Exhibit 6

US005495077A

United States Patent [19]

Miller et al.

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[45] **Date of Patent: * Feb. 27, 1996**

[54] **OBJECT POSITION AND PROXIMITY DETECTOR**

[75] Inventors: **Robert J. Miller**, Fremont; **Stephen Bisset**, Palo Alto; **Timothy P. Allen**, Los Gatos; **Günter Steinbach**, Palo Alto, all of Calif.

[73] Assignee: **Synaptics, Inc.**, San Jose, Calif.

[*] Notice: The portion of the term of this patent subsequent to Dec. 20, 2011, has been disclaimed.

[21] Appl. No.: **252,969**

[22] Filed: **Jun. 2, 1994**

Related U.S. Application Data

[63] Continuation of Ser. No. 115,743, Aug. 31, 1993, Pat. No. 5,374,787, which is a continuation-in-part of Ser. No. 895,934, Jun. 8, 1992.

[51] **Int. Cl.**[6] **G08C 21/00**; H03M 11/00

[52] **U.S. Cl.** **178/18**; 345/173; 341/33

[58] **Field of Search** 178/18; 345/173–178; 341/33, 34

[56] **References Cited**

U.S. PATENT DOCUMENTS

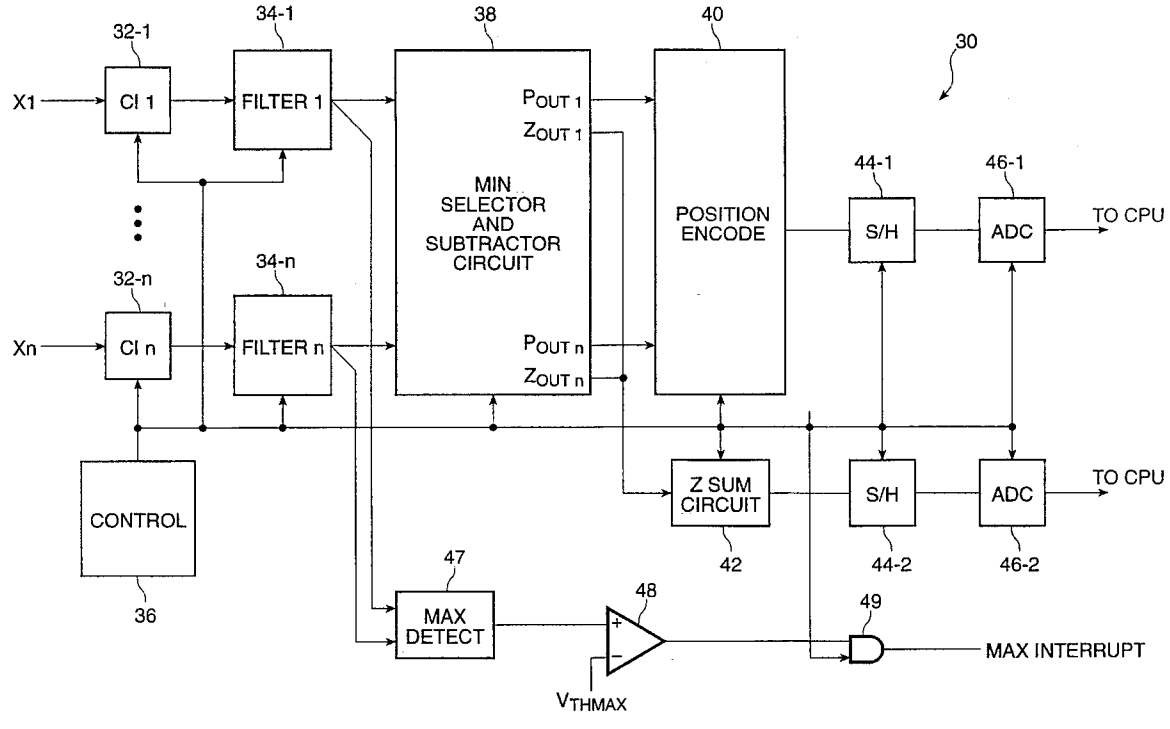
5,374,787 12/1994 Miller et al. 178/18

Primary Examiner—Stephen Chin
Assistant Examiner—Kevin Kim
Attorney, Agent, or Firm—D'Alessandro & Ritchie

[57] **ABSTRACT**

A proximity sensor system includes a sensor matrix array having a characteristic capacitance on horizontal and vertical conductors connected to sensor pads. The capacitance changes as a function of the proximity of an object or objects to the sensor matrix. The change in capacitance of each node in both the X and Y directions of the matrix due to the approach of an object is converted to a set of voltages in the X and Y directions. These voltages are processed by analog circuitry to develop electrical signals representative of the centroid of the profile of the object, i.e, its position in the X and Y dimensions. The profile of position may also be integrated to provide Z-axis (pressure) information.

11 Claims, 12 Drawing Sheets



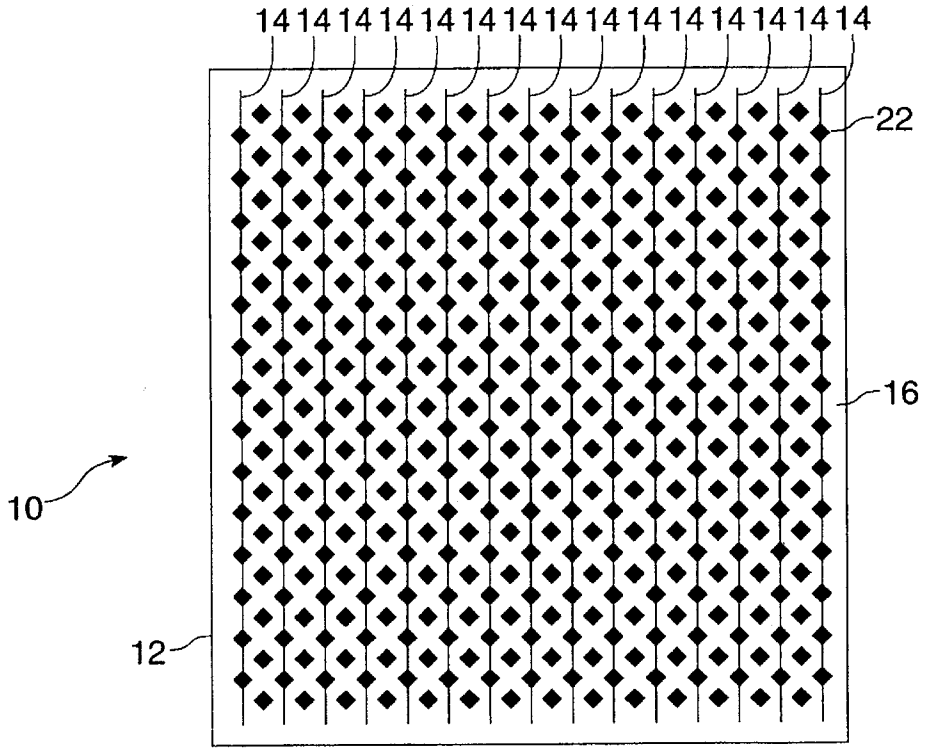

14 14 14 14 14 14 14 14 14 14 14 14 14 14 14
22
16
10
12

FIG. 1A

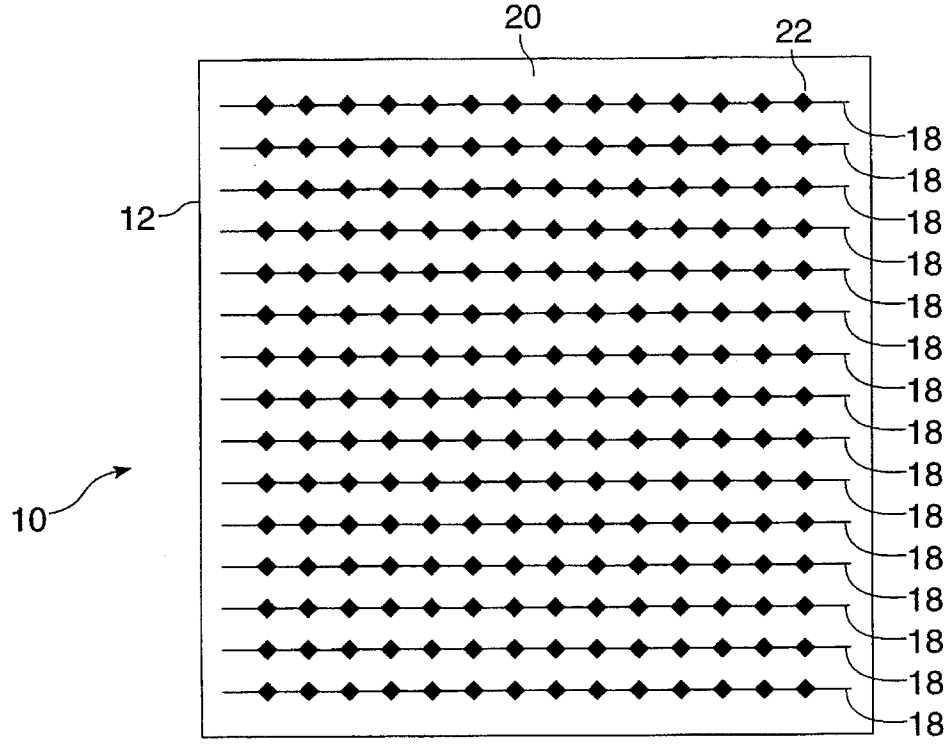

20
22
18
18
18
18
18
18
18
18
18
18
18
18
18
18
18
12
10

FIG. 1B

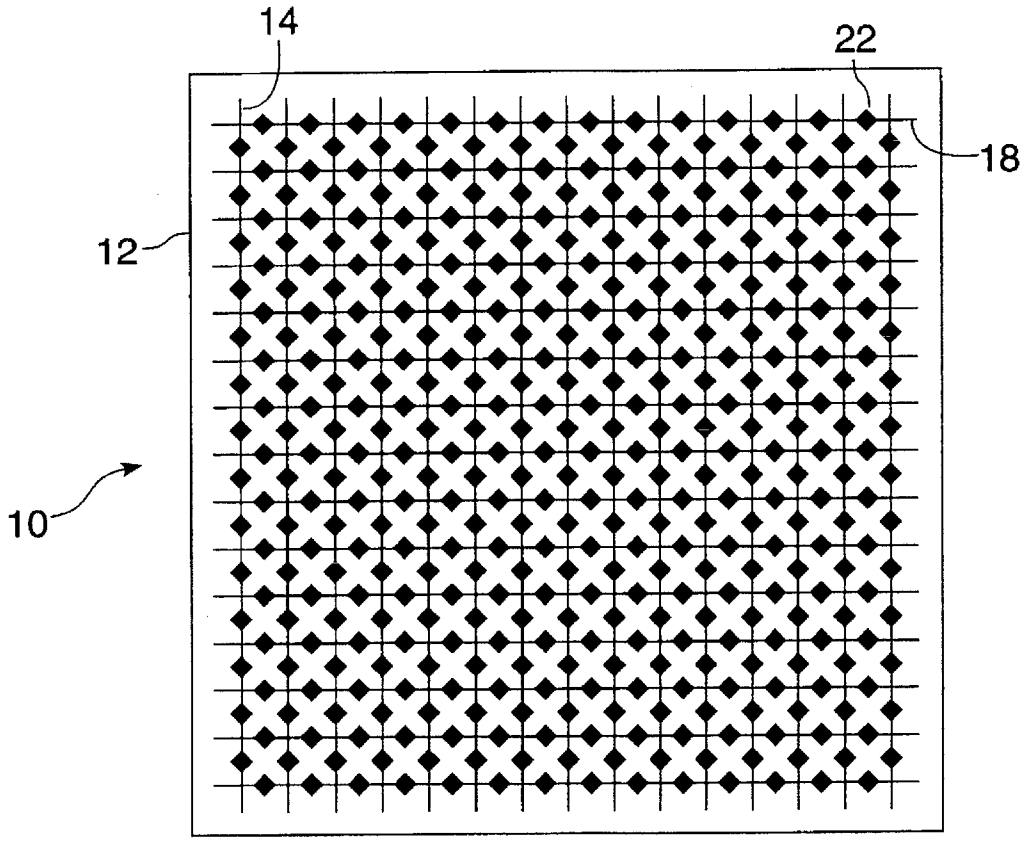


FIG. 1C

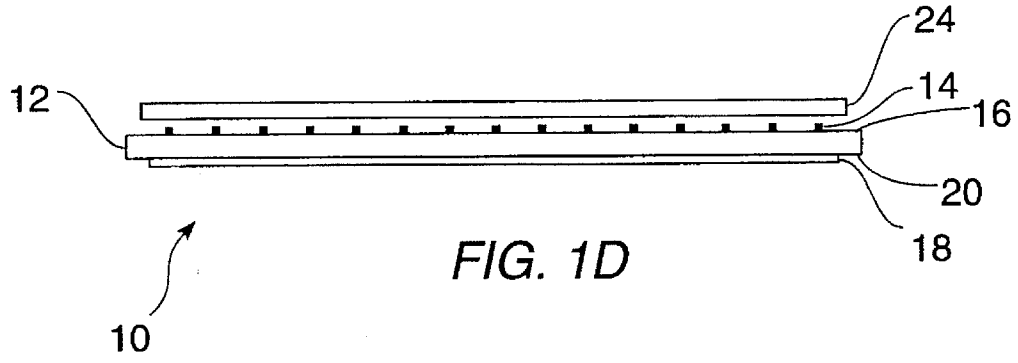


FIG. 1D

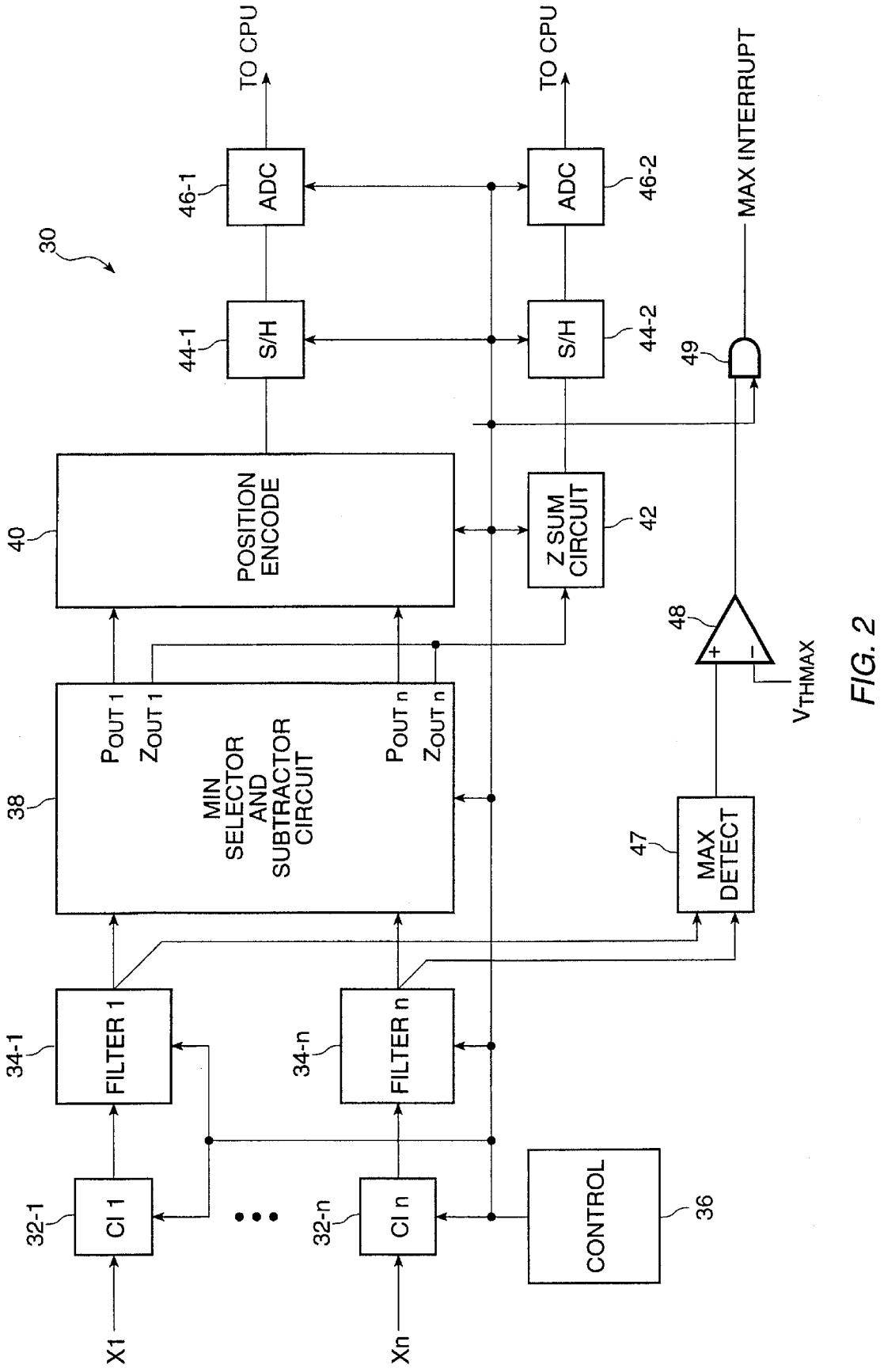

30
TO CPU
TO CPU
MAX INTERRUPT
46-1
ADC
46-2
ADC
44-1
S/H
44-2
S/H
49
40
POSITION ENCODE
Z SUM CIRCUIT
42
48
+
-
V_{THMAX}
38
$P_{OUT\ 1}$
$Z_{OUT\ 1}$
MIN SELECTOR AND SUBTRACTOR CIRCUIT
$P_{OUT\ n}$
$Z_{OUT\ n}$
47
MAX DETECT
34-1
FILTER 1
34-n
FILTER n
32-1
CI 1
32-n
CI n
CONTROL
36
X1
Xn

FIG. 2

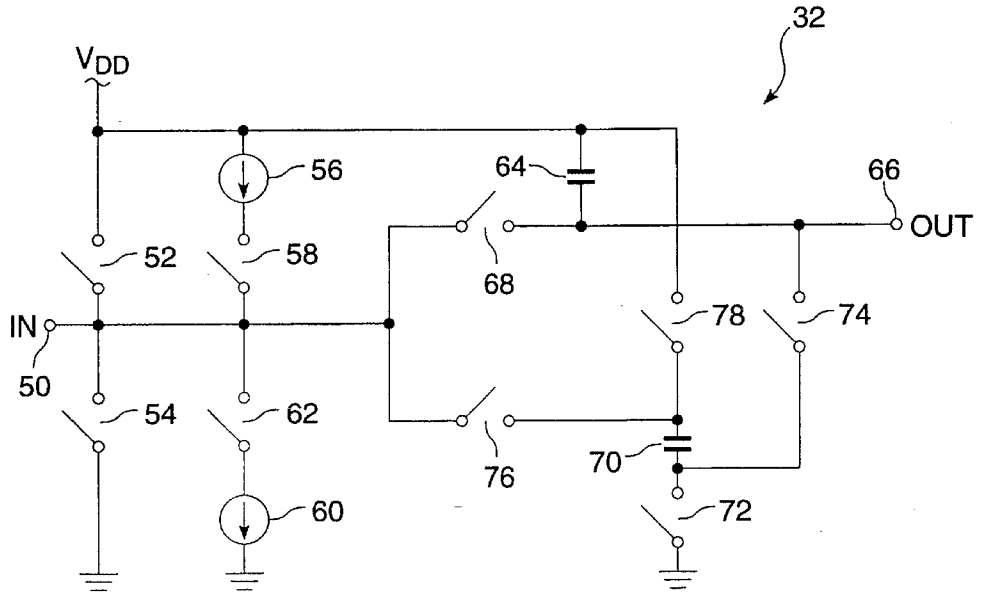

32
V_{DD}
56
64
66
OUT
52
58
68
IN
50
78
74
54
62
76
70
60
72

FIG. 3A

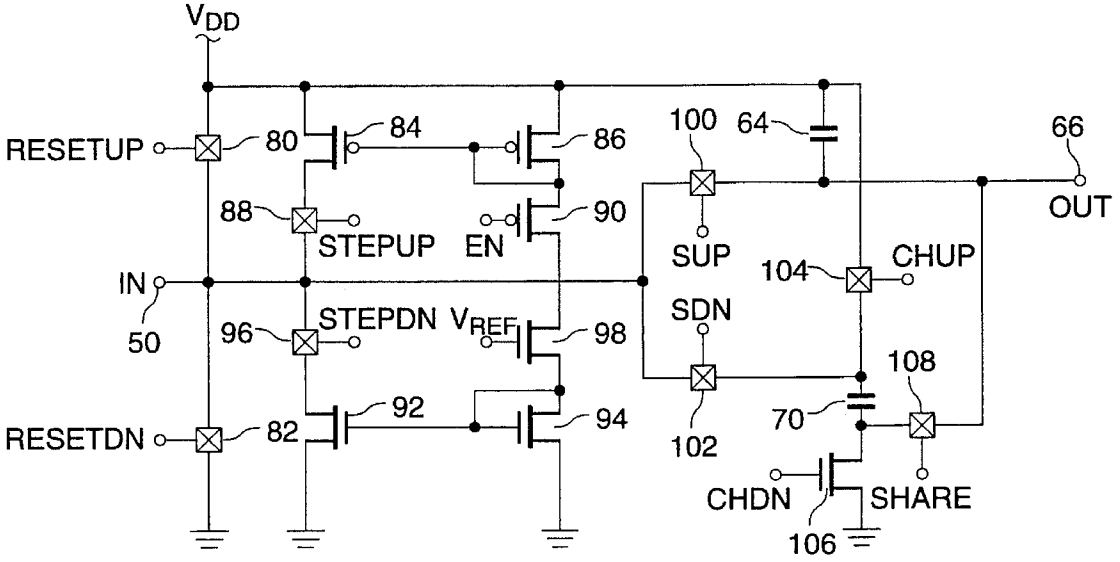

V_{DD}
RESETUP
80
84
86
100
64
66
OUT
88
STEPUP
EN
90
SUP
104
CHUP
IN
50
STEPDN
V_{REF}
96
98
SDN
108
92
70
RESETDN
82
94
102
CHDN
SHARE
106

FIG. 3B

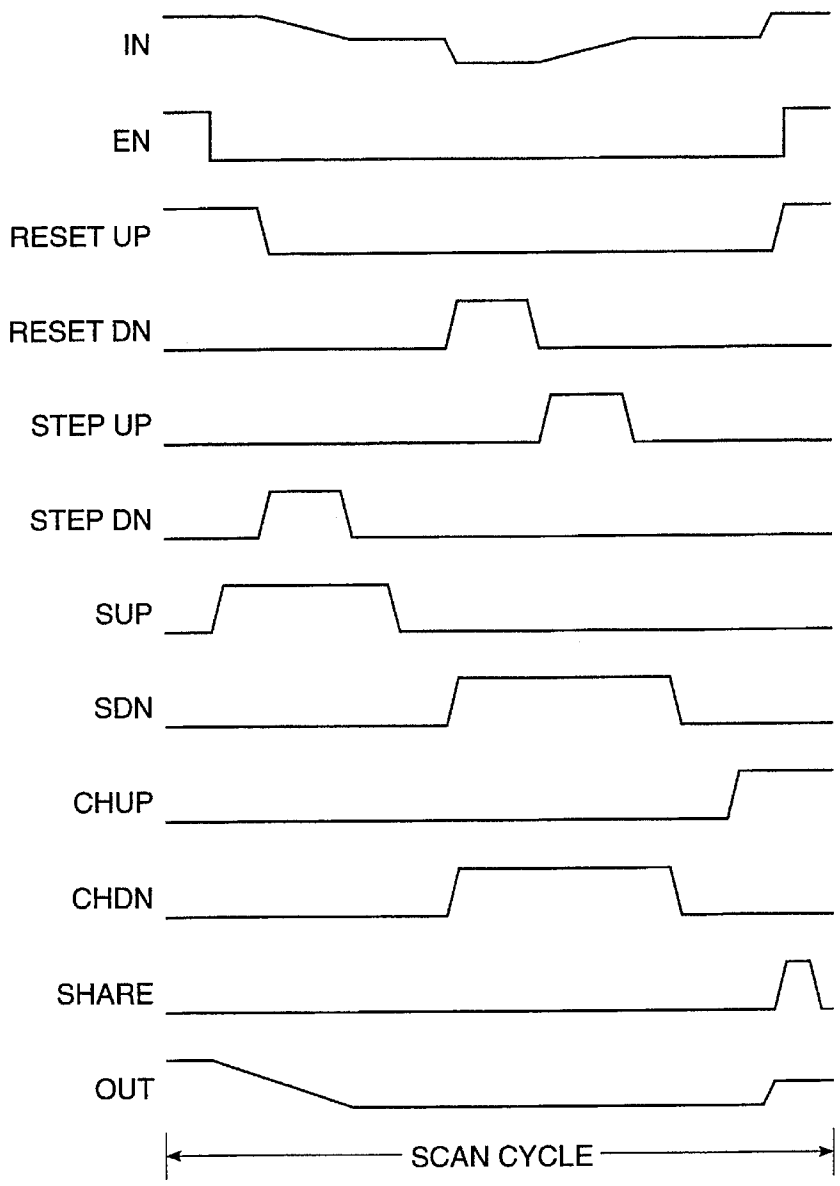

IN
EN
RESET UP
RESET DN
STEP UP
STEP DN
SUP
SDN
CHUP
CHDN
SHARE
OUT
SCAN CYCLE

FIG. 4

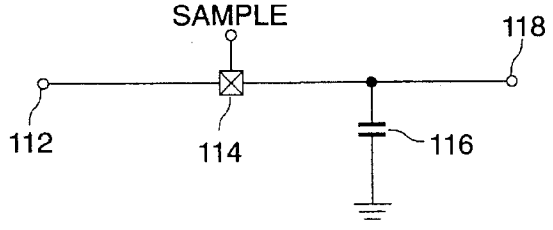

SAMPLE
118
112
114
116

FIG. 5

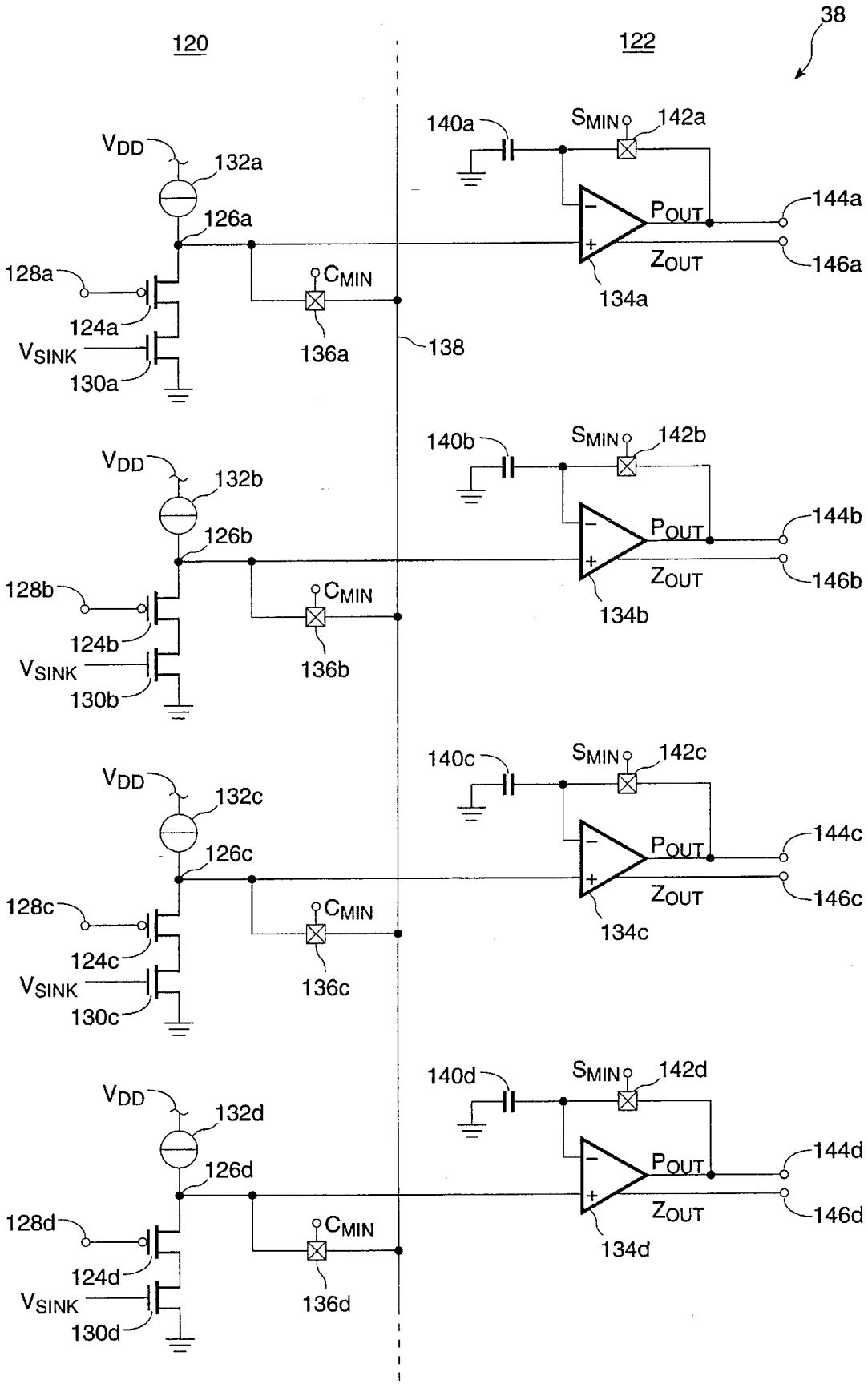

38
120
122
VDD
132a
126a
128a
124a
VSINK
130a
CMIN
136a
138
140a
SMIN
142a
144a
POUT
ZOUT
146a
134a
132b
126b
128b
124b
130b
136b
140b
142b
144b
146b
134b
132c
126c
128c
124c
130c
136c
140c
142c
144c
146c
134c
132d
126d
128d
124d
130d
136d
140d
142d
144d
146d
134d

FIG. 6A

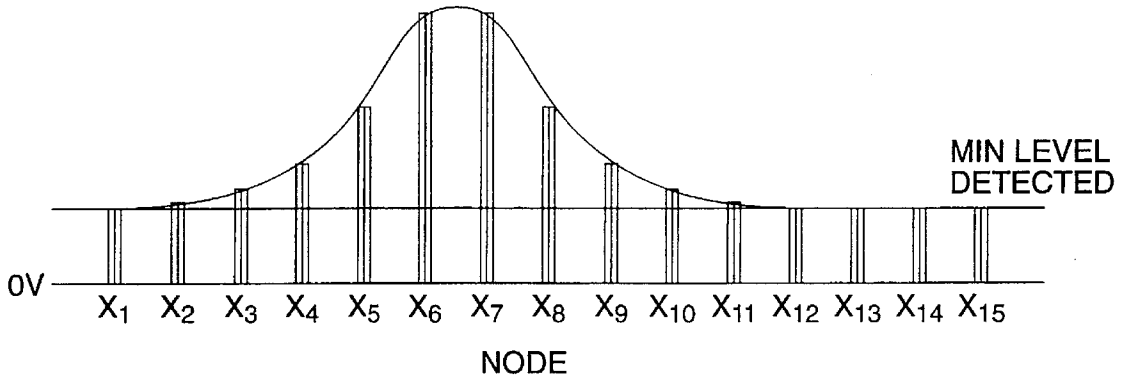

MIN LEVEL
DETECTED
0V
X1 X2 X3 X4 X5 X6 X7 X8 X9 X10 X11 X12 X13 X14 X15
NODE

FIG. 6B

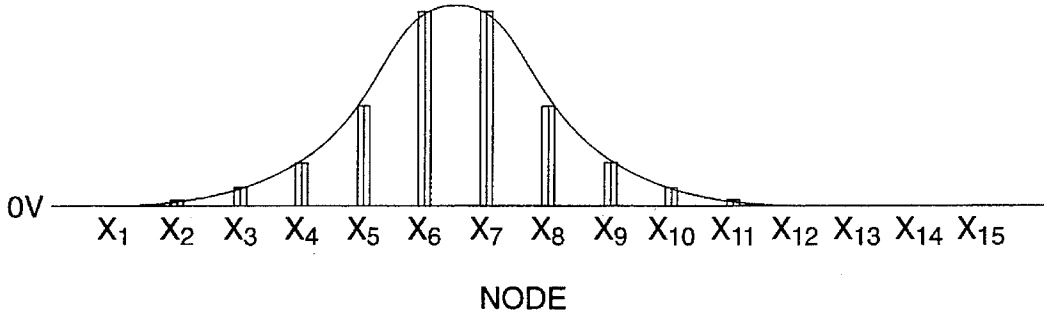

0V
X1 X2 X3 X4 X5 X6 X7 X8 X9 X10 X11 X12 X13 X14 X15
NODE

FIG. 6C

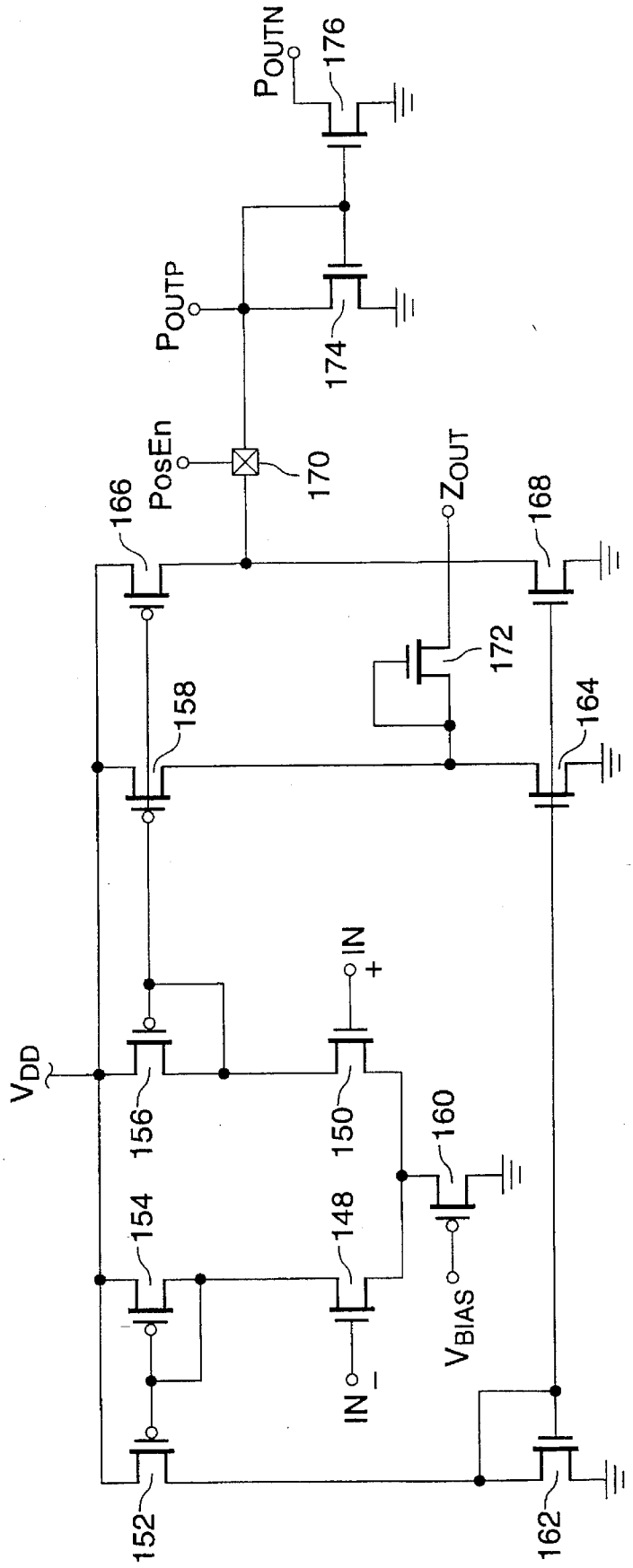

POUTN
176
POUTP
174
PosEn
170
166
ZOUT
168
172
158
164
VDD
156
IN+
150
160
154
148
VBIAS
IN−
152
162

FIG. 7

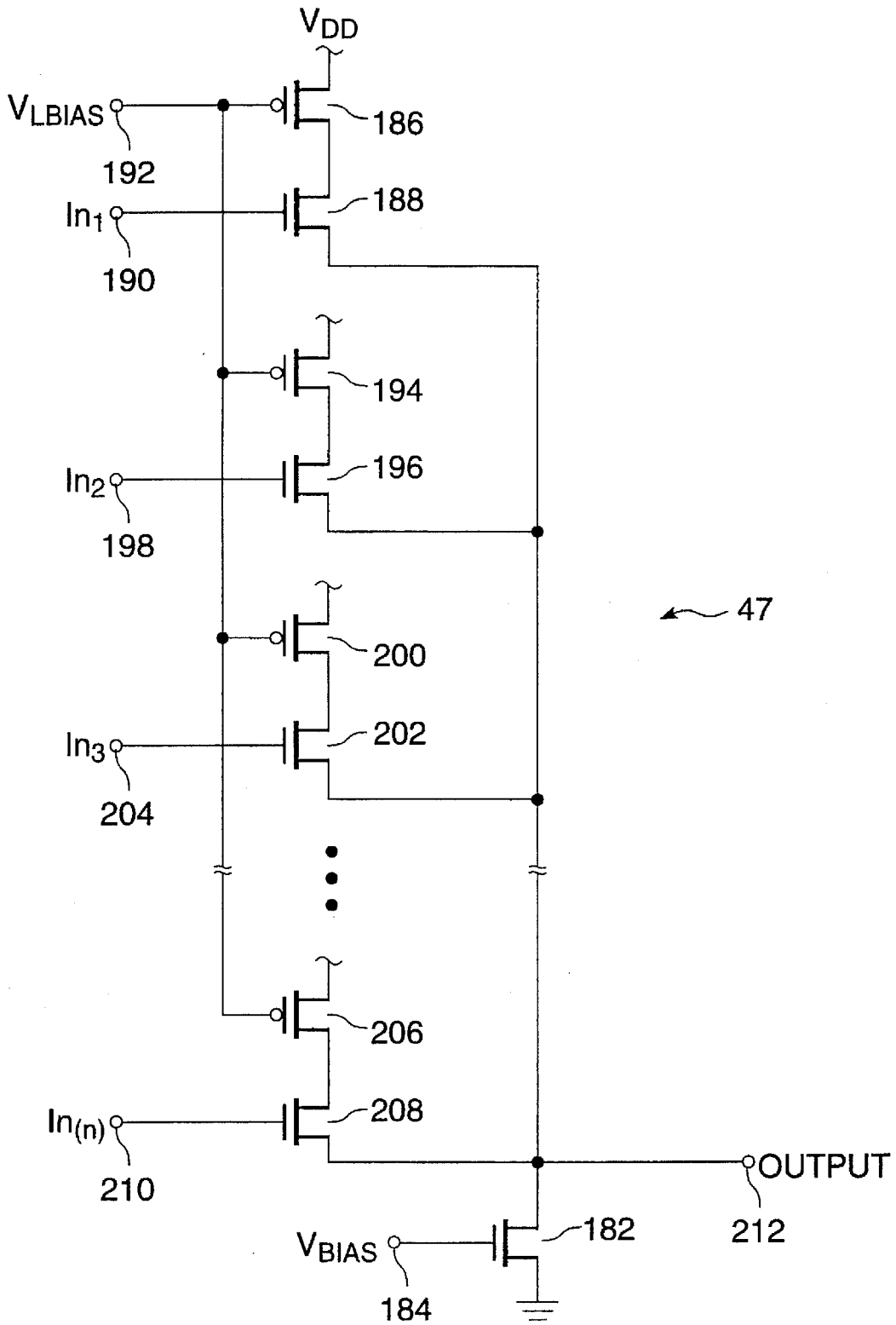

V_{DD}
V_{LBIAS}
192
186
188
In_1
190
194
196
In_2
198
47
200
202
In_3
204
206
208
$In_{(n)}$
210
OUTPUT
212
182
V_{BIAS}
184

FIG. 8

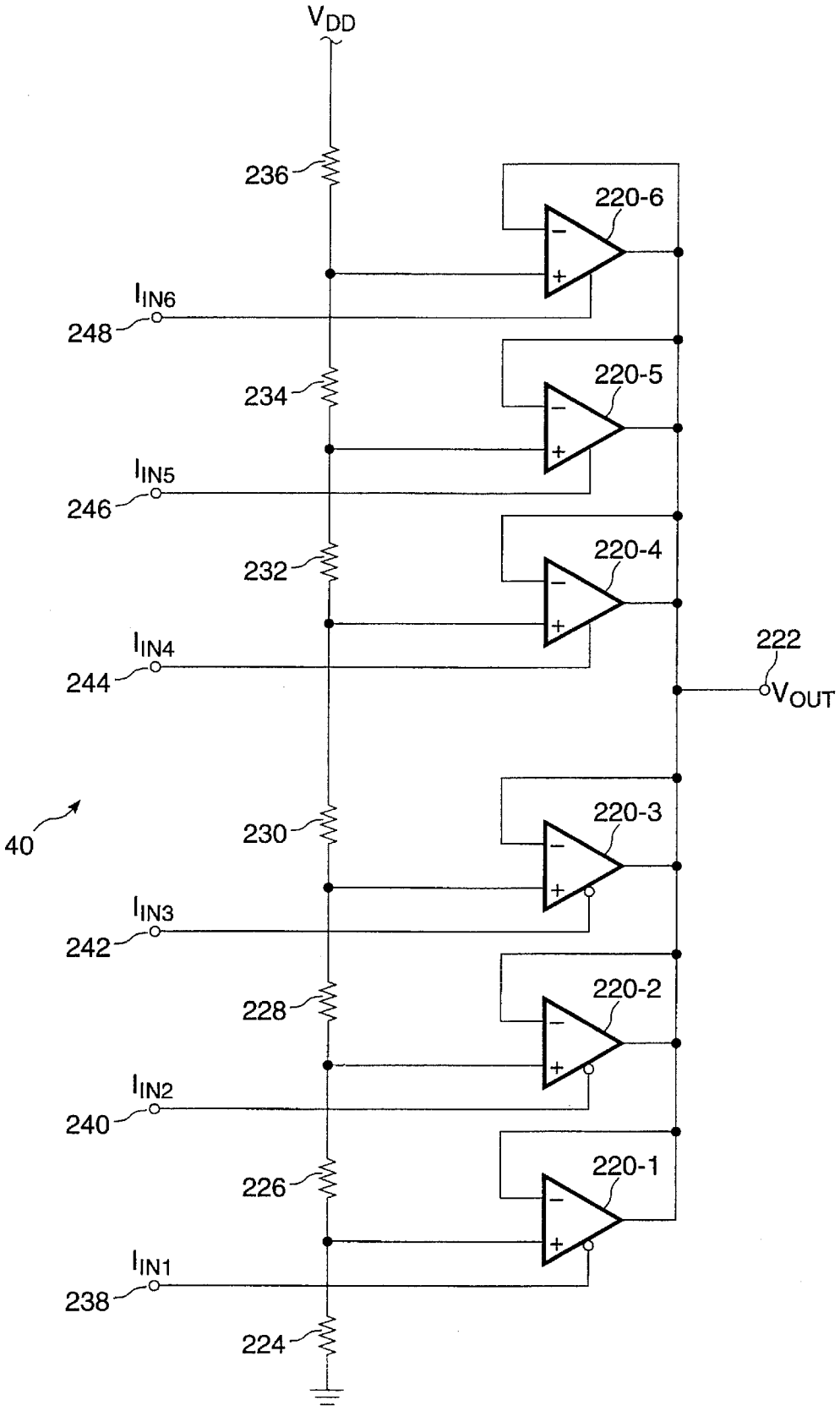

V_{DD}
236
220-6
I_{IN6}
248
234
220-5
I_{IN5}
246
232
220-4
I_{IN4}
244
222
V_{OUT}
40
230
220-3
I_{IN3}
242
228
220-2
I_{IN2}
240
226
220-1
I_{IN1}
238
224

FIG. 9A

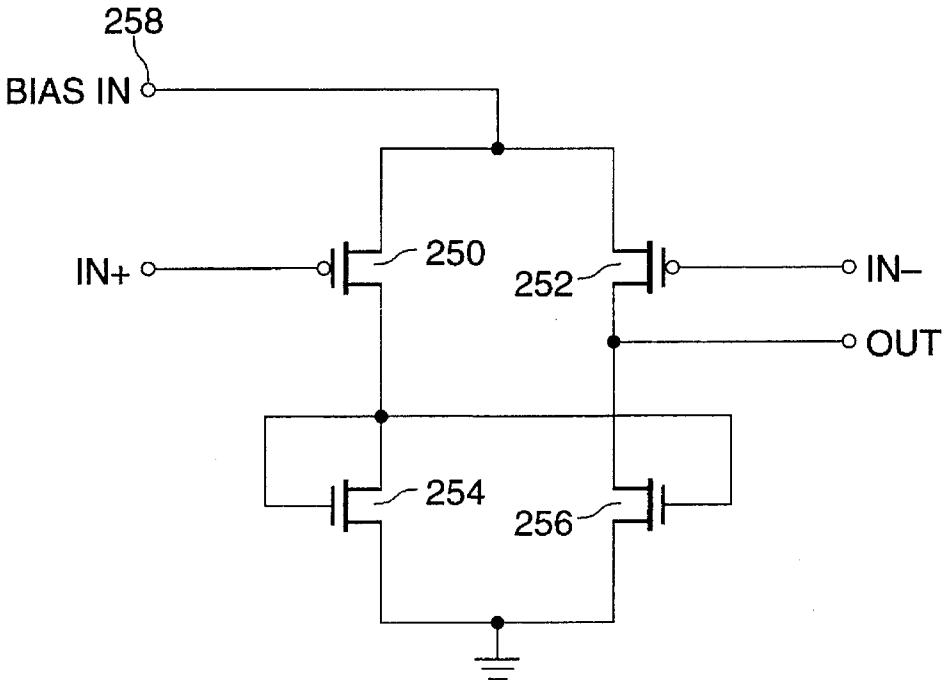

258
BIAS IN
IN+
250
252
IN–
OUT
254
256

FIG. 9B

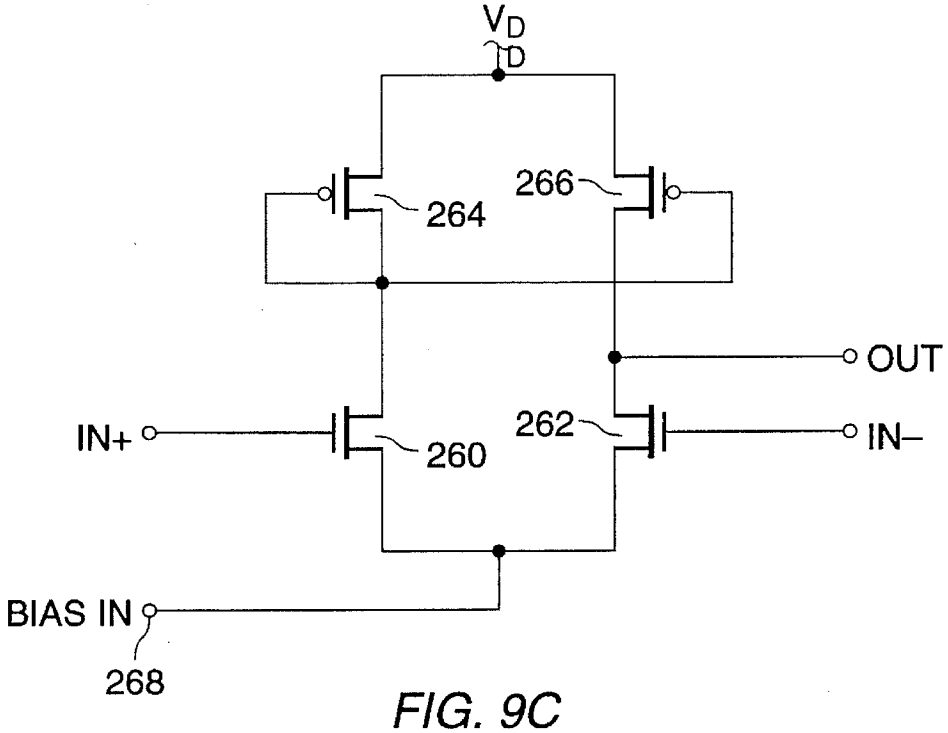

V_D
D
264
266
OUT
IN+
260
262
IN–
BIAS IN
268

FIG. 9C

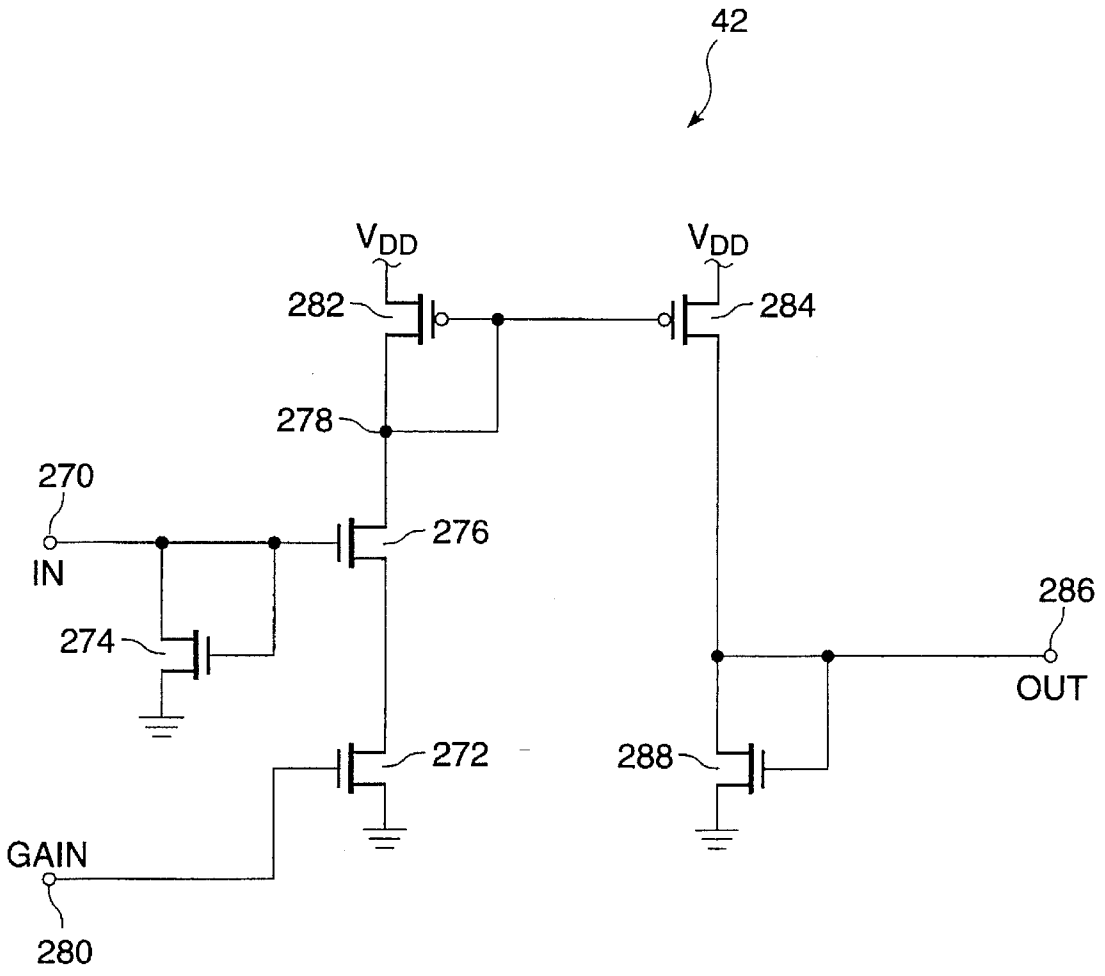


FIG. 10

OBJECT POSITION AND PROXIMITY DETECTOR

RELATED APPLICATIONS

This application is a continuation of application Ser. No. 08/115,743, filed Aug. 31, 1993, now U.S. Pat. No. 5,374,787, which is a continuation-in-part of co-pending application Ser. No. 7/895,934, filed Jun. 8, 1992 and assigned to the same assignee as the present invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to object position sensing transducers and systems. More particularly, the present invention relates to object position recognition useful in applications such as cursor movement for computing devices and other applications.

2. The Prior Art

Numerous devices are available or have been proposed for use as object position detectors for use in computer systems and other applications. The most familiar of such devices is the computer "mouse". While extremely popular as a position indicating device, a mouse has mechanical parts and requires a surface upon which to roll its position ball. Furthermore, a mouse usually needs to be moved over long distances for reasonable resolution. Finally, a mouse requires the user to lift a hand from the keyboard to make the cursor movement, thereby upsetting the prime purpose, which is usually typing on the computer.

Trackball devices are similar to mouse devices. A major difference, however is that, unlike a mouse device, a trackball device does not require a surface across which it must be rolled. Trackball devices are still expensive, have moving parts, and require a relatively heavy touch as do the mouse devices. They are also large in size and doe not fit well in a volume-sensitive application like a laptop computer.

There are several available touch-sense technologies which may be employed for use as a position indicator. Resistive-membrane position sensors are known and used in several applications. However, they generally suffer from poor resolution, the sensor surface is exposed to the user and is thus subject to wear. In addition, resistive-membrane touch sensors are relatively expensive. A one-surface approach requires a user to be grounded to the sensor for reliable operation. This cannot be guaranteed in portable computers. An example of a one-surface approach is the UnMouse product by MicroTouch, of Wilmington, Ma. A two-surface approach has poorer resolution and potentially will wear out very quickly in time.

Resistive tablets are taught by U.S. Pat. No. 4,680,430 to Yoshikawa, U.S. Pat. No. 3,497,617 to Ellis and many others. The drawback of all such approaches is the high power consumption and the high cost of the resistive membrane employed.

Surface Acoustic Wave (SAW) devices have potential use as position indicators. However, this sensor technology is expensive and is not sensitive to light touch. In addition, SAW devices are sensitive to residue buildup on the touch surfaces and generally have poor resolution.

Strain gauge or pressure plate approaches are an interesting position sensing technology, but suffer from several drawbacks. This approach may employ piezo-electric transducers. One drawback is that the piezo phenomena is an AC

phenomena and may be sensitive to the user's rate of movement. In addition, strain gauge or pressure plate approaches are a somewhat expensive because special sensors are required.

Optical approaches are also possible but are somewhat limited for several reasons. All would require light generation which will require external components and increase cost and power drain. For example, a "finger-breaking" infra-red matrix position detector consumes high power and suffers from relatively poor resolution.

There have been numerous attempts to provide a device for sensing the position of thumb or other finger for use as a pointing device to replace a mouse or trackball. Desirable attributes of such a device are low power, low profile, high resolution, low cost, fast response, and ability to operate reliably when the finger carries electrical noise, or when the touch surface is contaminated with dirt or moisture.

Because of the drawbacks of resistive devices, many attempts have been made to provide pointing capability based on capacitively sensing the position of the finger. U.S. Pat. No. 3,921,166 to Volpe teaches a capacitive matrix in which the finger changes the transcapacitance between row and column electrodes. U.S. Pat. No. 4,103,252 to Bobick employs four oscillating signals to interpolate x and y positions between four capacitive electrodes. U. S. Pat. No. 4,455,452 to Schuyler teaches a capacitive tablet wherein the finger attenuates the capacitive coupling between electrodes.

U.S. Pat. No. 4,550,221 to Mabusth teaches a capacitive tablet wherein the effective capacitance to "virtual ground" is measured by an oscillating signal. Each row or column is polled sequentially, and a rudimentary form of interpolation is applied to resolve the position between two rows or columns. An attempt is made to address the problem of electrical interference by averaging over many cycles of the oscillating waveform. The problem of contamination is addressed by sensing when no finger was present, and applying a periodic calibration during such no-finger-present periods. U.S. Pat. No. 4,639,720 to Rympalski teaches a tablet for sensing the position of a stylus. The stylus alters the transcapacitance coupling between row and column electrodes, which are scanned sequentially. U.S. Pat. No. 4,736,191 to Matzke teaches a radial electrode arrangement under the space bar of a keyboard, to be activated by touching with a thumb. This patent teaches the use of total touch capacitance, as an indication of the touch pressure, to control the velocity of cursor motion. Pulsed sequential polling is employed to address the effects of electrical interference.

U.S. Pat. Nos. 4,686,332 and 5,149,919, to Greanias, teaches a stylus and finger detection system meant to be mounted on a CRT. As a finger detection system, it's X/Y sensor matrix is used to locate the two matrix wires carrying the maximum signal. With a coding scheme these two wires uniquely determine the location of the finger position to the resolution of the wire stepping. For stylus detection, Greanias first coarsely locates it, then develops a virtual dipole by driving all lines on one side of the object in one direction and all lines on the opposite side in the opposite direction. This is done three times with different dipole phases and signal polarities. Assuming a predetermined matrix response to the object, the three measurements present a set of simultaneous equations that can be solved for position.

U.S. Pat. No. 4,733,222 to Evans is the first to teach a capacitance touch measurement system that interpolates to a high degree. Evans teaches a three terminal measurement

system that uses a drive, sense and electrode signal set (3 signals) in its matrix, and bases the measurement on the attenuation effect of a finger on the electrode node signal (uses a capacitive divider phenomena). Evans sequentially scans thru each drive set to measure the capacitance. From the three largest responses an interpolation routine is applied to determine finger position. Evans also teaches a zeroing technique that allows "no-finger" levels to be cancelled out as part of the measurement.

U.S. Pat. No. 5,016,008 to Gruaz describes a touch sensitive pad that also uses interpolation. Gruaz uses a drive and sense signal set (2 signals) in the touch matrix and like Evans relies on the attenuation effect of a finger to modulate the drive signal. The touch matrix is sequentially scanned to read each matrix lines response. An interpolation program then selects the two largest adjacent signals in both dimensions to determine the finger location, and ratiometrically determines the effective position from those 4 numbers.

Gerpheide, PCT application US90/04584, publication No. W091/03039, applies to a touch pad system a variation of the virtual dipole approach of Greanias. Gerpheide teaches the application of an oscillating potential of a given frequency and phase to all electrodes on one side of the virtual dipole,and an oscillating potential of the same frequency and opposite phase to those on the other side. Electronic circuits develop a "balance signal" which is zero when no finger is present, and which has one polarity if a finger is on one side of the center of the virtual dipole, and the opposite polarity if the finger is on the opposite side. To acquire the position of the finger initially, the virtual dipole is scanned sequentially across the tablet. Once the finger is located, it is "tracked" by moving the virtual dipole toward the finger once the finger has moved more than one row or column.

Because the virtual dipole method operates by generating a balance signal that is zero when the capacitance does not vary with distance, it only senses the perimeter of the finger contact area, rather than the entire contact area. Because the method relies on synchronous detection of the exciting signal, it must average for long periods to reject electrical interference, and hence it is slow. The averaging time required by this method, together with the necessity to search sequentially for a new finger contact once a previous contact is lost, makes this method, like those before it, fall short of the requirements for a fast pointing device that is not affected by electrical interference.

It should also be noted that all previous touch pad inventions that used interpolation placed rigorous design requirements on their sensing pad. Greanias and Evans use a complicated and expensive drive, sense and electrode line scheme to develop their signal. Gruaz and Gerpheide use a two signal drive and sense set. In the present invention the driving and sensing is done on the same line. This allows the row and column sections to be symmetric and equivalent. This in turn allows independent calibration of all signal paths, which makes board layout simpler and less constraining, and allows for more unique sensor topologies.

The shortcomings of the inventions and techniques described in the prior art can also be traced to the use of only one set of driving and sensing electronics, which was multiplexed sequentially over the electrodes in the tablet. This arrangement was cost effective in the days of discrete components, and avoided offset and scale differences among circuits.

The sequential scanning approach of previous systems also made them more susceptible to noise. Noise levels could change between successive measurements, thus changing the measured signal and the assumptions used in interpolation routines.

Finally, all previous approaches assumed a particular signal response for finger position versus matrix position. Because the transfer curve is very sensitive to many parameters and is not a smooth linear curve as Greanias and Gerpheide assume, such approaches are limited in the amount of interpolation they can perform.

It is thus an object of the present invention to provide a two-dimensional capacitive sensing system equipped with a separate set of drive/sense electronics for each row and for each column of a capacitive tablet, wherein all row electrodes are sensed simultaneously, and all column electrodes are sensed simultaneously.

It is a further object of the present invention to provide an electronic system that is sensitive to the entire area of contact of a finger with a capacitive tablet, and to provide as output the coordinates of some measure of the center of this contact area while remaining insensitive to the characteristic profile of the object being detected.

It is a further object of the present invention to provide an electronic system that provides as output some measure of area of contact of a finger with a capacitive tablet.

BRIEF DESCRIPTION OF THE INVENTION

With the advent of very high levels of integration, it has become possible to integrate many channels of driving/sensing electronics into one integrated circuit, along with the control logic for operating them, and the interface electronics to allow the pointing device to communicate directly with a host microprocessor. The present invention uses adaptive analog techniques to overcome offset and scale differences between channels, and can thus sense either transcapacitance or self-capacitance of all tablet rows or columns in parallel. This parallel-sensing capability, made possible by providing one set of electronics per row or column, allows the sensing cycle to be extremely short, thus allowing fast response while still maintaining immunity to very high levels of electrical interference.

The present invention comprises a position-sensing technology particularly useful for applications where finger position information is needed, such as in computer "mouse" or trackball environments. However the position-sensing technology of the present invention has much more general application than a computer mouse, because its sensor can detect and report if one or more points are being touched. In addition, the detector can sense the pressure of the touch.

According to a preferred embodiment of the present invention, referred to herein as a "finger pointer" embodiment, a position sensing system includes a position sensing transducer comprising a touch-sensitive surface disposed on a substrate, such as a printed circuit board, including a matrix of conductive lines. A first set of conductive lines runs in a first direction and is insulated from a second set of conductive lines running in a second direction generally perpendicular to the first direction. An insulating layer is disposed over the first and second sets of conductive lines. The insulating layer is thin enough to promote significant capacitive coupling between a finger placed on its surface and the first and second sets of conductive lines.

Sensing electronics respond to the proximity of a finger to translate the capacitance changes of the conductors caused by finger proximity into position and touch pressure infor-

mation. Its output is a simple X, Y and pressure value of the one object on its surface.

Different prior art pad scan techniques have different advantages in different environments. Parallel drive/sense techniques according to the present invention allow input samples to be taken simultaneously, thus all channels are affected by the same phase of an interfering electrical signal, greatly simplifying the signal processing and noise filtering.

There are two drive/sense methods employed in the touch sensing technology of the present invention. According to a first and presently preferred embodiment of the invention, the voltages on all of the X lines of the sensor matrix are simultaneously moved, while the voltages of the Y lines are held at a constant voltage, with the complete set of sampled points simultaneously giving a profile of the finger in the X dimension. Next, the voltages on all of the Y lines of the sensor matrix are simultaneously moved, while the voltages of the X lines are held at a constant voltage to obtain complete set of sampled points simultaneously giving a profile of the finger in the other dimension.

According to a second drive/sense method, the voltages on all of the X lines of the sensor matrix are simultaneously moved in a positive direction, while the voltages of the Y lines are moved in a negative direction. Next, the voltages on all of the X lines of the sensor matrix are simultaneously moved in a negative direction, while the voltages of the Y lines are moved in a positive direction. This technique doubles the effect of any transcapacitance between the two dimensions, or conversely, halves the effect of any parasitic capacitance to ground. In both methods, the capacitive information from the sensing process provides a profile of the proximity of the finger to the sensor in each dimension.

Both embodiments then take these profiles and calculate the centroid for X and Y position and integrate under the curve for the Z pressure information. The position sensor of these embodiments can only report the position of one object on its sensor surface. If more than one object is present, the position sensor of this embodiment computes the centroid position of the combined set of objects. However, unlike prior art, because the entire pad is being profiled, enough information is available to discern simple multi-finger gestures to allow for a more powerful user interface.

According to another aspect of the present invention, several power reduction techniques which can shut down the circuit between measurements have been integrated into the system. This is possible because the parallel measurement technique according to the present invention is so much faster than prior art techniques.

According to a further aspect of the invention, noise reduction techniques that are focused on reducing noise produced in typical computer environments are integrated into the system.

According to yet another aspect of the present invention, a capacitance measurement technique which is easier to calibrate and implement is employed.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1***a* is a top view of an object position sensor transducer according to a presently preferred embodiment of the invention showing the object position sensor surface layer including a top conductive trace layer and conductive pads connected to a bottom trace layer.

FIG. **1***b* is a bottom view of the object position sensor transducer of FIG. **1** a showing the bottom conductive trace layer.

FIG. **1***c* is a composite view of the object position sensor transducer of FIGS. **1***a* and **1***b* showing both the top and bottom conductive trace layers.

FIG. **1***d* is a cross-sectional view of the object position sensor transducer of FIGS. **1***a*–**1***c*.

FIG. **2** is a block diagram of sensor decoding electronics which may be used with the sensor transducer in accordance with a preferred embodiment of the present invention.

FIG. **3***a* is a simplified schematic diagram of a charge integrator circuit which may be used in the present invention.

FIG. **3***b* is a schematic diagram of an illustrative schematic diagram of the charge integrator circuit of FIG. **3***a*.

FIG. **4** is a timing of the operation of charge integrator circuit of FIGS. **3***a* and **3***b*.

FIG. **5** is a schematic diagram of an illustrative filter and sample/hold circuit for use in the present invention.

FIG. **6***a* is a schematic diagram of an illustrative minimum selector and subtractor circuit including peak rejection which may be employed in the present invention, showing circuit details of four individual channels and their interconnection.

FIG. **6***b* is a representation of what the output of the minimum selector and subtractor circuit of FIG. **6***a* would be like without the background level removed.

FIG. **6***c* is a representation of the output of the minimum selector and subtractor circuit of FIG. **6***a* with the background level removed.

FIG. **7** is a schematic diagram of an illustrative OTA circuit used in the minimum selector and subtractor circuit, showing how the outputs Pout and Zout are derived, and further showing a current sink and source options, Poutn and Poutp, respectively, for the Pout output.

FIG. **8** is a schematic diagram of an illustrative maximum detector circuit which may be used in the present invention.

FIG. **9***a* is a schematic diagram of an illustrative position encoder circuit which may be used in the present invention.

FIG. **9***b* is a schematic diagram of an P-type OTA circuit which may be used in the position encoder circuit of the present invention.

FIG. **9***c* is a schematic diagram of an N-type OTA circuit which may be used in the position encoder circuit of the present invention.

FIG. **10** is a schematic diagram of an illustrative ZSum circuit which may be used in the present invention.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

This application is a continuation-in-part of co-pending application Ser. No. 07/895,934, filed Jun. 8, 1992. The present invention continues the approach disclosed in the parent application and provides more unique features not previously available. These improvements provide increased sensitivity, and greater noise rejection, increased data acquisition rate and decreased power consumption.

Those of ordinary skill in the art will realize that the following description of the present invention is illustrative only and not in any way limiting. Other embodiments of the invention will readily suggest themselves to such skilled persons.

The present invention brings together in combination a number of unique features which allow for new applications not before possible. Because the object position sensor of the

present invention has very low power requirements, it is beneficial for use in battery operated or low power applications such as lap top or portable computers. It is also a very low cost solution, has no moving parts (and is therefore virtually maintenance free), and uses the existing printed circuit board traces for sensors. The sensing technology of the present invention can be integrated into a computer motherboard to even further lower its cost in computer applications. Similarly, in other applications the sensor can be part of an already existent circuit board.

Because of its small size and low profile, the sensor technology of the present invention is useful in lap top or portable applications where volume is important consideration. The sensor technology of the present invention requires circuit board space for only a single sensor interface chip that can interface directly to a microprocessor, plus the area needed on the printed circuit board for sensing.

The sensor material can be anything that allows creation of a conductive X/Y matrix of pads. This includes not only standard PC board, but also flexible PC board, conductive elastomer materials, silk-screened conductive lines, and piez-oelectric Kynar plastic materials. This renders it useful as well in any portable equipment application or in human interface where the sensor needs to be molded to fit within the hand.

The sensor can be conformed to any three dimensional surface. Copper can be plated in two layers on most any surface contour producing the sensor. This will allow the sensor to be adapted to the best ergonomic form needed for a application. This coupled with the "light-touch" feature will make it effortless to use in many applications. The sensor can also be used in an indirect manner, i.e it can have a conductive foam over the surface and be used to detect any object (not just conductive) that presses against it's surface.

Small sensor areas are practical, i.e., a presently conceived embodiment takes about 1.5"×1.5" of area, however those of ordinary skill in the art will recognize that the area is scalable for different applications. The matrix area is scaleable by either varying the matrix trace spacing or by varying the number of traces. Large sensor areas are practical where more information is needed.

Besides simple X and Y position information, the sensor technology of the present invention also provides finger pressure information. This additional dimension of information may be used by programs to control special features such as "brush-width" modes in Paint programs, special menu accesses, etc., allowing provision of a more natural sensory input to computers. It has also been found useful for implementing "mouse click and drag" modes and for simple input gestures.

The user will not even have to touch the surface to generate the minimum reaction. This feature can greatly minimize user strain and allow for more flexible use.

The sense system of the present invention depends on a transducer device capable of providing position and pressure information regarding the object contacting the transducer. Referring first to FIGS. **1***a*–**1***d*, top, bottom, composite, and cross-sectional views, respectively, are shown of a presently-preferred touch sensor array for use in the present invention. Since capacitance is exploited by this embodiment of the present invention, the sensor surface is designed to maximize the capacitive coupling.

A presently preferred sensor array **10** according to the present invention comprises a substrate **12** including a set of first conductive traces **14** disposed on a top surface **16** thereof and run in a first direction to comprise row positions of the array. A set of second conductive traces **18** are disposed on a bottom surface **20** thereof and run in a second direction preferably orthogonal to the first direction to form the column positions of the array. The sets of first and second conductive traces **14** and **18** are alternately in contact with periodic sense pads **22** comprising enlarged areas, shown as diamonds in FIGS. **1***a*–**1***c*. While sense pads **22** are shown as diamonds in FIGS. **1***a*–**1***c*, any shape, such as circles, which allows close packing of the sense pads, is equivalent for purposes of this invention. As an arbitrary convention herein, the set of first conductive traces **14** will be referred to as being oriented in the "X" or "row" direction and may be referred to herein sometimes as "X lines" and the set of second conductive traces **18** will be referred to as being oriented in the "Y" or "column" direction and may be referred to herein sometimes as "Y lines".

The number and spacing of these sense pads **22** depends upon the resolution desired. For example, in an actual embodiment constructed according to the principles of the present invention, a 0.10 inch center-to-center diamond-shaped pattern of sense pads disposed along a matrix of **15** rows and **15** columns of conductors is employed. Every other sense pad **22** in each direction in the pad pattern is connected sets of first and second conductive traces **14** and **18** on the top and bottom surfaces **16** and **20**, respectively of substrate **12**.

Substrate **12** may be a printed circuit board, a flexible circuit board or any of a number of available circuit interconnect technology structures. Its thickness is unimportant as long as contact may be made therethrough from the bottom conductive traces **18** to their sense pads **22** on the top surface **16**. The printed circuit board comprising substrate **12** can be constructed using standard industry techniques. Board thickness is not important. Connections from the sense pads **22** to the bottom traces **18** may be made employing standard plated-through hole techniques well known in the printed circuit board art.

In an alternate embodiment of the present invention, the substrate material **12** may have a thickness on the order of 0.005 to 0.010 inches. Then the diamonds on the top surface **16** and the plated thru holes that connect to the bottom surface traces **18**, can be omitted, further reducing the cost of the system.

An insulating layer **24** is disposed over the sense pads **22** on top surface **16** to insulate a human finger or other object therefrom. Insulating layer **24** is preferably a thin layer (i.e., approximately 5 mils) to keep capacitive coupling large and may comprise a material, such as mylar, chosen for its protective and ergonomic characteristics. The term "significant capacitive coupling" as used herein shall mean capacitive coupling having a magnitude greater than about 0.5 pF.

There are two different capacitive effects taking place when a finger approaches the sensor array **10**. The first capacitive effect is trans-capacitance, or coupling between sense pads **22**, and the second capacitive effect is self-capacitance, or coupling to virtual ground. Sensing circuitry is coupled to the sensor array **10** of the present invention and responds to changes in either or both of these capacitances. This is important because the relative sizes of the two capacitances change greatly depending on the user environment. The ability of the present invention to detect changes in both self capacitance and trans-capacitance results in a very versatile system having a wide range of applications.

According to the preferred embodiment of the invention, a position sensor system including sensor array **10** and associated touch detector circuitry will detect a finger posi-

tion on a matrix of printed circuit board traces via the capacitive effect of finger proximity to the sensor array **10**. The position sensor system will report the X, Y position of a finger placed near the sensor array **10** to much finer resolution than the spacing between the row and column traces **14** and **18**. The position sensor according to this embodiment of the invention will also report a Z value proportional to the outline of that finger and hence indicative of the pressure with which the finger contacts the surface of insulating layer **24** over the sensor array

According to the presently preferred embodiment of the invention, a very sensitive, light-touch detector circuit may be provided using adaptive analog VLSI techniques. The circuit of the present invention is very robust and calibrates out process and systematic errors. The detector circuit of the present invention will process the capacitive input information and provide digital information to a microprocessor.

According to this embodiment of the invention, sensing circuitry is contained on a single sensor processor integrated circuit chip. The sensor processor chip can have any number of X and Y "matrix" inputs. The number of X and Y inputs does not have to be equal. The Integrated circuit has a digital bus as output. In the illustrative example disclosed in FIGS. **1***a*–**1***d* herein, the sensor array **10** has 15 traces in both the Y and Y directions. The sensor processor chip thus has 15 X inputs and 15 Y inputs.

The X and Y matrix nodes are driven and sensed in parallel, with the capacitive information from each line indicating how close a finger is to that node. The scanned information provides a profile of the finger proximity in each dimension. According to this aspect of the present invention, the profile centroid is derived in both the X and Y directions and is the position in that dimension. The profile curve of proximity is also integrated to provide the Z information.

There are two drive and sense methods employed in the touch sensing technology of the present invention. According to a first and presently preferred embodiment of the invention, the voltages on all of the X lines of the sensor array **10** are simultaneously moved, while the voltages of the Y lines are held at a constant voltage. Next, the voltages on all of the Y lines of the sensor array **10** are simultaneously moved, while the voltages of the X lines are held at a constant voltage. This scanning method accentuates the measurement of capacitance to virtual ground provided by the finger. Those of ordinary skill in the art will recognize that order of these two steps is somewhat arbitrary and may be reversed.

According to a second drive/sense method, the voltages on all of the X lines of the sensor array **10** are simultaneously moved in a positive direction, while the voltages of the Y lines are moved in a negative direction. Next, the voltages on all of the X lines of the sensor array **10** are simultaneously moved in a negative direction, while the voltages of the Y lines are moved in a positive direction. This second drive/sense method accentuates transcapacitance and de-emphasizes virtual ground capacitance. As with the first drive/sense method, those of ordinary skill in the art will recognize that order of these two steps is somewhat arbitrary and may be reversed.

Referring now to FIG. **2**, a block diagram of the presently preferred sensing circuitry **30** for use according to the present invention is presented. This block diagram shows the sensing circuitry **30** in one dimension (X) only. Those of ordinary skill in the art will appreciate that an identical circuit would be used for sensing the opposite (Y) dimension. Such skilled persons will further note that these dimensions do not need to be orthogonal. For example, they can be radial or of any other nature to match the contour of the sensing pad and the needs of the system.

The capacitance at each sensor matrix node is measured simultaneously using charge integrator circuits **32-1** through **32**-n. The function of each charge integrator is to develop an output voltage proportional to the capacitance sensed on the corresponding X matrix line.

According to the presently preferred drive/sense method, the capacitance measurements are performed simultaneously across all inputs in one dimension to overcome a problem which is inherent in all prior art approaches that scan individual inputs. The problem with the prior-art approach is that it is sensitive to high frequency and large amplitude noise (large dv/dt noise) that is coupled to the circuit via the touching object. Such noise may distort the finger profile because of noise appearing in a later scan cycle but not an earlier one, due to a change in the noise level. The present invention overcomes this problem by taking a snapshot of all inputs simultaneously. The injected noise is proportional to the finger signal strength across all inputs and therefore symmetric around the finger centroid. Because it is symmetric around the finger centroid it does not affect the finger position.

Because of the nature of the charge integrator circuits **32-1** through **32**-n, their outputs will be changing over time and will have the desired voltage output for only a short time. This desired voltage is captured by the filter and sample/hold circuits **34-1** through **34**-n. As controlled by the control circuitry, **36**, the filter and sample/hold circuits **34-1** through **34**-n will capture the desired voltage and store it. Additionally, the result may also be filtered depending on the size of the sample and hold capacitor in the cell.

The filter and sample/hold circuits **34-1** through **34**-n then provides an input for the Minimum Selector and Subtractor circuit **38**, which computes an average of its n smallest input values (n=3 is presently preferred) and subtracts that value from each input. Minimum Selector and Subtractor circuit **38** then generates a current output for every input which is proportional to the difference at that input between the actual value at the input and the computed average minimum value. This circuit performs the task of subtracting out the background capacitance seen by the sensing circuitry and then providing a current proportional to the additional capacitance seen above the background level. If n=1, then the minimum value is selected. Any n>1 will select an average of the n values.

This current is then replicated and sent to two destinations. One copy is sent to the position encoder circuit **40**, and the second is sent to the Zsum circuit **42**.

The position encoder circuit **40** uses the current inputs as weights, and provides a scaled weighted mean (centroid) of the set of input currents and their relation to their position in the sensor. Position encoder circuit **40** is a linear position encoder having a voltage output which varies between the power supply rails. Because the circuit produces a continuous weighted mean over all input values, it is capable of interpolation to a much finer resolution than the spacing of the matrix grid spacing.

The output of the position encoder circuit **40** is then presented to sample/hold circuit **44-1** and analog to digital (ND) converter **46-1**. The operation of this portion of the circuit uses devices that are well known to those knowledgeable in the art.

The minimum selector and subtractor circuit **38** also generates a second set of outputs which are all tied together

and sent to the Zsum circuit **42**. Since these lines are shorted together, the individual output currents are all summed together. The total effect of the finger on the sensor in one dimension is thus integrated, producing a current sum result proportional to the pressure or proximity of the input object. The Zsum circuit **42** takes this current sum and then converts it back to a voltage which is proportional to the current sum. Those of ordinary skill in the art will appreciate that there are many conversion choices depending on the particular use to which the invention is put, it can be a linear conversion, square root (compressive), or squared (expansive). In presently preferred embodiment a compressive conversion is chosen to compress large changes and emphasize small changes, since detecting very light touches is of particular interest.

The output of the ZSum circuit **42** is presented to a sample/hold circuit **44-2** which stores the results. The output of sample hold circuit **44-2** drives A/D converter circuit **46-2** which converts the analog information to a digital form useable by microcomputers.

Control circuitry **36** of FIG. **2** orchestrates the operation of the remainder of the circuitry. Because the system is discretely sampled and pipelined in its operation, control circuitry **36** is present to manage the signal flow. The functions performed by control circuitry **36** may be conventionally developed via what is commonly known in the art as a state machine or by a microcontroller.

The output of the filter and sample/hold circuits, **34-1** thru **34**-n, is also monitored by a maximum detector circuit **47**. The purpose of this section of circuitry is to generate an interrupt signal to a microprocessor if there is a finger signal greater than a preset threshold. The maximum detector circuit **47** outputs a signal which is related to the largest input voltage. This signal is then compared against a predetermined threshold, noted as VTHMAX with the comparator **48**. If the signal is greater than the preset threshold the comparator will output a logic 1 level which, after conditioned with proper timing thru AND gate **49**, provides an interrupt signal to a microprocessor. Those skilled in the art will recognize that this signal is not limited to being an interrupt and could be used for polling, for example, or in other ways that better fit the needs of the entire system.

The structure and operation of the individual blocks of FIG. **2** will now be disclosed. Referring now to FIGS. **3***a*, **3***b*, and **4**, a typical charge integrator circuit will be described. Charge integrator circuit **32** is shown as a simplified schematic diagram in FIG. **3***a* and as an illustrative schematic diagram in FIG. **3***b*. The timing of the operation of charge integrator circuit **32** is shown in FIG. **4**.

Charge integrator circuit **32** is based on the fundamental physical phenomena of using a current to charge a capacitor. If the capacitor is charged for a constant time by a constant current then a voltage will be produced on the capacitor which is inversely proportional to the capacitance. The capacitance to be charged is the sensor array line capacitance in parallel with an internal capacitor. This internal capacitor will contain the voltage of interest.

Referring now to FIG. **3***a*, a simplified schematic diagram of an illustrative charge integrator circuit **32** is shown. A charge integrator circuit input node **50** is connected to one of the X (or Y) lines of the sensor array. A first shorting switch **52** is connected between the charge integrator circuit input node **50** and V_{DD}, the positive supply rail. A second shorting switch **54** is connected between the charge integrator circuit input node **50** and ground, the negative supply rail. A positive constant current source **56** is connected to V_{DD}, the positive supply rail and to the charge integrator circuit input node **50** and through a first current source switch **58**. A negative constant current source **60** is connected to ground and to the charge integrator circuit input node **50** and through a second current source switch **62**.

A first internal capacitor **64** is connected between V_{DD} and output node **66** of charge integrator circuit **32**. A positive voltage storage switch **68** is connected between output node **66** and input node **50**. A second internal capacitor **70** has one of its plates connected to ground through a switch **72** and to output node **66** of charge integrator circuit **32** through a switch **74**, and the other one of its plates connected to input node **50** through a negative voltage storage switch **76** and to V_{DD} through a switch **78**. The capacitance of first and second internal capacitors **64** and **70** should be a small fraction (i.e., about 10%) of the capacitance of the individual sensor array lines. In a typical embodiment, the sensor array line capacitance will be about 10 pF and the capacitance of capacitors **64** and **70** should be about 1 pF.

According to the presently preferred embodiment of the invention, the approach used is a differential measurement for added noise immunity, the benefit of which is that any low frequency common mode noise gets subtracted out. For the following discussion, it is to be assumed that all switches are open unless they are noted as closed. First, the sensor array line is momentarily shoaled to V_{DD} through switch **52**, switch **68** is closed connecting capacitor **64** in parallel with the capacitance of the sensor line. Then the parallel capacitor combination is discharged with a constant current from current source **60** through switch **62** for a fixed time period. At the end of the fixed time period, switch **68** is opened, thus storing the voltage on the sensor array line on capacitor **64**.

The sensor line is then momentarily shorted to ground through switch **54**, and switches **72** and **76** are closed to place capacitor **70** in parallel with the capacitance of the sensor line. Switch **58** is closed and the parallel capacitor combination is charged with a constant current from current source **56** for a fixed time period equal to the fixed time period of the first cycle. At the end of the fixed time period, switch **76** is opened, thus storing the voltage on the sensor array line on capacitor **70**.

The first and second measured voltages are then averaged. This is accomplished by opening switch **72** and closing switches **78** and **74**, which places capacitor **70** in parallel with capacitor **64**. Because capacitors **64** and **70** have the same capacitance, the resulting voltage across them is equal to the average of the voltages across each individually. This final result is the value that is then passed onto the appropriate one of filter and sample/hold circuits **34-1** through **34**-n.

The low frequency noise, notably 50/60 Hz and their harmonics, behaves as a DC current component that adds in one measurement and subtracts in the other. When the two results are added together that noise component is canceled out. The amount of noise rejection is a function of how quickly in succession the two charge/discharge cycles are performed. One of the reasons for the choice of this charge integrator circuit is that it allows measurements to be taken quickly.

Referring now to FIG. **3***b*, a more complete schematic diagram of an illustrative embodiment of charge integrator circuit **32** of the simplified diagram of FIG. **3***a* is shown. Input node **50** is shown connected to V_{DD} and ground through pass gates **80** and **82**, which replace switches **52** and **54** of FIG. **3***a*. Pass gate **80** is controlled by a signal ResetUp presented to its control input and pass gate **82** is controlled

by a signal ResetDn presented to its control input. Those of ordinary skill in the art will recognize that pass gates **80** and **82**, as well as all of the other pass gates which are represented by the same symbol in FIG. **3***b* may be conventional CMOS pass gates as are known in the art. The convention used herein is that the pass gate will be off when its control input is held low and will be on and present a low impedance connection when its control input is held high.

P-Channel MOS transistors **84** and **86** are configured as a current mirror. P-Channel MOS transistor **84** serves as the current source **56** and pass gate **88** serves as switch **58** of FIG. **3***a*. The control input of pass gate **88** is controlled by a signal StepUp,

N-Channel MOS transistors **92** and **94** are also configured as a current mirror. N-Channel MOS transistor **92** serves as the current source **60** and pass gate **96** serves as switch **62** of FIG. **3***a*. The control input of pass gate **96** is controlled by a signal StepDn. P-Channel MOS transistor **90** and N-Channel MOS transistor **98** are placed in series with P-Channel MOS current mirror transistor **86** and N-Channel MOS current mirror transistor **94**. The control gate of P-Channel MOS transistor **90** is driven by an enable signal EN, which turns on P-Channel MOS transistor **90** to energize the current mirrors. This device is used as a power conservation device so that the charge integrator circuit **32** may be turned off to conserve power when it is not in use.

N-Channel MOS transistor **98** has its gate driven by a reference voltage Vref, which sets the current through current mirror transistors **86** and **94**. The voltage Vref may be individually adjusted for each charge integrator circuit **32** to compensate for manufacturing variations. Each Vref may be developed from a analog programmable voltage source, such as described in van Steenwijk, Hoen, and Wallinga "A Nonvolatile Analog Voltage Programmable Voltage Source Using VIP MOS EEPROM Structure," IEEE Journal of Solid State Circuits, Jul. 1993. Alternatively, a writable analog reference voltage storage device, such as disclosed in U.S. Pat. No. 5,166,562 may be employed. This allows the circuit to be calibrated in the factory to zero out process variations as well as capacitance variations in the sensor. The calibration focus is to generate a constant and equal output from all the charge integrator circuits **32**-1 through **32**-n of FIG. **2** if no finger is present. Although the present approach is very robust, those of ordinary skill in the art will also appreciate an embodiment in which calibration will be allowed to occur in real time (via long time constant feedback) thereby zeroing out any long term effects due to sensor environmental changes.

Note that proper sizing of MOS transistors **94** and **98** may provide temperature compensation. This is accomplished by taking advantage of the fact that the threshold of N-Channel MOS transistor **98** reduces with temperature while the mobility of both N-Channel MOS transistors **94** and **98** reduce with temperature. The threshold reduction has the effect of increasing the current while the mobility reduction has the effect of decreasing the current. By proper device sizing these effects can cancel each other out over a significant part of the operating range.

Capacitor **64** has one plate connected to V_{DD} and the other plate connected to the output node **66** and to the input node **50** through pass gate **100**, shown as switch **68** in FIG. **3***a*. The control input of pass gate **100** is driven by the control signal SUp. One plate of capacitor **70** is connected to input node **50** through pass gate **102** (switch **76** in FIG. **3***a*) and to VDD through pass gate **104** (switch **72** in FIG. **3***a*). The control input of pass gate **102** is driven by the control signal SDn and the control input of pass gate **104** is driven by the control signal ChUp. The other plate of capacitor **70** is connected to ground through N-Channel MOS transistor **106** (switch **72** in FIG. **3***a*) and to output node **66** through pass gate **108**. The control input of pass gate **108** is driven by control signal Share.

Referring now to FIGS. **3***a*, **3***b* and the timing diagram of FIG. **4**, the operation of charge integrator circuit **32** during one scan cycle may be observed. First the EN (enable) control signal goes active by going to 0 v. This turns on the current mirrors and energizes the charge and discharge current sources, MOS transistors **84** and **92**. The ResetUp control signal is active high at this time, which shorts the input node **50** (and the sensor line to which it is connected) to V_{DD}. The SUp control signal is also active high at this time which connects capacitor **64** and the output node **66** to input node **50**. This arrangement guarantees that the following discharge portion of the operating cycle always starts from a known equilibrium state.

The discharge process starts after ResetUp control signal goes inactive. The StepDn control signal goes active, connecting MOS transistor **92**, the discharge current source, to the input node **50** and its associated sensor line. StepDn is active for a set amount of time, allowing the combined capacitance of the sensor line and capacitor **64** to charge down during that time. StepDn is then turned off. A short time later the SUp control signal goes inactive, storing the measured voltage on capacitor **64** to end the discharge cycle.

Next, ResetDn control signal becomes active and shorts the sensor line to ground. Simultaneously the SDn and ChDn control signals become active and connect capacitor **70** between ground and the sensor line. Capacitor **70** is discharged to ground, guaranteeing that the following charge up cycle always starts from a known state.

The chargeup cycle starts after ResetDn control signal becomes inactive and the StepUp control signal becomes active. At this point the current charging source, MOS transistor **84**, is connected to the sensor line and the sensor line charges up. The StepUp control signal is active for a set amount of time (preferably equal to the time for the previously mentioned cycle) allowing the capacitance to charge, and then it is turned off. The SDn control signal then goes inactive, leaving the measured voltage across capacitor **70**.

The averaging cycle now starts. First the voltage on capacitor **70** is level shifted. This is done by the ChDn control signal going inactive, letting one plate of the capacitor **70** float. Then the ChUp control signal goes active, connecting the second plate of the capacitor to V_{DD}. Then the Share control signal becomes active which connects the first plate of capacitor **70** to output node **66**, thus placing capacitors **64** and **70** in parallel. This has the effect of averaging the voltages across the two capacitors, thus subtracting out common mode noise as previously described. This average voltage is also then available on output node **66**.

According to the present invention, two different drive/sense methods have been disclosed. Those of ordinary skill in the art will readily observe that the charge integrator circuit **32** disclosed with reference to FIGS. **3***a*, **3***b*, and **4** is adaptable to operate according to either scanning method disclosed herein.

As is clear from an understanding of the operation of charge integrator circuit **32**, its output voltage is only available for a short period of time. In order to capture this voltage a sample/hold circuit is used. Referring now to FIG. **5**, a schematic diagram of an illustrative filter and sample/

hold circuit is presented. Those of ordinary skill in the art will recognize this circuit, which comprises an input node **112**, a pass gate **114** having a control input driven by a Sample control signal, a capacitor **116** connected between the output of the pass gate **114** and a fixed voltage such as ground, and an output node comprising the common connection between the capacitor **116** and the output of the pass gate **114**. In a typical embodiment, capacitor **116** will have a capacitance of about 10 pF.

The sample/hold circuit of FIG. **5** is well known in the art, but is applied in a way so that it acts as a filter as well. The filter time constant is K times the sample signal period, where K is the ratio of capacitor **116** to the sum of capacitors **64** and **70** of the charge integrator circuit **32** of FIGS. **3***a* and **3***b*. This filter further reduces noise injection. In the preferred embodiment, K=10/2=5.

As shown in FIG. **2**, the output of all of the filter and sample/hold circuits **34-1** thru **34**-n drive minimum selector and subtractor circuit **38**. Referring now to FIG. **6***a*, a schematic diagram of an illustrative minimum selector and subtractor circuit **38** useful for employment in the present invention is shown. The illustrative circuit of FIG. **6***a* is shown having four channels, although those of ordinary skill in the art will readily recognize that the circuit could be arbitrarily extended to a larger number of channels.

The minimum selector and subtractor circuit **38** is designed to take a set of inputs, detect the average of the three smallest input values and subtract that average value from each individual value in the entire input set. The circuit then produces a current which is proportional to this subtracted value, which for most background inputs will be zero. This sequence of steps is illustrated in FIGS. **6***b* and **6***c* for an example where there are 15 inputs (X1 to X15) in the set. FIG. **6***b* shows the input to the minimum selector/subtractor circuit as generated by the Filter circuits, **34-1** thru **34**-n. The drawing shows a typical finger profile with the background or minimum level noted. After the minimum selector and subtractor circuit **38** processes the input, it produces an output like that shown in FIG. **6***c*, which is the input set with the background value subtracted out.

Each individual channel, even though constituting a single functional unit, can be thought of as consisting of a minimum selector circuit **120** and a subtractor circuit **122**. In the minimum selector circuit **120**, the active elements are P-channel MOS transistors **124***a*–**124***d*, each having its source electrode connected to an intermediate node **126***a*–**126***d*, its gate electrode connected to the channel input nodes **128***a*–**128***d*, its drain electrode connected to the drain electrodes of N-channel MOS current-limiting transistors **130***a*–**130***d*, respectively. N-channel MOS transistors **130***a*–**130***d* have their source electrodes connected to a fixed voltage, such as ground, and their gate electrodes held at a potential V_{sink} above (more positive than) their source electrodes such that they function as current sinks with limited voltage compliance.

Each intermediate node **126***a*–**126***d* is also connected to a current source **132***a*–**132***d* that supplies the operating current of the P-channel MOS transistors **124***a*–**124***d* from a fixed voltage source V_{DD}. Intermediate nodes **126***a*–**126***d* are also connected to the non-inverting input of an operational transconductance amplifier **134***a*–**134***d* (OTA), which comprises the heart of the subtractor circuit **122** of each channel. A pass gate **136***a*–**136***d* allows connecting the intermediate node **126***a*–**126***d* to a minimum rail **138** which is common to all signal channels in the system. The inverting input of each OTA **134***a*–**134***d* is connected to a storage capacitor **140***a*–**140***d* as well as to one end of a pass gate **142***a*–**142***d* which permits selectively connecting the inverting input of the OTA **134***a*–**134***d* to its Pout output **144***a*–**144***d*. Each OTA also has a Zout output **146***a*–**146***d*.

The N-Channel MOS current sink transistors **130***a*–**130***d* have the effect of limiting the current that any one of the P-channel MOS transistors **124***a*–**124***d* can draw. As is well known to those of ordinary skill in the art, this is because the common drain connections of the N-channel and P-channel MOS transistors will assume such a potential as to reduce the drain-to-source voltage difference of one or the other of the two transistors far enough to prevent it from drawing more current than the other transistor allows to flow.

If the sink current of N-Channel MOS current sink transistors **130***a*–**130***d* is chosen to be larger than the current of sources **132***a*–**132***d* but smaller than the sum of all source currents, then no single P-Channel MOS transistor **124***a*–**124***d* can conduct all the current in the minimum selection phase of operation. Instead, several transistors have to share it. Thus it may be seen that the minimum select and subtractor circuit of FIG. **6***a* selects not the absolute minimum of the input voltages of all channels, but rather an average of the several lowest input voltages from among all channels. The gate voltage of the N-Channel MOS current-limiting transistors **130***a*–**130***d* is selected to set their saturation current to be W/n times the value of the current source **132**, where W is the number of channels present in the system and n is the number of channels to be averaged over to obtain the minimum.

For example, assuming an embodiment including fifteen identical signal channels, and the currents of the N-channel MOS transistors **130** in each channel are five times larger than the currents of current sources **132**, then the three P-channel transistors **124** with the lowest gate potentials must share the total system current because the total is equal to fifteen times the source current. The effect is to reject or at least attenuate negative peaks on the input voltages. This property is highly desirable in applications where it is expected that several or most channel input voltages will always be equal to a common minimum or baseline potential, but that considerable noise existing on the inputs may create false negative peaks.

As may be seen from FIG. **6***a*, each OTA **134***a*–**134***d* has two output types, designated as Pout **144***a*–**144***d* and Zout **146***a*–**146***d*. Referring now to FIG. **7**, the circuitry for generating these outputs may be seen in detail. As shown in FIG. **7**, each OTA comprises N-Channel MOS input transistors **148** and **150**, P-Channel MOS current mirror pairs configured from transistors **152** and **154**, **156** and **158**, and N-Channel MOS bias transistor **160**. An N-Channel MOS current mirror comprising transistors **162** and **164** is connected to P-Channel current mirror transistors **152** and **158** as shown.

As thus far described, the circuit is conventional and the common drain node of transistors **158** and **164** would form an output node for the circuit. An extra P-channel MOS transistor **166** and N-Channel MOS transistor **168** are added to the circuit to form a second output node by replicating the output buffer of the typical wide range output transamplifier. The common drain node of transistors **166** and **168**, through pass gate **170**, forms the Pout output section of the circuit. The diode-connected N-Channel MOS transistor **172** between the common drain node of transistors **158** and **164** and the Zout node assures that the Zout lines of minimum selector and subtractor circuit **38** will only source current, thus guaranteeing that only object-created signals above the baseline contribute to the Zout signal.

In the presently preferred embodiment of the invention, the Pout outputs of half of the minimum selector and subtractor circuit **38** are configured as current source outputs and may be designated Poutp outputs. The other half of the outputs are current sink outputs and may be designated Poutn outputs. This feature is also shown in FIG. **7**. Pass gate **170**, controlled by control signal PosEn is present to disconnect the position encode load during the sample phase of the minimum select and subtract circuit. The current source node for the Poutp outputs is at the output of pass gate **170**. In this configuration, transistors **174** and **176** are not present and Poutp goes to output Pout. This output would be used to drive the BiasIn line of the position encoder OTA as shown in FIG. **9***b*. The current sink path is developed from the transamplifier output current at the output of pass gate **170**. That current is fed into an NMOS current mirror comprising N-Channel MOS transistors **174** and **176**. The drain of N-Channel transistor **176** is the current sink Poutn output node and is connected to output Pout. This output would be used to drive the BiasIn line of the position encoder OTA as shown in FIG. **9***c*.

Referring now to FIG. **8**, an illustrative maximum detector circuit **47** for use in the present invention is shown. As previously mentioned, the function of maximum detector circuit **47** is to monitor the outputs of filter and sample/hold circuits, **34-1** thru **34**-n and to generate an interrupt signal to a microprocessor if there a finger signal greater than a preset threshold VTHMAX is present. Those skilled in the art will recognize that the signal is not limited to being an interrupt and could be used for other purposes such as polling etc.

Maximum detector circuit **47** includes an N-channel MOS bias transistor **182** having its source connected to ground and its gate connected to a bias voltage V_{BIAS} at node **184**. The inputs of the maximum detector circuit **47** are connected to the outputs of filter and sample/hold circuits **34-1** to **34**-n as shown in FIG. **2**. In the maximum detector circuit **47** illustrated in FIG. **8**, there are (n) inputs. Each input section comprises a series pair of MOS transistors connected between the drain of N-channel MOS bias transistor **182** and a voltage source V_{DD}.

Thus, the input section for In_1 comprises P-channel MOS current-limiting transistor **186** having its source connected to V_{DD} and its drain connected to the drain of N-channel MOS input transistor **188**. The gate of N-channel MOS input transistor **188** is connected to In_1 input node **190** and the gate of P-channel MOS current-limiting transistor **186** is connected to a source of bias voltage VLBIAS at node **192**.

Similarly, the input section for In_2 comprises P-channel MOS current-limiting transistor **194** having its source connected to V_{DD} and its drain connected to the drain of N-channel MOS input transistor **196**. The gate of N-channel MOS input transistor **196** is connected to In_2 input node **198** and the gate of P-channel MOS current-limiting transistor **194** is connected to node **192**.

The input section for In_3 comprises P-channel MOS current-limiting transistor **200** having its source connected to VDD and its drain connected to the drain of N-channel MOS input transistor **202**. The gate of N-channel MOS input transistor **202** is connected to In_3 input node **204** and the gate of P-channel MOS current-limiting transistor **200** is connected to node **192**.

The input section for $In_{(n)}$ comprises P-channel MOS current-limiting transistor **206** having its source connected to VDD and its drain connected to the drain of N-channel MOS input transistor **208**. The gate of N-channel MOS input transistor **208** is connected to $In_{(n)}$ input node **210** and the gate of N-channel MOS current-limiting transistor **206** is connected to node **192**. The sources of N-channel MOS input transistors **188**, **196**, **202**, and **208** are connected together to the drain of N-channel MOS bias transistor **182**. The output of maximum detector circuit **47** is node **212** at the common connection of the drain of N-channel MOS bias transistor **182** and the sources of the N-channel MOS input transistors **188**, **196**, **202** and **208**.

The maximum detector circuit **47** acts analogously to the minimum detector circuit **46** of parent application Ser. No. 07/895,934, filed Jun. 8, 1992. The difference is that an N-channel bias transistor is used instead of a P-channel bias transistor and an N-channel transconductance amplifier is used in place of a P-channel transconductance amplifier. The result is the output will now track approximately an N-channel bias drop below the largest input (in non-averaging mode), since that much difference is needed to guarantee at least one input pair is on (186/188, 194/196 , . . . 206/208).

However for this circuit the output is not used for feedback, but is instead used to drive a comparator **48** (FIG. **2**) which is set to trip if the input is greater than the voltage V_{Thmax}. If tripped, a MAX INTERRUPT signal is generated. The MAX INTERRUPT is used to "wake-up" a microprocessor and tell it that there is an object detected at the sensor. The signal is prevented from appearing on the MAX INTERRUPT line by AND gate **49** and a control signal from control circuitry **36**. The control signal only allows the interrupt signal to pass after the circuit has settled completely. The control signal presented to AND gate **49** may be a SAMPLE signal which may be generated, for example, by the trailing edge of the SHARE signal shown in FIG. **4**.

As may be seen from FIG. **2**, the outputs of minimum selector and subtractor circuit **38** are presented to position encoder circuit **40**. There are two identical position encoder circuits, one each for the X and Y directions. The function of position encode circuit **40** is to convert the input information into a signal representing object proximity in the X (or Y) dimension of the sensor array matrix. According to a presently preferred embodiment of the invention, this circuit will provide a scaled weighted mean (centroid) of the set of input currents. The result is a circuit which is a linear position encoder, having an output voltage which varies between the power supply rails. Because it is a weighted mean, it averages all current inputs and can in turn generate an output voltage which represents an X (or Y) position with a finer resolution than the spacing of the matrix grid spacing.

Referring now to FIG. **9***a*, a presently preferred embodiment of a position encoder circuit **40** of FIG. **2** is shown in schematic diagram form. Because the position encoder circuits in the X and Y dimensions are identical, only one will be shown. The position encoder circuit **40** of FIG. **9***a* is shown having six inputs, but those of ordinary skill in the art will recognize that, due to its symmetry, it may be arbitrarily expanded for other numbers of inputs.

As presently preferred, position encoder circuit **38** includes a plurality of transconductance amplifiers **220-1** through **220-6** connected as followers. The outputs of all amplifiers **220-1** through **220-6** are connected together to a common node **222**, which comprises the position encoder output node of the circuit **38**.

The non-inverting inputs of amplifiers **220-1** through **220-6** are connected to a resistive voltage divider network comprising resistors **224**, **226**, **228**, **230**, **232**, **234**, and **236**, shown connected between V_{DD} and ground.

Amplifiers **220-1** through **220-3** have P-channel MOS bias transistors and differential pair inputs due to the input

operating range between zero volts and $V_{DD}/2$, and are shown in schematic diagram form in FIG. **9***b*. The P-Channel MOS devices **250** and **252** form the differential input pair while **254** and **256** form a current mirror load. This is the standard configuration for a typical transconductance amplifier. Normally the bias current is provided by a P-Channel MOS current source device at node **258**. However in this application the bias current is provided externally by the Poutp output (output of pass gate **170** in FIG. **7**.) of the minimum selector/subtractor circuit through nodes **238**, **240** and **242** (I_{IN1} thru I_{IN3}, respectively, of FIG. **9***a*).

Amplifiers **220-4** through **220-6** have N-channel MOS bias transistors and differential pair inputs due to the input operating range between $V_{DD}/2$ and V_{DD}, and are shown in schematic diagram form in FIG. **9***c*. The N-Channel MOS transistors **260** and **262** form the differential input pair while P-Channel MOS transistors **264** and **266** form a current mirror load. This is the standard configuration for a typical transconductance amplifier. Normally the bias current is provided by a N-Channel MOS current source at node **268**. However in this application the bias current is provided externally by the Poutn output (drain of transistor **174** in FIG. **7**) of the minimum selector and subtractor circuit through nodes **244**, **246** and **248** (I_{IN4} thru I_{IN6}, respectively, of FIG. **9***a*). Those of ordinary skill in the art will readily recognize that amplifiers **220-4** through **220-6** will be configured exactly like amplifiers **220-1** through **220-3**, except that all transistor and supply voltage polarities are reversed.

The position encoder circuit of FIG. **9***a* will provide a weighted mean (centroid) of the input currents weighted by the voltages on the resistor divider circuit to which the inputs of the amplifiers **220-1** through **200-6** are connected. If the resistors **224**, **226**, **228**, **230**, **232**, **234**, and **236** are all equal then the result is a circuit which is a linear position encoder, with its output voltage varying between the power supply rails. Because it is a weighted mean, it averages all current inputs which in turn generates an interpolated output. This arrangement affords finer resolution than the voltage spacing of voltage nodes "n" at the input. This is key to making a dense circuit function. This circuit is an improvement of a circuit described in DeWeerth, Stephen P., Analog VLSI Circuits For Sensorimotor Feedback, Ph.D Thesis, California Institute of Technology, 1991.

The output voltage of X position encoder circuit **40** is presented to sample/hold circuit **44-1**, the output of which, as is well known in the art, either follows the input or holds a value present at the input depending on the state of its control input. The structure and operation of sample/hold circuits are well known in the art.

The output of sample/hold circuit **44-1** drives the input of analog-to-digital (ND) converter **46-1**. The output of A/D converter **46-1** is a digital value proportional to the position of the object in the X dimension of the sensor array matrix **10**.

Referring now to FIG. **10**, a schematic diagram of a presently preferred embodiment of a ZSum circuit **42** is shown. ZSum circuit **42** takes a current as an input on node **270**. If N-Channel MOS transistor **272** was not present then the combination of N-Channel MOS transistors **274** and **276** would be a current mirror and the current on input node **270** would appear on node **278**. Transistor **272** is a source degradation resistor that, depending on the gain setting on node **280**, reduces the current mirror transfer factor from an ideal factor of 1 to something less than 1. The smaller the voltage present on node **280** the smaller the transfer factor.

P-Channel MOS transistors **282** and **284** create another current mirror that copies the current in node **278** into node **286**, the output node. Diode connected N-Channel MOS transistor **288** converts the current back into a voltage with a square root transfer function or a compressive non-linearity. This is chosen to accentuate the low level currents and hence is suited to process a light touch at the sensor.

The increased sensitivity of the touch sensor system of the present invention allows for a lighter input finger touch which makes it easy for human use. Increased sensitivity also makes it easier to use other input objects, like pen styli, etc. Additionally this sensitivity allows for a trade-off against a thicker protective layer, or different materials, which both allow for lower manufacturing costs.

Greater noise rejection allows for greater flexibility in use and reduced sensitivity to spurious noise problems. Two techniques are employed which allow derivation of the most noise-rejection benefit.

Due to the drive and sense techniques employed in the present invention, the data acquisition rate has been increased by about a factor of **30** over the prior art. This offers several obvious side effects. First, for the same level of signal processing, the circuitry can be turned off most of the time and reduce power consumption by roughly a factor of **30** in the analog section of the design. Second, since more data is available, more signal processing, such as filtering, and gesture recognition, can be performed.

The sensor electronic circuit employed in the present invention is very robust and calibrates out process and systematic errors. It will process the capacitive information from the sensor and provide digital information to an external device, for example, a microprocessor.

Because of the unique physical features of the present invention, there are several ergonomically interesting applications that were not previously possible. Presently a Mouse or Trackball is not physically convenient to use on portable computers. The present invention provides a very convenient and easy-to-use cursor position solution that replaces those devices.

In mouse-type applications, the sensor of the present invention may be placed in a convenient location, e.g., below the "space bar" key in a portable computer. When placed in this location, the thumb of the user may be used as the position pointer on the sensor to control the cursor position on the computer screen. The cursor may then be moved without the need for the user's fingers to leave the keyboard. Ergonomically, this is similar to the concept of the Macintosh Power Book with it's trackball, however the present invention provides a significant advantage in size over the track ball. Extensions of this basic idea are possible in that two sensors could be placed below the "space bar" key for even more feature control.

The computer display with it's cursor feedback is one small example of a very general area of application where a display could be a field of lights or LED's, a LCD display, or a CRT. Examples include touch controls on laboratory equipment where present equipment uses a knob/button/touch screen combination. Because of the articulating ability of this interface, one or more of those inputs could be combined into one of our inputs.

Consumer Electronic Equipment (stereos, graphic equalizers, mixers) applications often utilize significant front panel surface area for slide potentiometers because variable control is needed. The present invention can provide such control in one small touch pad location. As Electronic Home Systems become more common, denser and more powerful human interface is needed. The sensor technology of the present invention permits a very dense control panel. Hand

Held TV/VCR/Stereo controls could be ergonomically formed and allow for more powerful features if this sensor technology is used.

The sensor of the present invention can be conformed to any surface and can be made to detect multiple touching points, making possible a more powerful joystick. The unique pressure detection ability of the sensor technology of the present invention is also key to this application. Computer games, "remote" controls (hobby electronics, planes), and machine tool controls are a few examples of applications which would benefit from the sensor technology of the present invention.

Musical keyboards (synthesizers, electric pianos) require velocity sensitive keys which can be provided by the pressure sensing ability of this sensor. There are also pitch bending controls, and other slide switches that could be replaced with this technology. An even more unique application comprises a musical instrument that creates notes as a function of the position and pressure of the hands and fingers in a very articulate 3-d interface.

The sensor technology of the present invention can best detect any conducting material pressing against it. By adding a conductive foam material on top of the sensor the sensor of the present invention may also indirectly detect pressure from any object being handled, regardless of its electrical conductivity.

Because of the amount of information available from this sensor it will serve very well as an input device to virtual reality machines. It is easy to envision a construction that allows position-monitoring in three dimensions and some degree of response (pressure) to actions.

While embodiments and applications of this invention have been shown and described, it would be apparent to those skilled in the art that many more modifications than mentioned above are possible without departing from the inventive concepts herein. The invention, therefore, is not to be restricted except in the spirit of the appended claims.

What is claimed is:

1. An object proximity sensor, including:

a touch-sensitive transducer disposed on a substrate, said touch sensitive transducer including a matrix of row conductive lines disposed in a first direction and column conductive lines disposed in a second direction generally perpendicular to said first direction, said row conductive lines and said column conductive lines insulated from one another, and an insulating layer disposed over said row conductive lines and said column conductive lines, said insulating layer forming a touch surface, said insulating layer having a thickness selected to promote capacitive coupling between a finger placed proximate to the touch surface of said insulating layer and said row conductive lines and said column conductive lines;

means for simultaneously injecting electrical charge onto each of said row conductive lines, and for sensing a row-sense voltage created on each of said row conductive lines by said electrical charge onto each of said row conductive lines;

means for simultaneously injecting electrical charge onto each of said column conductive lines, and for sensing a column-sense voltage created on each of said column conductive lines by said electrical charge onto each of said column conductive lines; and

means for producing a set of object-sensed electrical signals related to said row-sense voltage and said column-sense voltage; and

means for processing said set of row electrical signals and said set of column electrical signals to create a proximity electrical signal proportional to the proximity of said object to said touch surface.

2. The object proximity sensor of claim **1** wherein said row conductive lines are disposed on a first face of said substrate and said column conductive lines are disposed on a second face of said substrate opposite said first face, said touch sensitive transducer further including a plurality of spaced-apart conductive sensor pads disposed in a row and column matrix pattern on said substrate, each of said sensor pads connected to a corresponding one of said row conductive lines or column conductive lines.

3. The object proximity sensor of claim **1**, further including:

means for sensing a minimum no-object proximate capacitance from among said row conductive lines, for sensing a minimum no-object proximate capacitance from among said column conductive lines, for producing a set of minimum background electrical signals related thereto; and

means for subtracting said set of minimum background electrical signals from said set of object-sensed electrical signals.

4. The object proximity sensor of claim **1**, further including:

means for producing a set of average no-object-proximate electrical signals related to an average no-object-proximate capacitance from among said row conductive lines and an average no-object-proximate capacitance from among said column conductive lines; and

means for subtracting said set of average no-object-proximate electrical signals from said set of object-sensed electrical signals.

5. The object proximity sensor of claim **1** wherein the ones of said sensor pads associated with odd numbered ones of said row conductive lines are disposed along a first set of column positions and the ones of said sensor pads associated with even numbered ones of said row conductive lines are disposed at a second set of column positions offset from said first set of column positions wherein said sensor pads form a closely packed repetitive pattern wherein each pad is not in contact with adjoining pads.

6. A method for providing an electrical signal representative of the position of an object in a two dimensional sensing plane and of the proximity of the object to the two dimensional sensing plane, including the steps of:

providing a sensing plane including a matrix of conductors arranged as a plurality of rows and columns of spaced apart row conductive lines and column conductive lines, said sensing plane having an inherent capacitance on the various ones of said row conductive lines and column conductive lines, said capacitance varying with the proximity of an object to said row and column conductors;

simultaneously generating from among said row conductive lines a first electrical signal proportional to a no-object-proximate value of said capacitance when no object is proximate to said sensing plane from among said row conductive lines;

simultaneously generating from among said row conductive lines a corresponding second electrical signal proportional to the value of said capacitance when an object is located proximate to but not necessarily in contact with said sensing plane;

subtracting each of said corresponding first electrical signals from said second electrical signals to produce a set of row electrical signals;

simultaneously generating from among said column conductive lines a third electrical signal proportional to the no-object-proximate value of said capacitance when no object is proximate to said sensing plane from among said column conductive lines;

simultaneously generating for each conductor in the column dimensions a corresponding fourth electrical signal proportional to the value of said capacitance when an object is located proximate to but not necessarily in contact with said sensing plane;

subtracting each of said corresponding third electrical signals from said fourth electrical signals to produce a set of column electrical signals;

encoding said set of row electrical signals and said set of column electrical signals into electrical signals indicating the position of said object in said row dimension and said column dimension; and

processing said set of row electrical signals and said set of column electrical signals to create proximity electrical signal proportional to proximity of said object to said sensing plane.

7. The method of claim **6** wherein the step of encoding said set of row electrical signals and said set of column electrical signals into electrical signals indicating the position of said object in said row dimension and said column dimension comprises separately encoding said set of row electrical signals into a first digital signal and encoding said set of column electrical signals into a second digital signal.

8. The method of claim **6** wherein the step of encoding said set of row electrical signals and said set of column electrical signals into electrical signals indicating the position of said object in said row dimension and said column dimension comprises separately encoding said set of row electrical signals into a first digital signal and encoding said set of column electrical signals into a second digital signal, and further including the step of encoding said proximity electrical signal into a third digital signal.

9. The method of claim **6** further including the step of providing a signal when said row electrical signal for any of said row or column electrical signal exceeds a threshold value.

10. The method of claim **6**, wherein said first and third electrical signals are proportional to the minimum no-object-proximate value of said capacitance from among said row conductive lines and column conductive lines.

11. The method of claim **6**, wherein said first and third electrical signals are proportional to the average no-object-proximate value of said capacitance from among said row conductive lines and column conductive lines.

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UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,495,077
DATED : February 27, 1996
INVENTOR(S) : Robert J. Miller, Stephen Bisset, Timothy P. Allen, Günter Steinbach

It is certified that error appears in the above-indentified patent and that said Letters Patent is hereby corrected as shown below:

Title page, item [*] "Notice", replace "Dec. 20, 2011" with --August 31, 2013--.

Column 1, line 38, replace "doe" with --does--.

Column 2, line 3, after "are" delete "a".

Column 5, line 65, replace "FIG. 1 a" with --FIG. 1a--.

Column 7, line 22, replace "piez-oelectric" with --piezo-electric--.

Column 7, line 30, replace "a" with --an--.

Column 8, line 24, after "connected" insert --to--.

Column 9, line 10, after "array" insert --10.--.

Column 9, line 22, replace "Integrated" with --integrated--.

Column 9, line 25, replace the first occurrence of "Y" with --X--.

Column 10, line 62, replace "(ND)" with --(A/D)--.

Column 11, line 18, replace "sample hold" with --sample/hold--.

Column 11, line 35, replace "VTHMAX" with --V_{THMAX}--.

Column 12, line 26, replace "shoaled" with --shorted--.

Column 13, line 32, replace "a" with --an--.

Column 14, line 10, replace "0 v" with --0v--.

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It is certified that error appears in the above-indentified patent and that said Letters Patent is hereby corrected as shown below:

Column 17, line 28, replace "VTHMAX" with --V_{THMAX}--.

Column 17, line 47, replace "VLBIAS" with --V_{LBIAS}--.

Column 18, line 36, replace "encode" with --encoder--.

Column 19, line 32, replace "200-6" with --220-6--.

Column 19, line 51, replace "(ND)" with --(A/D)--.

Signed and Sealed this

Twenty-second Day of October, 1996

Attest:

BRUCE LEHMAN

Attesting Officer

Commissioner of Patents and Trademarks