includes a dipole.

7. The tactile sensor of claim 2 wherein each of said elements includes a plurality of said magnetoresistive sensors oriented at essentially 90° to one another and at essentially 45° to said dipole.

8. The tactile sensor of claim 7 including at least four magnetoresistive sensors oriented along the edges of a square, said dipole being oriented along a diagonal of said square.

9. The tactile sensor of claim 8 including means forming a randomizing magnetic field adjacent said medium.

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FIG.1

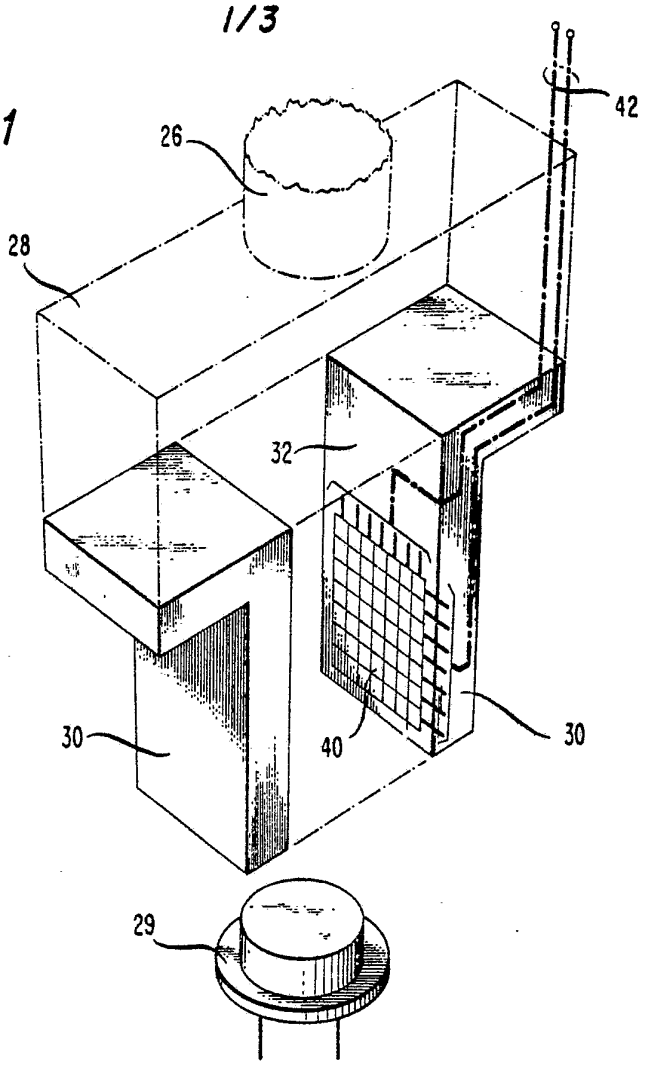
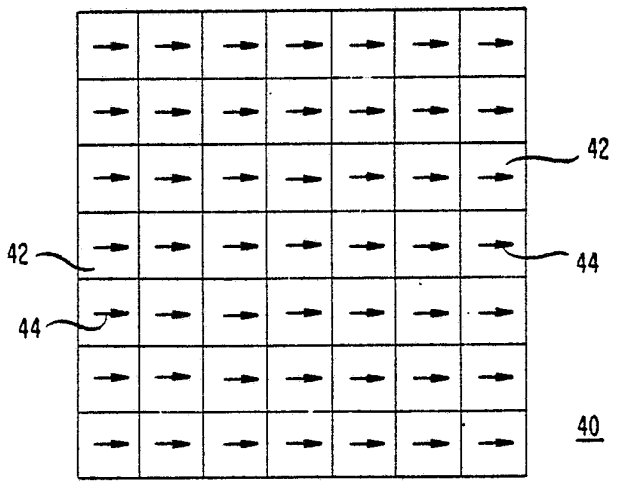


FIG.2



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FIG.3

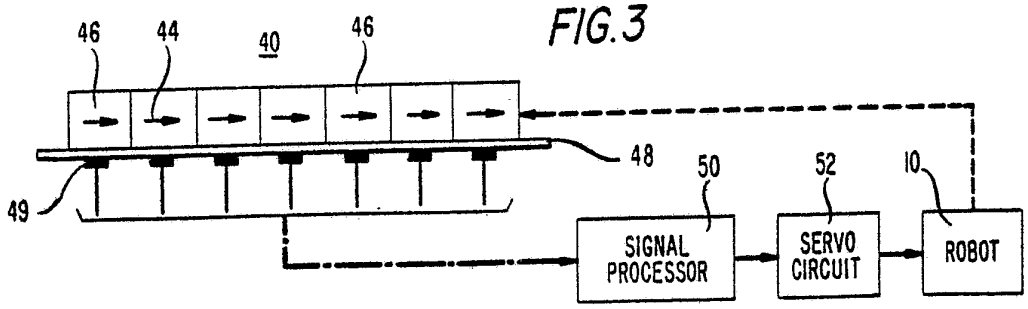


FIG.4

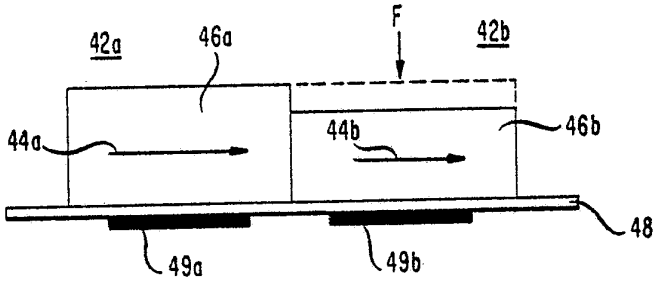


FIG.5

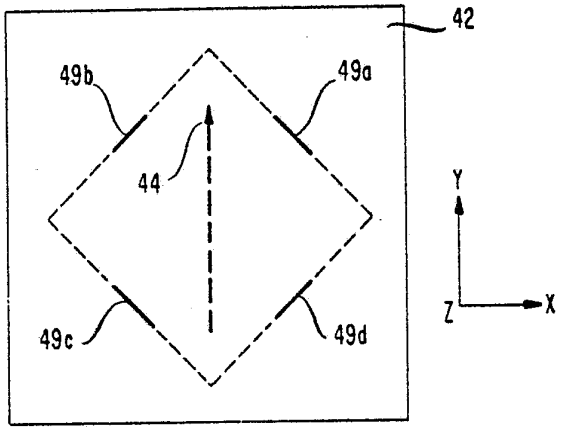
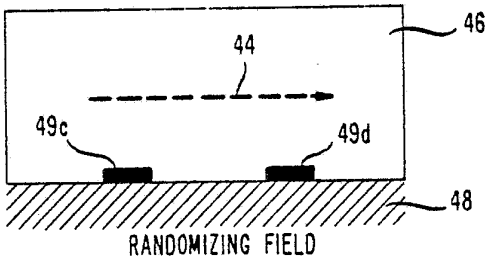


FIG.6



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FIG. 7

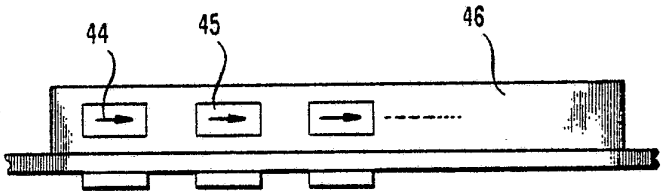
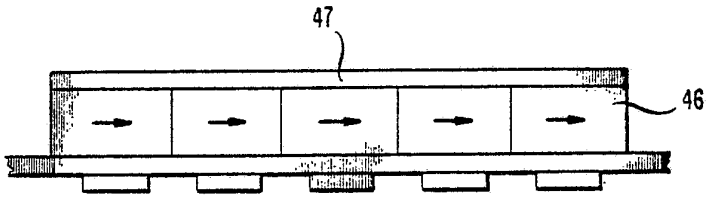


FIG. 8



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INTERNATIONAL SEARCH REPORT

International Application No PCT/US84/00680

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int Cl[3] G01R 33/02; B25J 15/02.
US. Cl 324/252; 340/825.79; 414/735; 901/33.

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
US	294/Dig2; 324/207,235,249,252; 338/32R,H,69,99,114; 340/365L, 825.79; 414/729,730,735; 901/15,33,34,35.

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
X	US,A, 4,385,273, (LIENHARD ET AL) 24 May 1983	1-4, 6-9
X	US,A, 3,553,498, (YAMADA) 05 January 1971	1-4
Y,P	US,A, 4,426,884, (POLCHANINOFF) 24 January 1984	5
Y	SU,A, 844,267, (GIPROUGLEARTOMA) 22 July 1981	6

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IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
29 June 1984	16 JUL 1984
International Searching Authority [1]	**Signature of Authorized Officer [20]**
ISA/US	Donald W. Underwood

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