Thesis (1984). The best they can do is count fingertips which happen to lie in a straight row, and even that will fail if a thumb or palm is introduced in the same column as a fingertip.

**[0017]** In U.S. Pat. Nos. 5,565,658 and 5,305,017, Gerpheide et al. measure the mutual capacitance between row and column electrodes by driving one set of electrodes at some clock frequency and sensing how much of that frequency is coupled onto a second electrode set. Such synchronous measurements are very prone to noise at the driving frequency, so to increase signal-to-noise ratio they form virtual electrodes comprised of multiple rows or multiple columns, instead of a single row and column, and scan through electrode combinations until the various mutual capacitances are nulled or balanced. The coupled signal increases with the product of the rows and columns in each virtual electrodes, but the noise only increases with the sum, giving a net gain in signal-to-noise ratio for virtual electrodes consisting of more than two rows and two columns. However, to uniquely distinguish multiple objects, virtual electrode sizes would have to be reduced so the intersection of the row and column virtual electrodes would be no larger than a finger tip, i.e. about two rows and two columns, which will degrade the signal-to-noise ratio. Also, the signal-to-noise ratio drops as row and column lengths increase to cover a large area.

**[0018]** In U.S. Pat. Nos. 5,543,591, 5,543,590, and 5,495,077, Gillespie et al measure the electrode-finger self-capacitance for row and column electrodes independently. Total electrode capacitance is estimated by measuring the electrode voltage change caused by injecting or removing a known amount of charge in a known time. All electrodes can be measured simultaneously if each electrode has its own drive/sense circuit. The centroid calculated from all row and column electrode signals establishes an interpolated vertical and horizontal position for a single object. This method may in general have higher signal-to-noise ratio than synchronous methods, but the signal-to-noise ratio is still degraded as row and column lengths increase. Signal-to-noise ratio is especially important for accurately locating objects which are floating a few millimeters above the pad. Though this method can detect such objects, it tends to report their position as being near the middle of the pad, or simply does not detect floating objects near the edges.

**[0019]** Thus there exists a need in the art for a capacitance-sensing apparatus which does not suffer from poor signal-to-noise ratio and the multiple finger indistinguishability problems of touchpads with long row and column electrodes.

**[0020]** U.S. Pat. No. 5,463,388 to Boie et al. has a capacitive sensing system applicable to either keyboard or mouse input, but does not consider the problem of integrating both types of input simultaneously. Though they mention independent detection of arrayed unit-cell electrodes, their capacitance transduction circuitry appears too complex to be economically reproduced at each electrode. Thus the long lead wires connecting electrodes to remote signal conditioning circuitry can pickup noise and will have significant capacitance compared to the finger-electrode self-capacitance, again limiting signal-to-noise ratio. Also, they do not recognize the importance of independent electrodes for multiple finger tracking, or mention how to track multiple fingers on an independent electrode array.

**[0021]** Lee built an early multi-touch electrode array with 7 mm by 4 mm metal electrodes arranged in 32 rows and 64 columns. The "Fast Multiple-Touch-Sensitive Input Device (FMTSID)" total active area measured 12" by 16", with a 0.075 mm Mylar dielectric to insulate fingers from electrodes. Each electrode had one diode connected to a row charging line and a second diode connected to a column discharging line. Electrode capacitance changes were measured singly or in rectangular groups by raising the voltage on one or more row lines, selectively charging the electrodes in those rows, and then timing the discharge of selected columns to ground through a discharge resistor. Lee's design required only two diodes per electrode, but the principal disadvantage of Lee's design is that the column diode reverse bias capacitances allowed interference between electrodes in the same column.

**[0022]** All of the related capacitance sensing art cited above utilize interpolation between electrodes to achieve high pointing resolution with economical electrode density. Both Boie et al. and Gillespie et al. discuss computation of a centroid from all row and column electrode readings. However, for multiple finger detection, centroid calculation must be carefully limited around local maxima to include only one finger at a time. Lee utilizes a bisective search technique to find local maxima and then interpolates only on the eight nearest neighbor electrodes of each local maximum electrode. This may work fine for small fingertips, but thumb and palm contacts may cover more than nine electrodes. Thus there exists a need in the art for improved means to group exactly those electrodes which are covered by each distinguishable hand contact and to compute a centroid from such potentially irregular groups.

**[0023]** To take maximum advantage of multi-touch surface sensing, complex proximity image processing is necessary to track and identify the parts of the hand contacting the surface at any one time. Compared to passive optical images, proximity images provide clear indications of where the body contacts the surface, uncluttered by luminosity variation and extraneous objects in the background. Thus proximity image filtering and segmentation stages can be simpler and more reliable than in computer vision approaches to free-space hand tracking such as S. Ahmad, "A Usable Real-Time 3D Hand Tracker", *Proceedings of the 28th Asilomar Conference on Signals, Systems, and Computers—Part* 2, vol. 2, IEEE (1994) or Y. Cui and J. Wang, "Hand Segmentation Using Learning-Based Prediction and Verification for Hand Sign Recognition,"*Proceedings of the* 1996 *IEEE Computer Society Conference on Computer Vision and Pattern Recognition,* pp. 88-93 (1996). However, parts of the hand such as intermediate finger joints and the center of the palms do not show up in capacitive proximity images at all if the hand is not flattened on the surface. Without these intermediate linkages between fingertips and palms the overall hand structure can only be guessed at, making hand contact identification very difficult. Hence the optical flow and contour tracking techniques which have been applied to free-space hand sign language recognition as in F. Quek, "Unencumbered Gestural Interaction,"*IEEE Multimedia,* vol. 3, pp. 36-47 (1996), do not address the special challenges of proximity image tracking.

**[0024]** Synaptics Corp. has successfully fabricated their electrode array on flexible mylar film rather than stiff circuit board. This is suitable for conforming to the contours of