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Zaliva

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(54) **SEQUENTIAL CLASSIFICATION RECOGNITION OF GESTURE PRIMITIVES AND WINDOW-BASED PARAMETER SMOOTHING FOR HIGH DIMENSIONAL TOUCHPAD (HDTP) USER INTERFACES**

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Related U.S. Application Data

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(51) **Int. Cl.**
G06F 3/041 (2006.01)

(52) **U.S. Cl.**
USPC **345/173**

(58) **Field of Classification Search**
CPC G06F 3/03; G06F 3/045; G06F 3/0304
USPC 345/156–184
See application file for complete search history.

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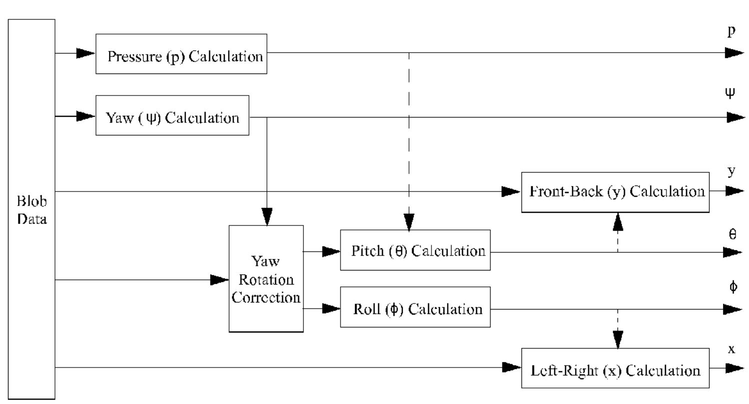
(57) **ABSTRACT**

A method for classification recognition of gestures and gesture primitives in a touch-based user interface. In an implementation the method comprises receiving tactile image data responsive to data generated from user touch of a user touch interface comprising a sensor array. The tactile image data is processed to create a plurality of numerical values responsive to data generated from the user touch interface. These numerical values are applied to a principle component analysis operation to produce a reduced-dimensionality data vector which is applied to a classifier having a plurality of classifier outputs interpretable as probabilities. The classifier outputs provide likelihoods that an execution gesture is from a collection of pre-defined gestures, and a decision test is used to produce a decision output indicating a gesture outcome useful in user interface applications. The arrangement can recognize single finger "6D" actions of roll, pitch, yaw, left-right, forward-back, and variations in applied pressure.

16 Claims, 29 Drawing Sheets



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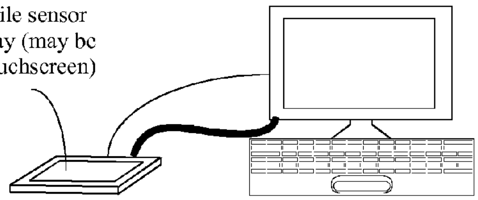


FIG. 1a

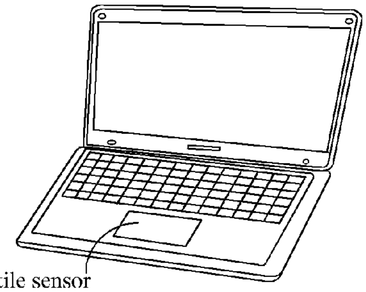


FIG. 1b

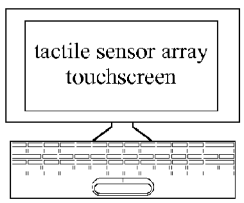


FIG. 1c

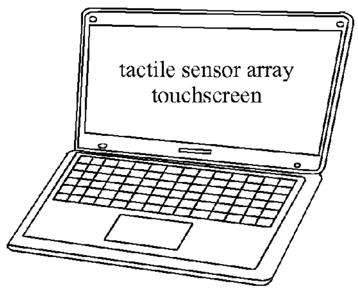


FIG. 1d

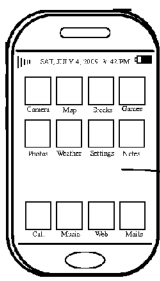


FIG. 1e

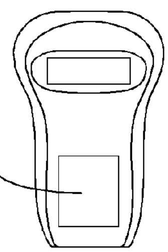


FIG. 1f

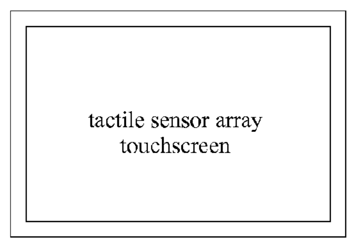


FIG. 1g

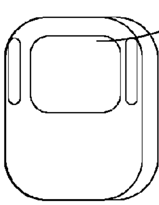


FIG. 2a

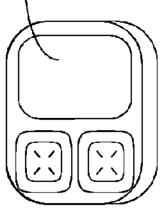


FIG. 2b

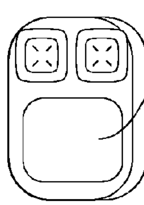


FIG. 2c

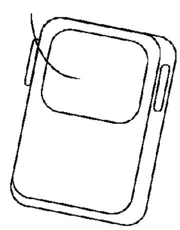


FIG. 2d

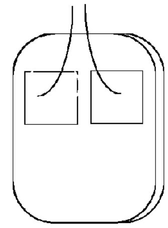


FIG. 2e

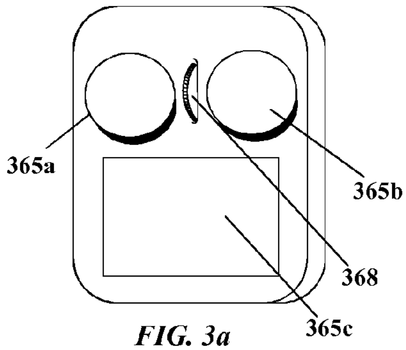


FIG. 3a

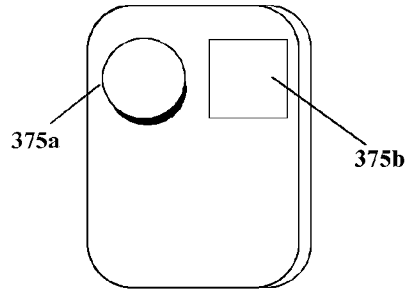


FIG. 3b

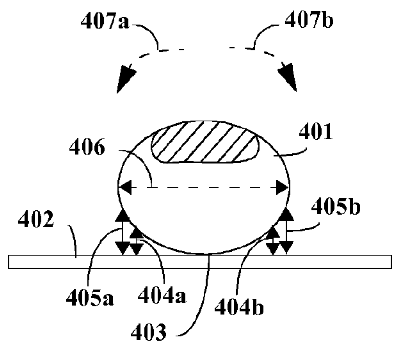


FIG. 4

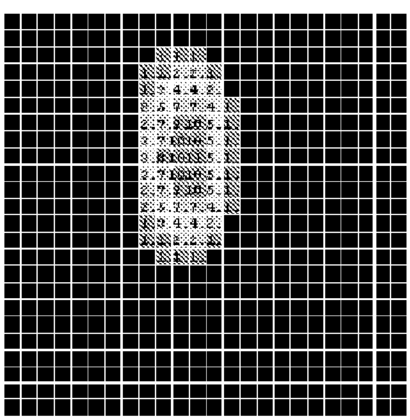


FIG. 5a

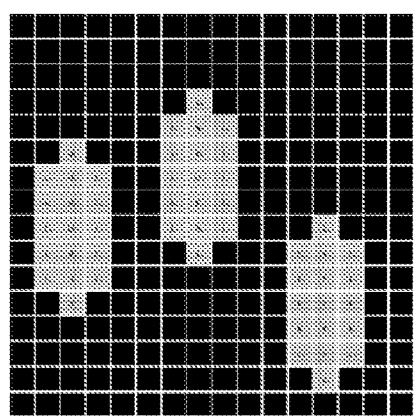


FIG. 5b

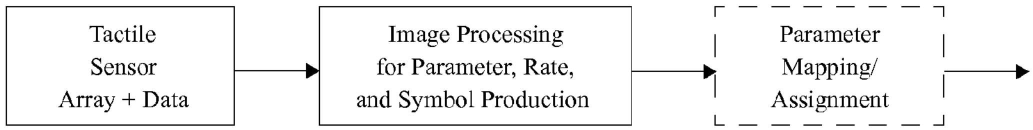


FIG. 6

— PRIOR ART —

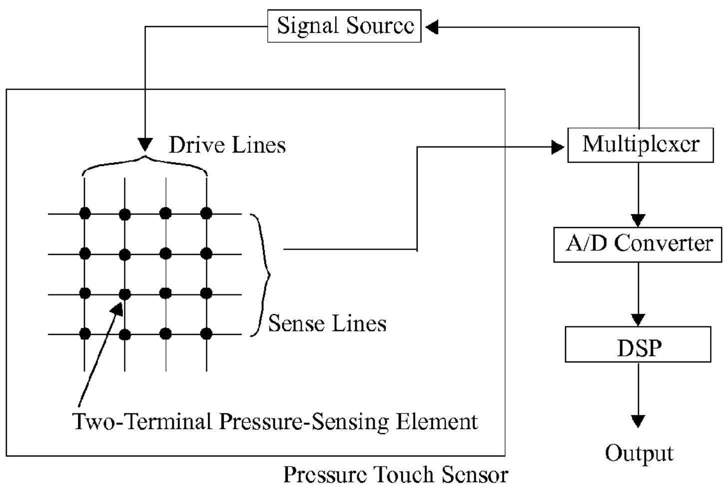


FIG. 7

— PRIOR ART —

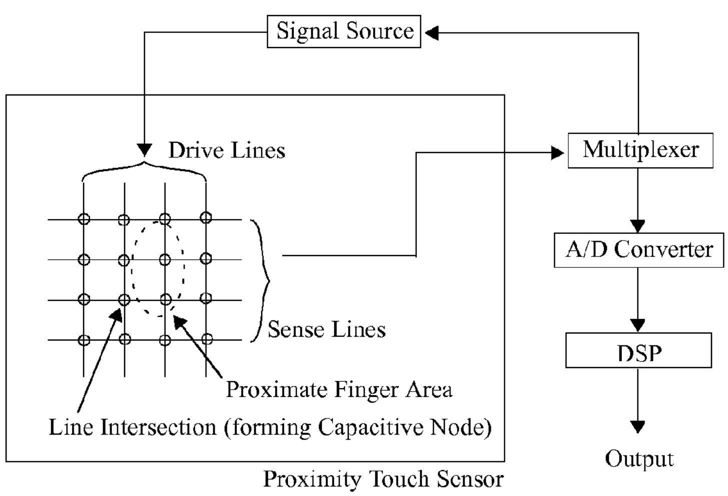


FIG. 8

— PRIOR ART —

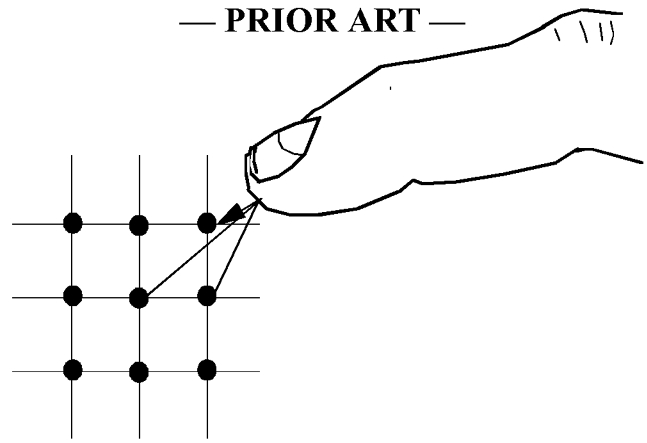


FIG. 9

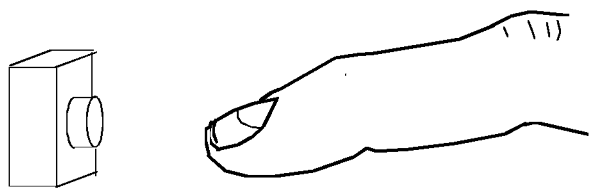


FIG. 10a

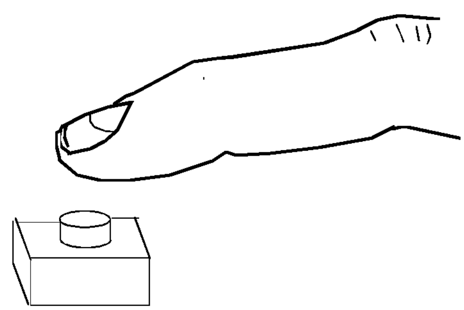


FIG. 10b

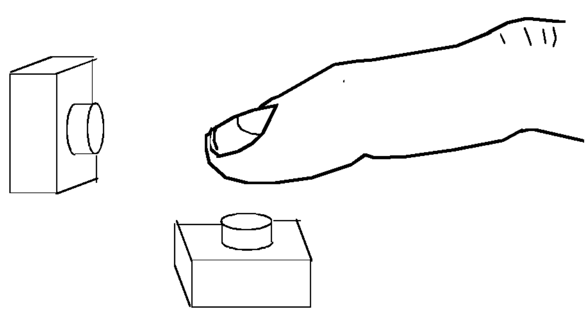


FIG. 10c

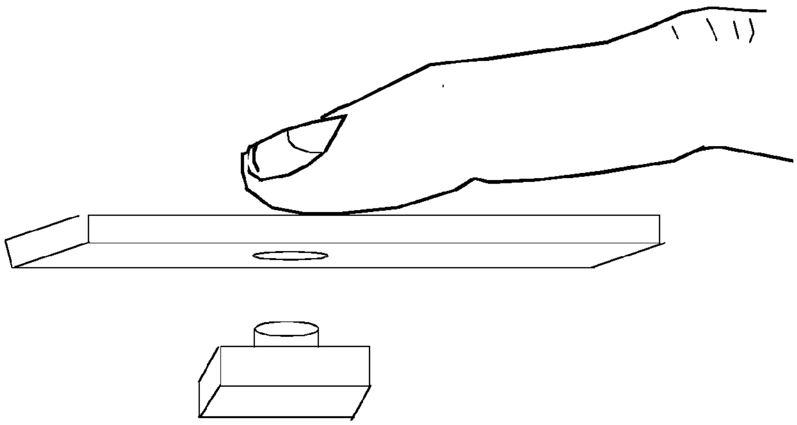


FIG. 11

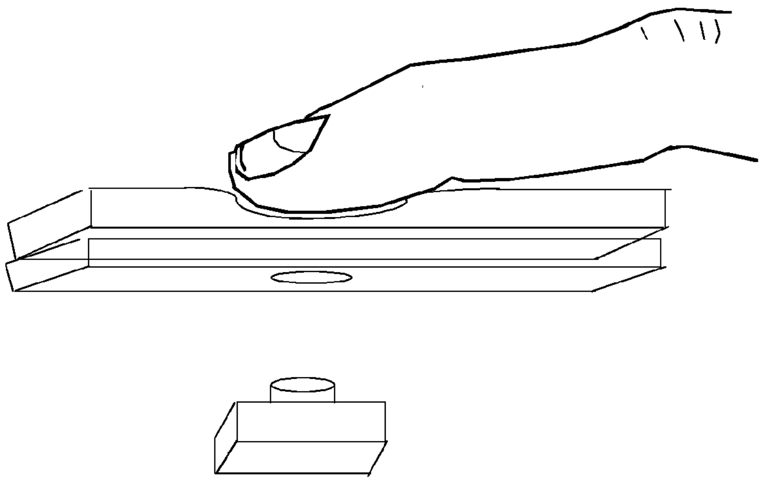


FIG. 12a

— PRIOR ART —

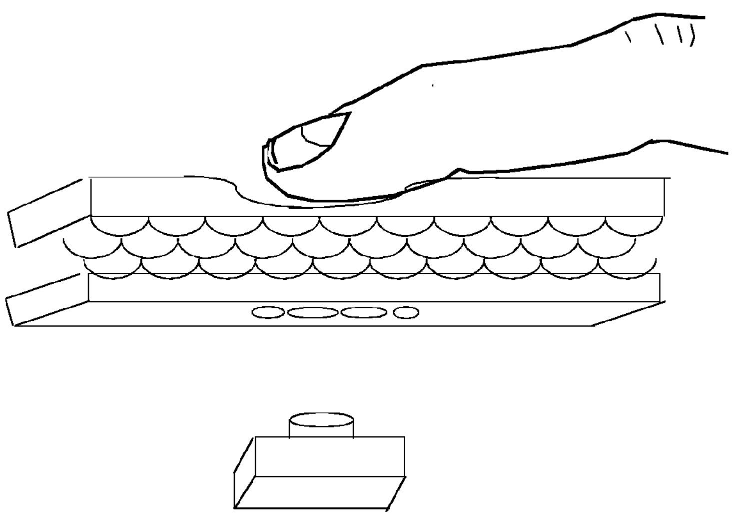


FIG. 12b

— PRIOR ART —

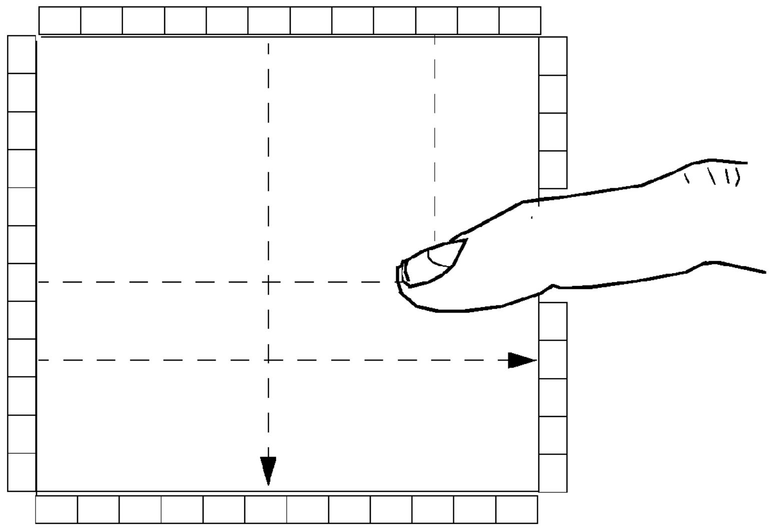


FIG. 13

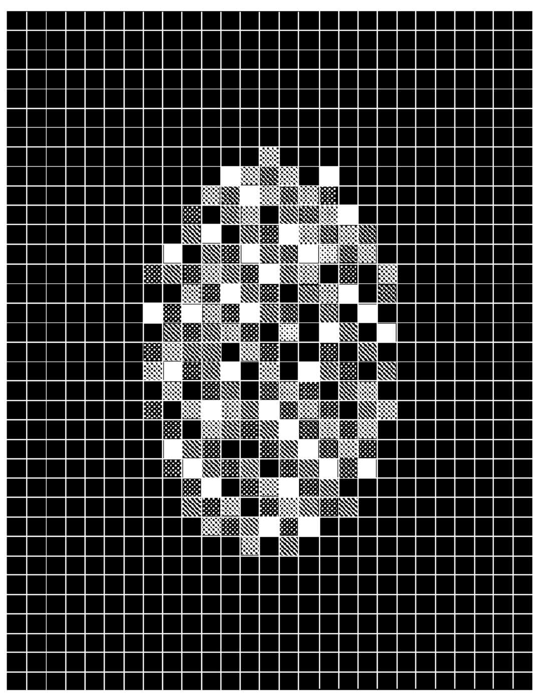


FIG. 14

— PRIOR ART —

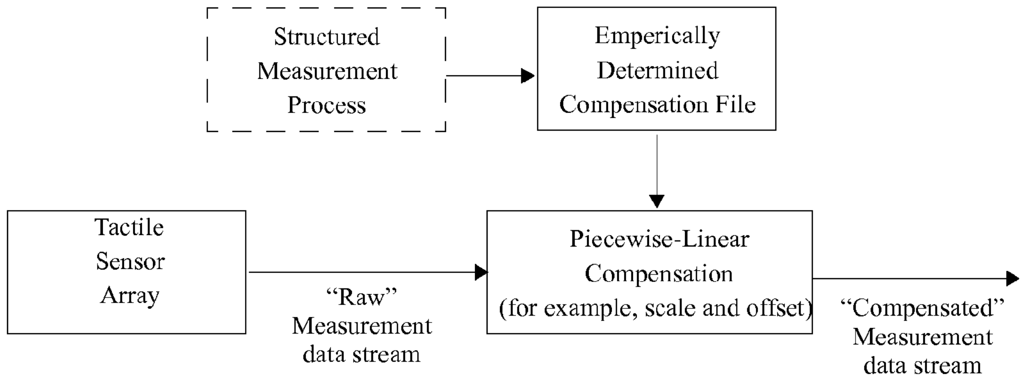


FIG. 15

— PRIOR ART —

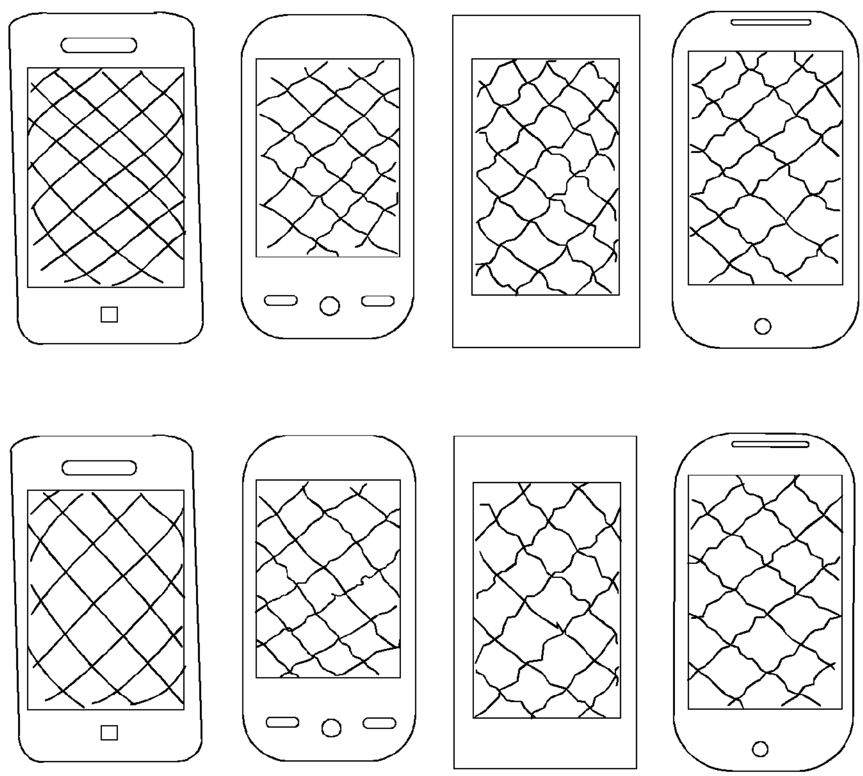


FIG. 16

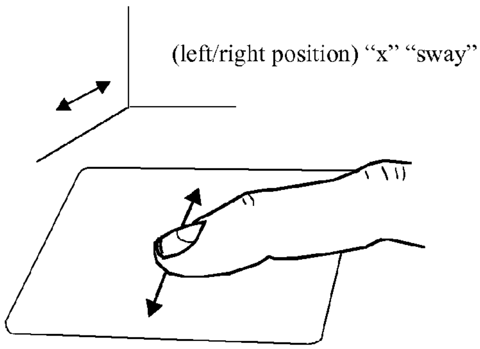


FIG. 17a

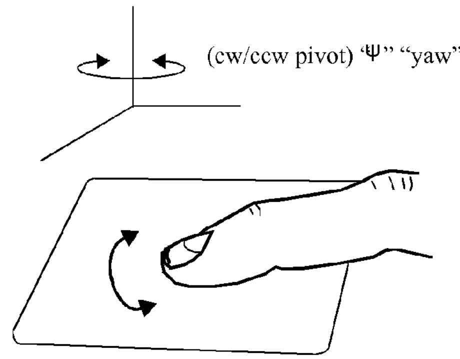


FIG. 17d

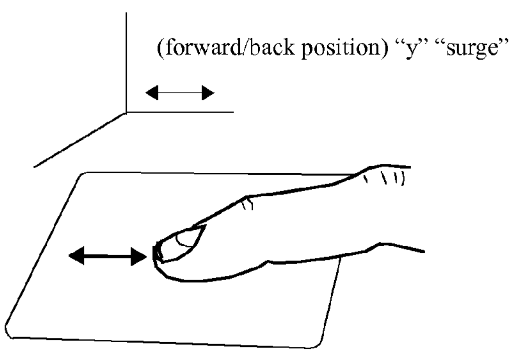


FIG. 17b

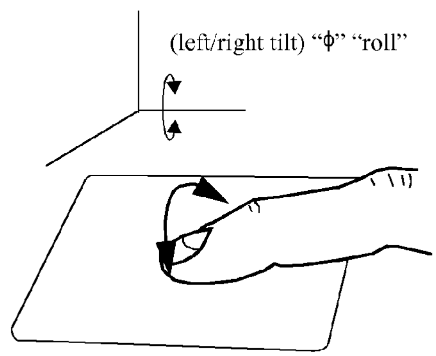


FIG. 17e

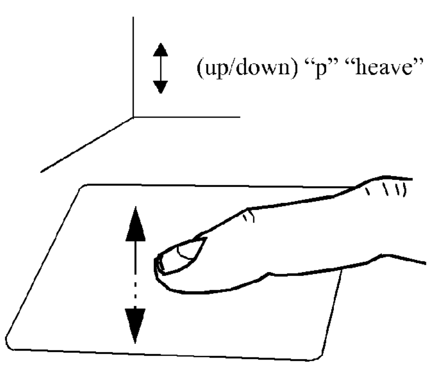


FIG. 17c

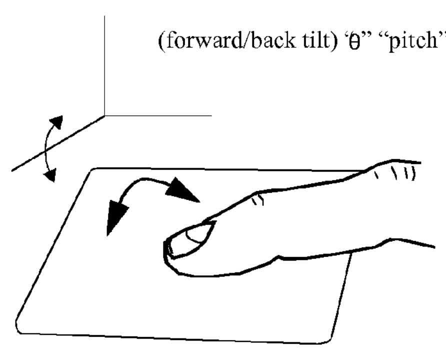


FIG. 17f

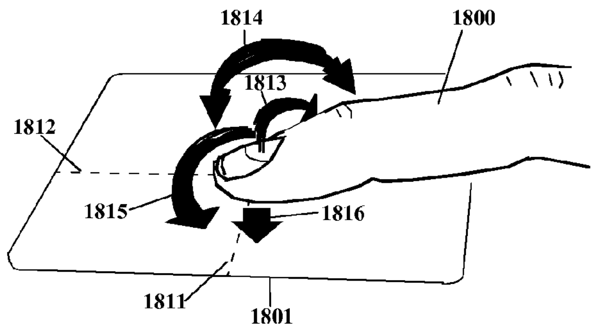

1814
1800
1813
1812
1815
1816
1811
1801

FIG. 18

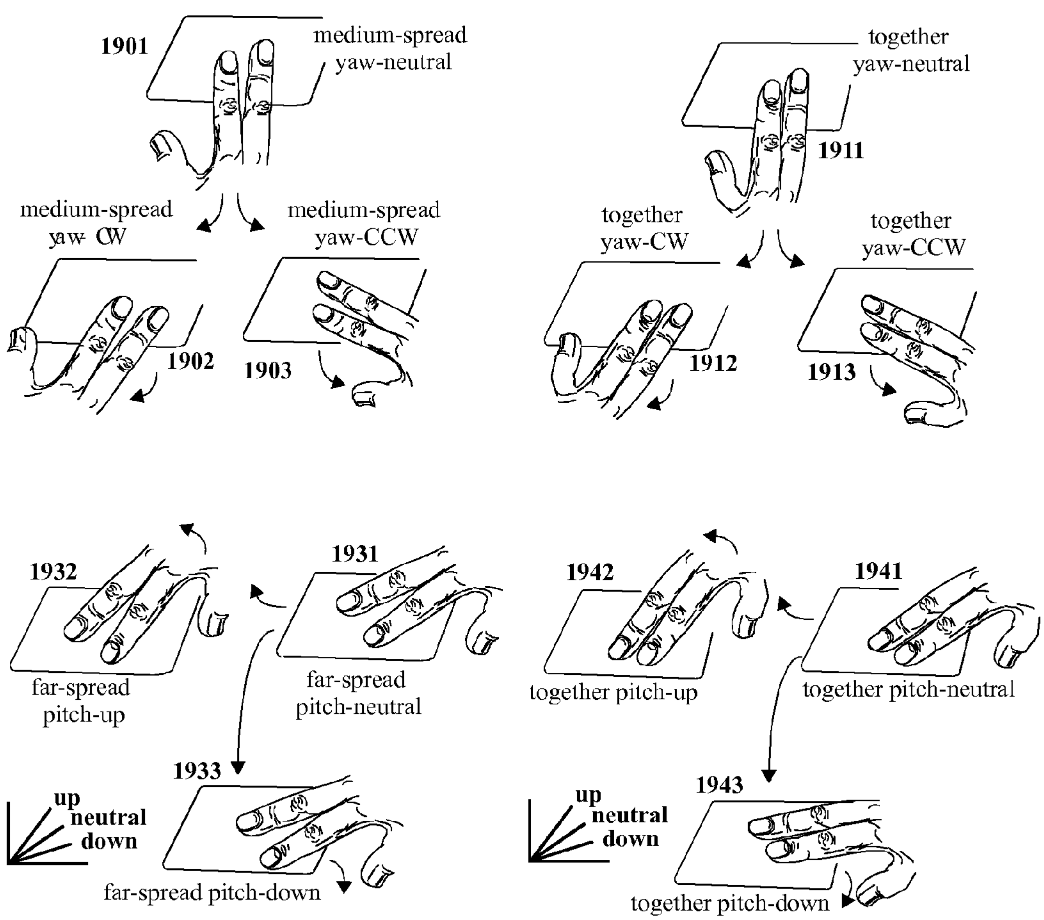

1901
medium-spread
yaw-neutral
medium-spread
yaw-CW
medium-spread
yaw-CCW
1902
1903
together
yaw-neutral
1911
together
yaw-CW
together
yaw-CCW
1912
1913
1932
1931
far-spread
pitch-up
far-spread
pitch-neutral
1933
up
neutral
down
far-spread pitch-down
1942
1941
together pitch-up
together pitch-neutral
1943
up
neutral
down
together pitch-down

FIG. 19

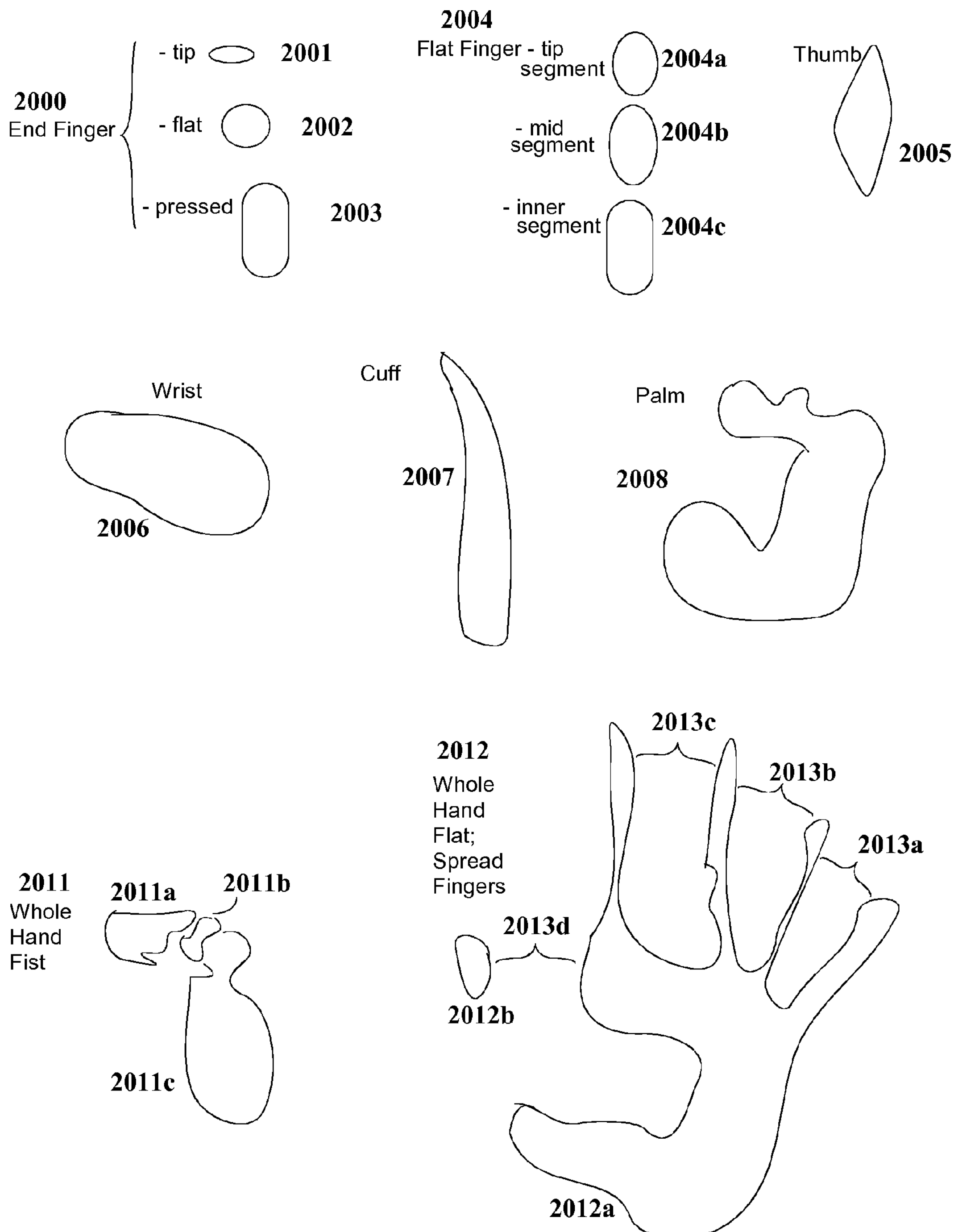
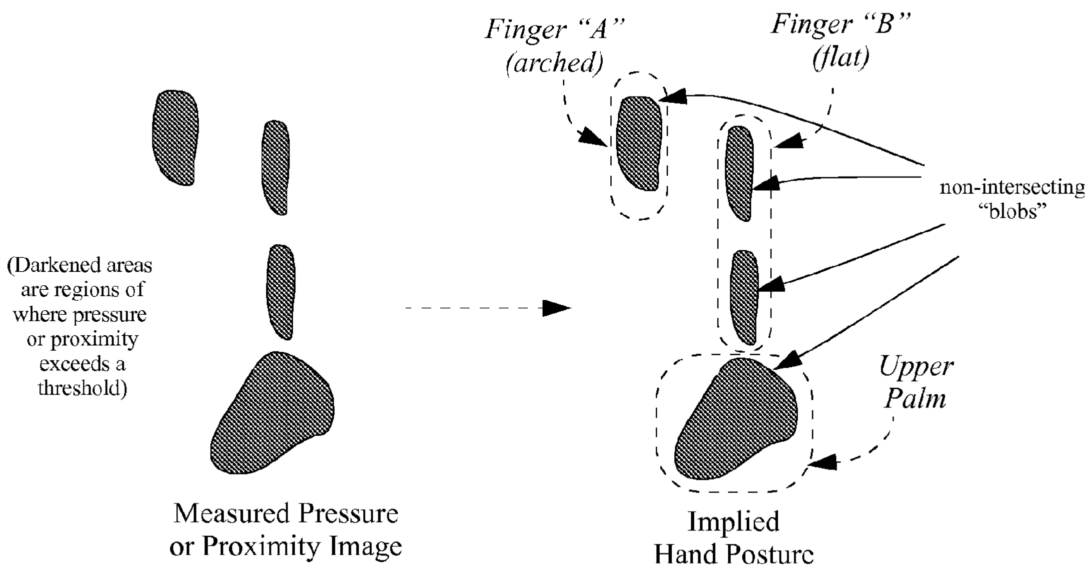

2000
End Finger
- tip
2001
- flat
2002
- pressed
2003
2004
Flat Finger - tip segment
2004a
- mid segment
2004b
- inner segment
2004c
Thumb
2005
Wrist
2006
Cuff
2007
Palm
2008
2011
Whole Hand Fist
2011a
2011b
2011c
2012
Whole Hand Flat; Spread Fingers
2013c
2013b
2013a
2013d
2012b
2012a

FIG. 20



Finger "A"
(arched)
Finger "B"
(flat)
non-intersecting
"blobs"
(Darkened areas
are regions of
where pressure
or proximity
exceeds a
threshold)
Upper
Palm
Measured Pressure
or Proximity Image
Implied
Hand Posture

FIG. 21

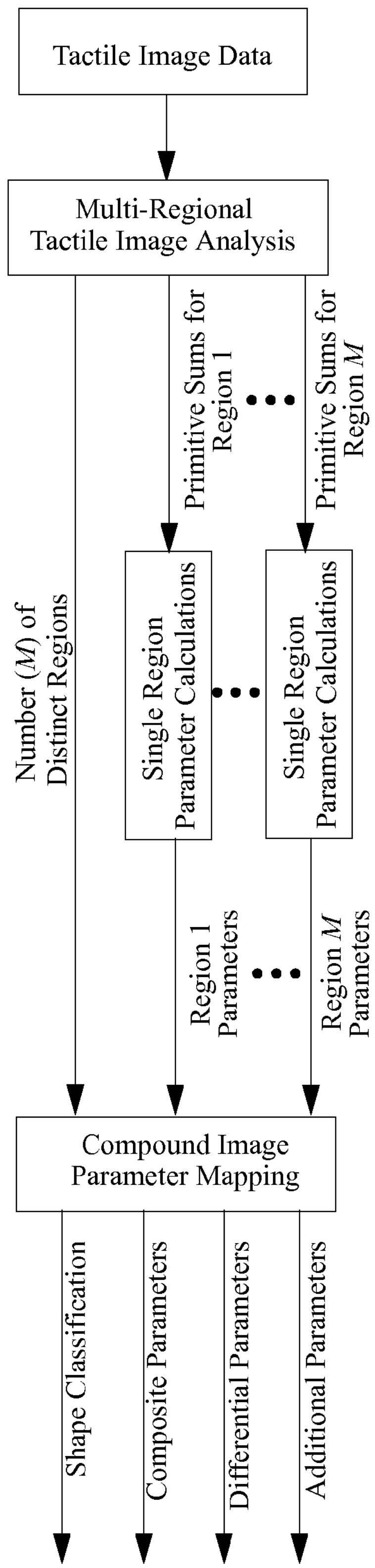


FIG. 22a

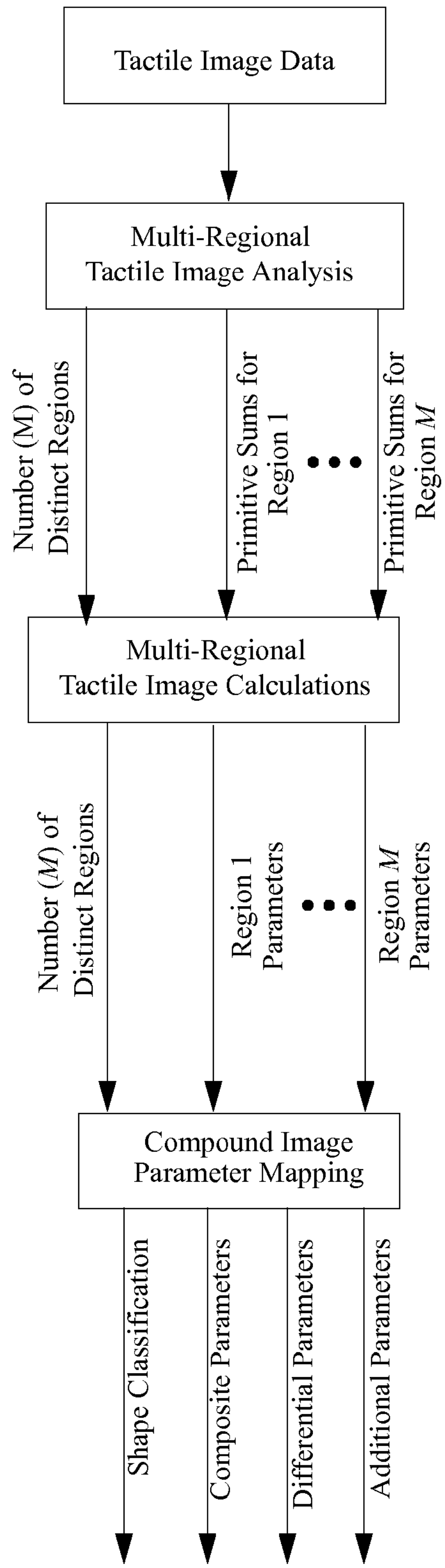


FIG. 22b

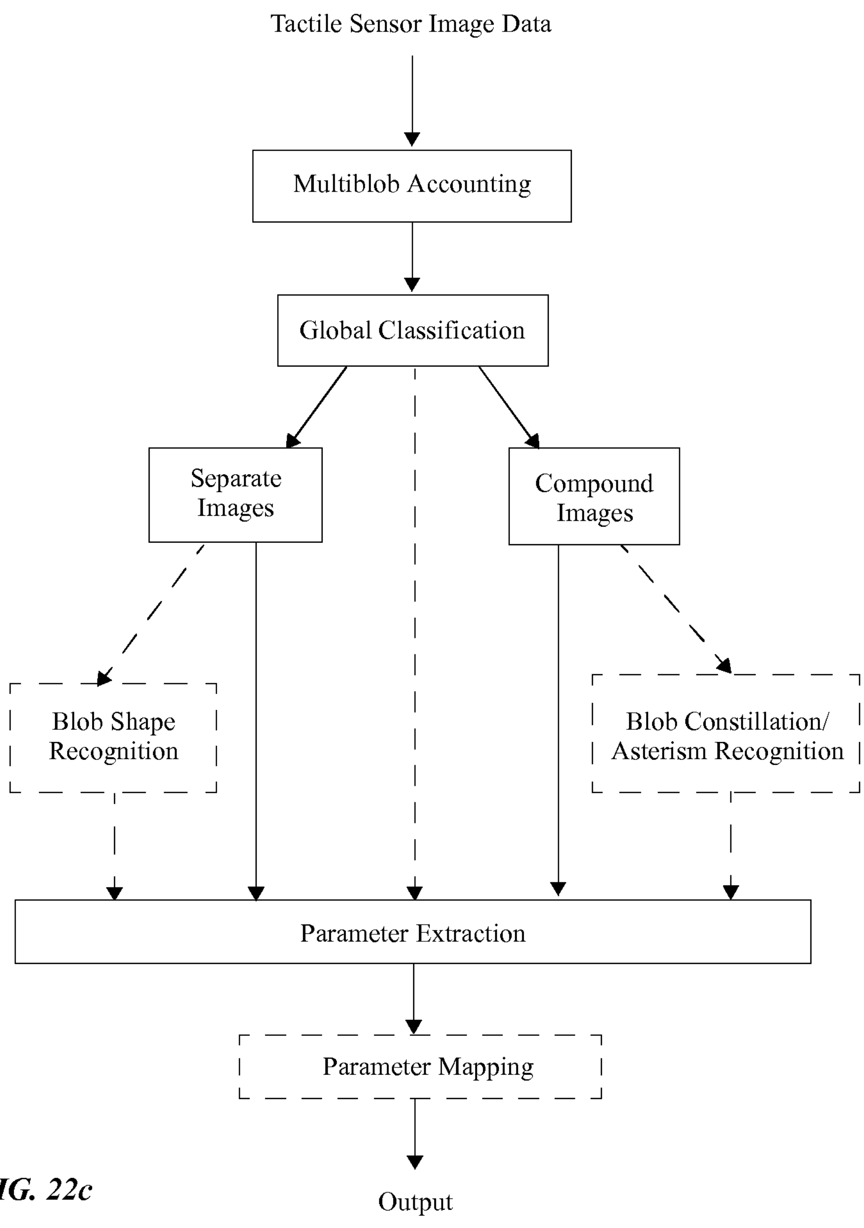

Tactile Sensor Image Data
Multiblob Accounting
Global Classification
Separate Images
Compound Images
Blob Shape Recognition
Blob Constillation/ Asterism Recognition
Parameter Extraction
Parameter Mapping
Output

FIG. 22c

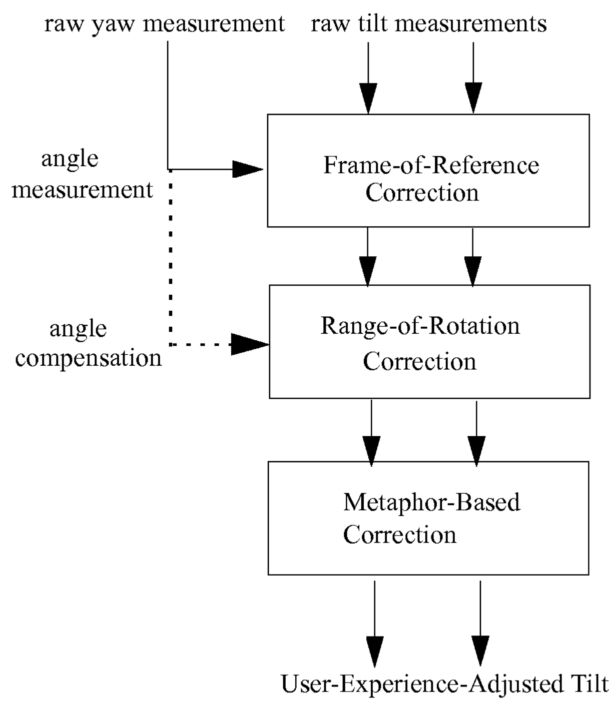

raw yaw measurement
raw tilt measurements
angle measurement
Frame-of-Reference Correction
angle compensation
Range-of-Rotation Correction
Metaphor-Based Correction
User-Experience-Adjusted Tilt

FIG. 23

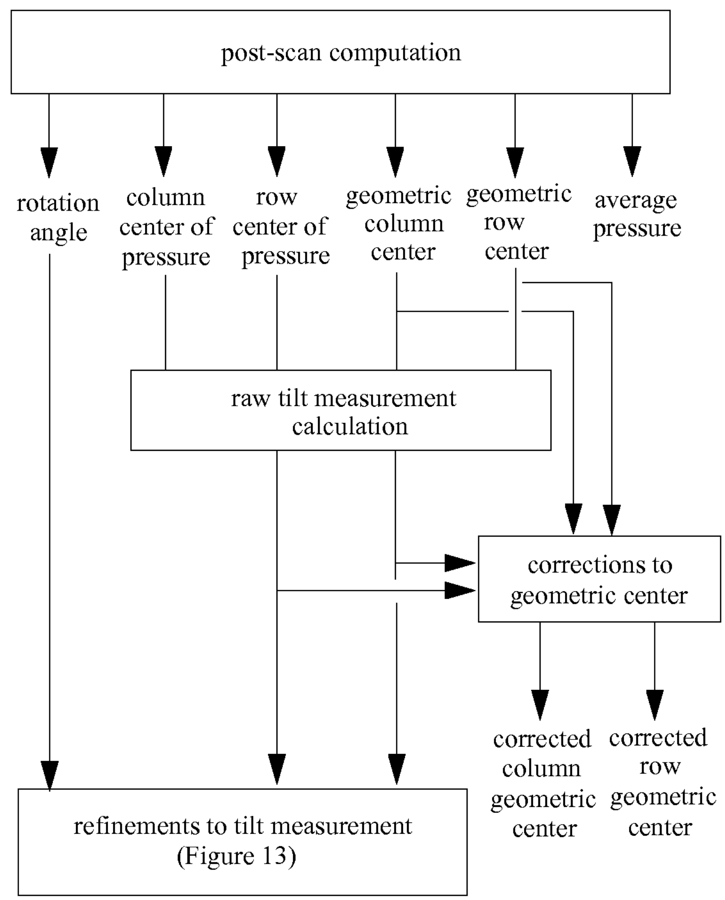


FIG. 24a

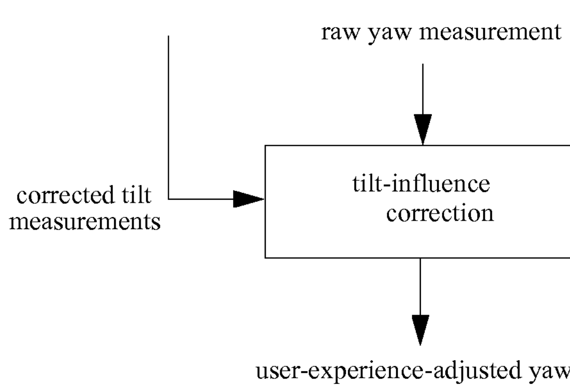
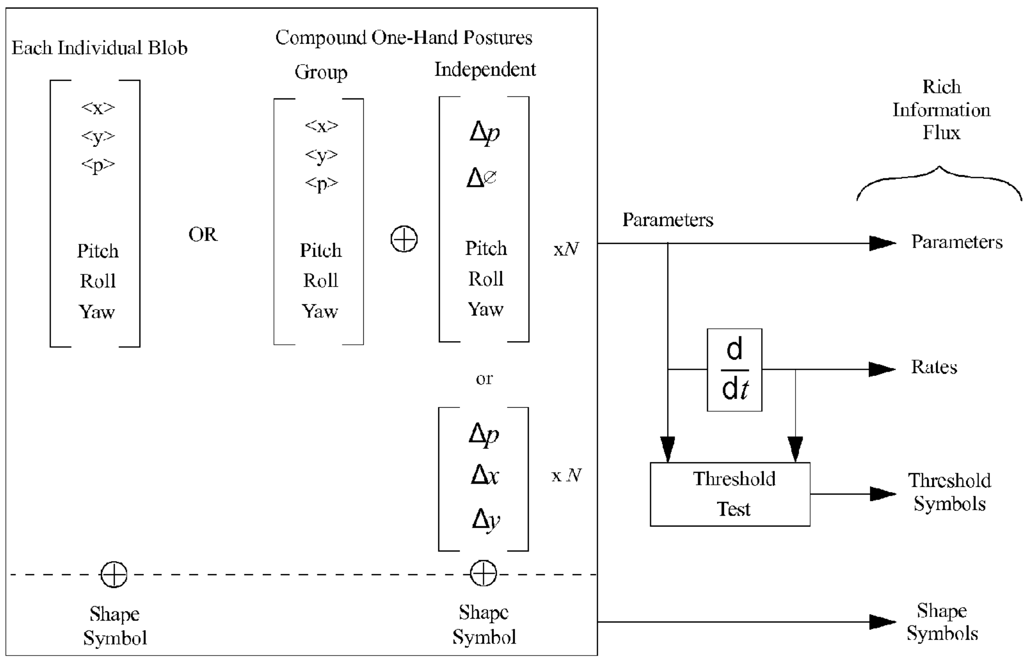
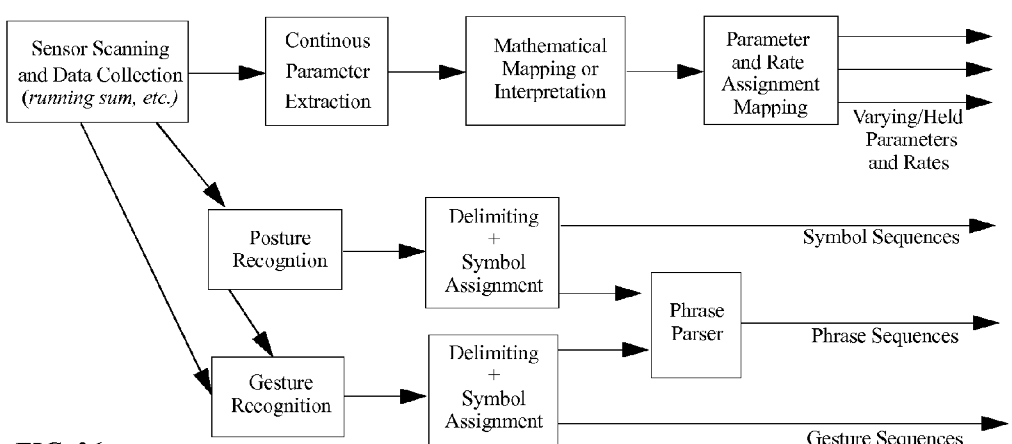


FIG. 24b



Each Individual Blob
<x>
<y>
<p>
Pitch
Roll
Yaw
OR
Compound One-Hand Postures
Group
<x>
<y>
<p>
Pitch
Roll
Yaw
Independent
Δp
Δ∅
Pitch
Roll
Yaw
xN
or
Δp
Δx
Δy
x N
Shape Symbol
Shape Symbol
Parameters
d/dt
Threshold Test
Rich Information Flux
Parameters
Rates
Threshold Symbols
Shape Symbols

FIG. 25



Sensor Scanning and Data Collection (running sum, etc.)
Continous Parameter Extraction
Mathematical Mapping or Interpretation
Parameter and Rate Assignment Mapping
Varying/Held Parameters and Rates
Posture Recognition
Delimiting + Symbol Assignment
Symbol Sequences
Phrase Parser
Phrase Sequences
Gesture Recognition
Delimiting + Symbol Assignment
Gesture Sequences

FIG. 26

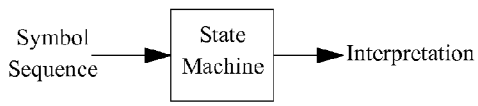


FIG. 27a

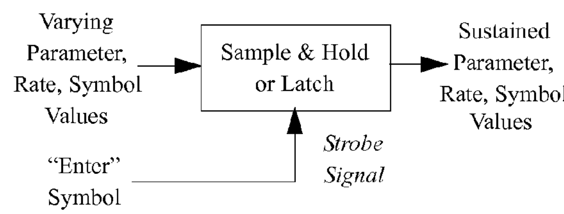


FIG. 27b

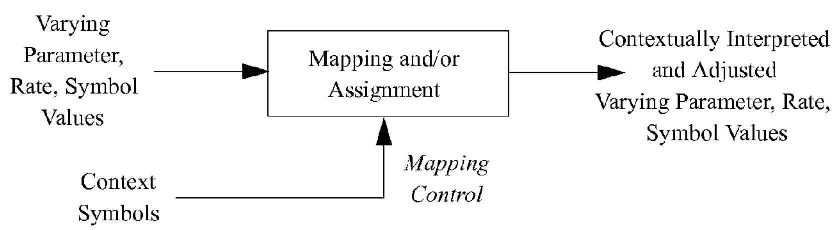


FIG. 27c

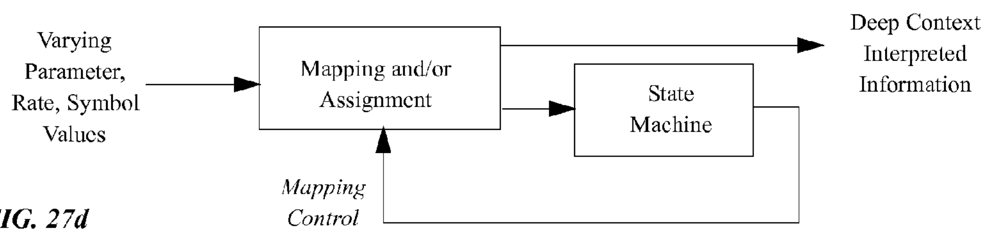


FIG. 27d

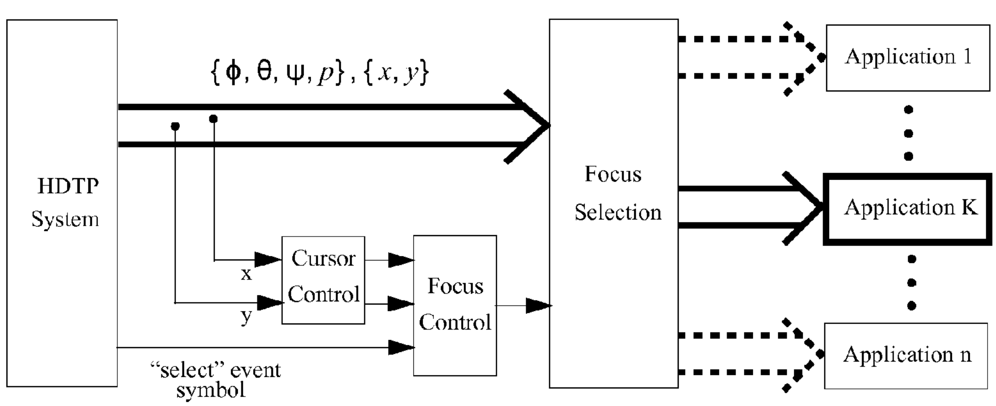


FIG. 28

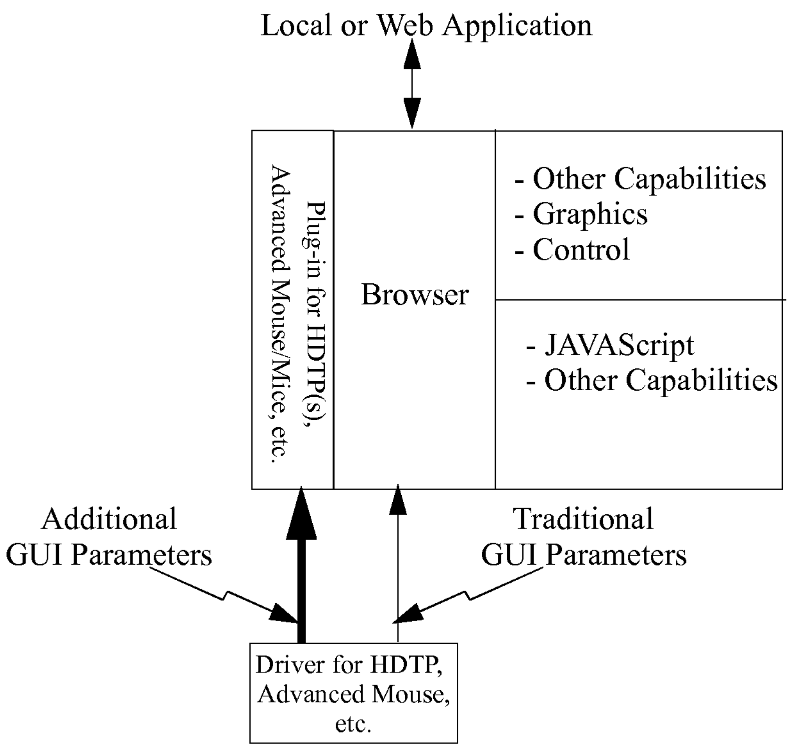


FIG. 29a

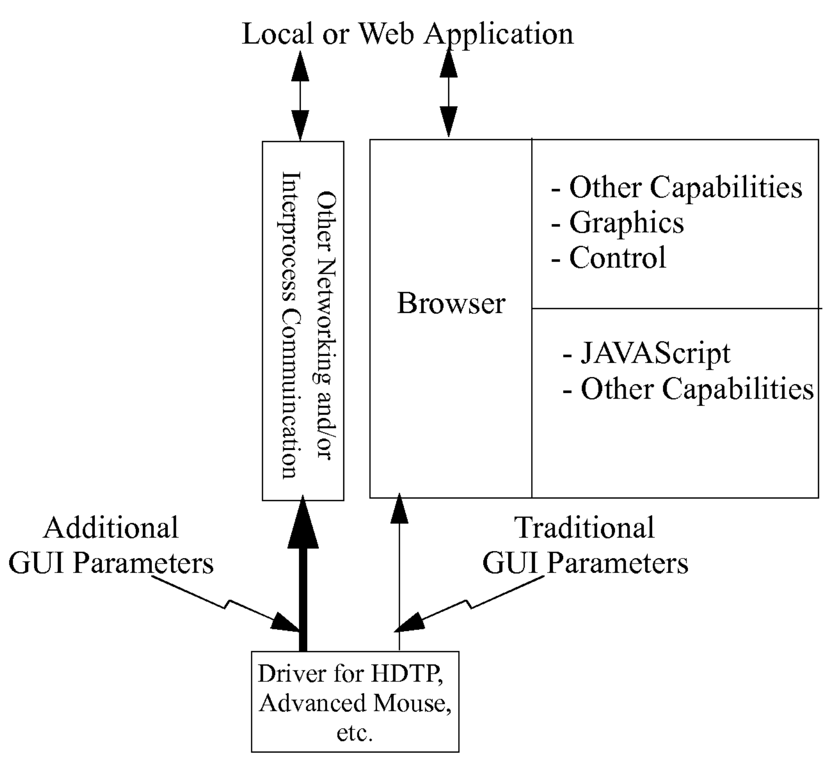


FIG. 29b

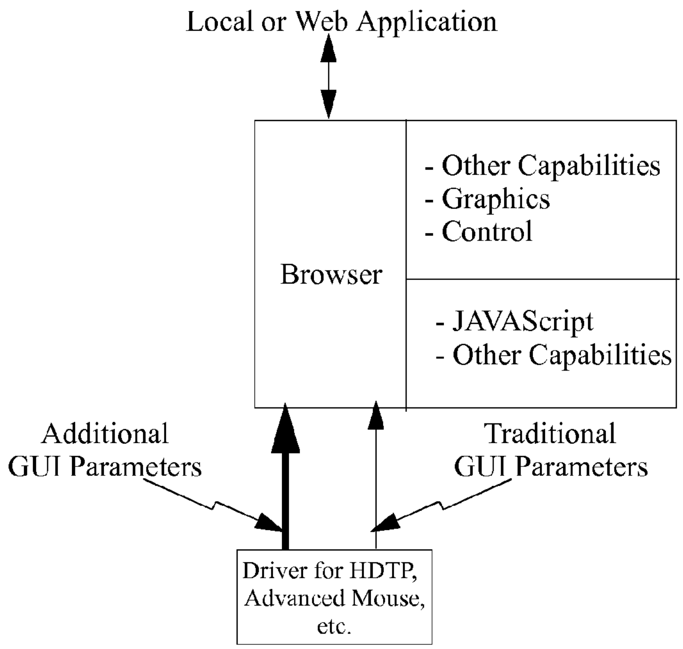


FIG. 29c

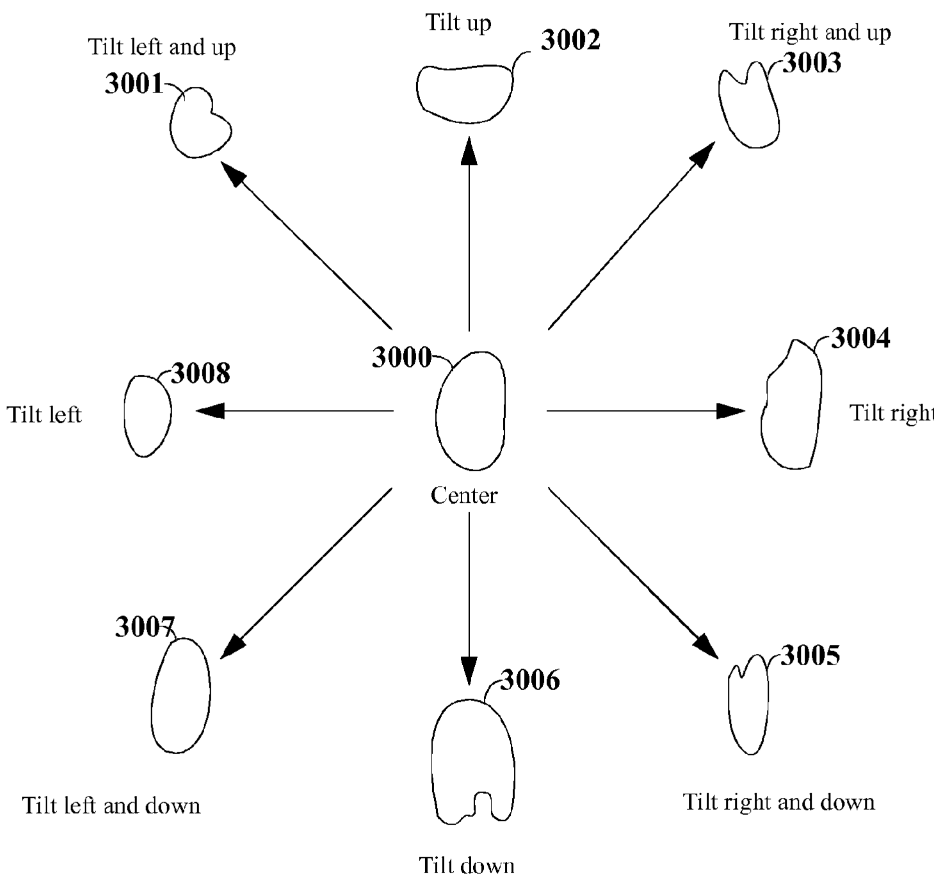


FIG. 30a

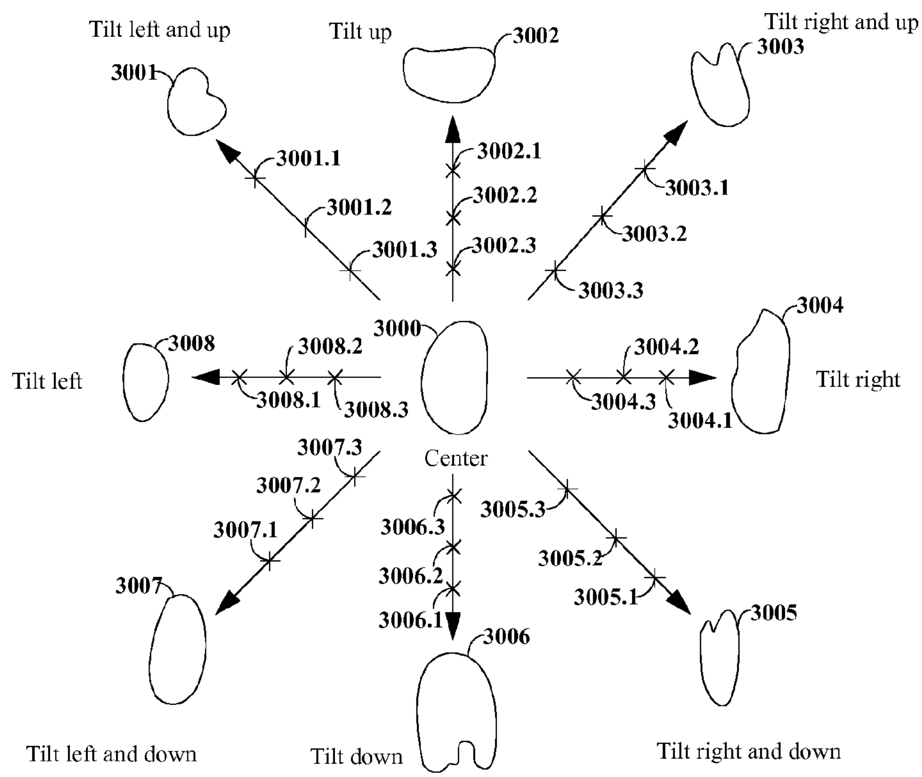


FIG. 30b

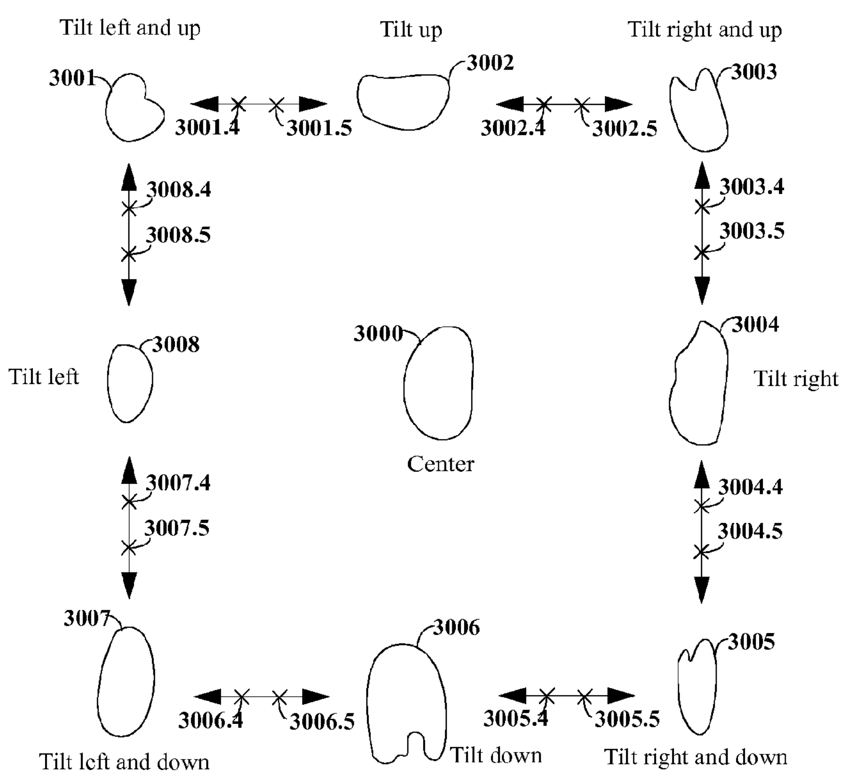


FIG. 30c

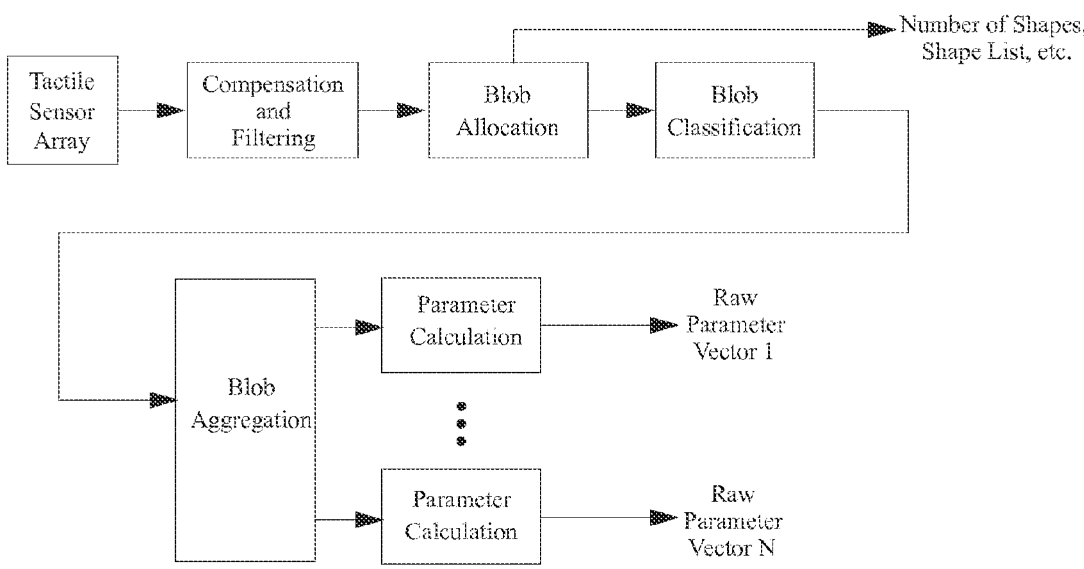

Tactile Sensor Array
Compensation and Filtering
Blob Allocation
Blob Classification
Number of Shapes, Shape List, etc.
Blob Aggregation
Parameter Calculation
Raw Parameter Vector 1
Parameter Calculation
Raw Parameter Vector N

FIG. 31

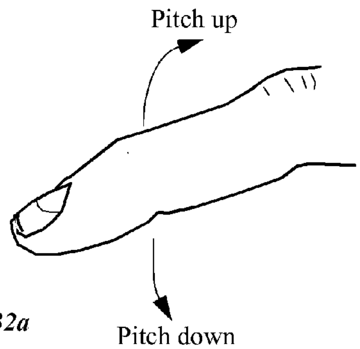


FIG. 32a

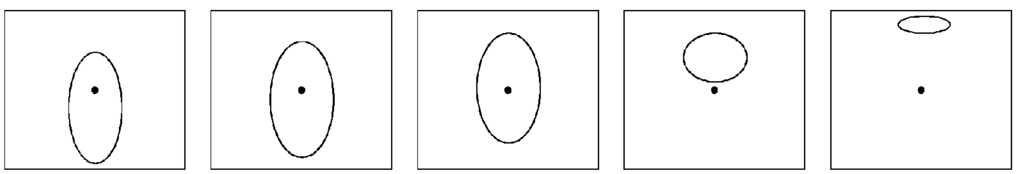


FIG.32b FIG. 32c FIG.32d FIG. 32e FIG. 32f

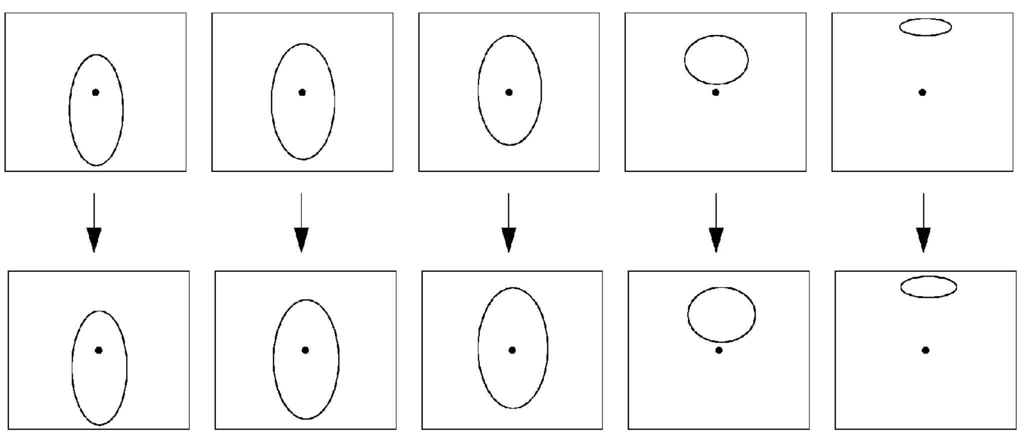


FIG. 33a FIG.33b FIG.33c FIG. 33d FIG.33e

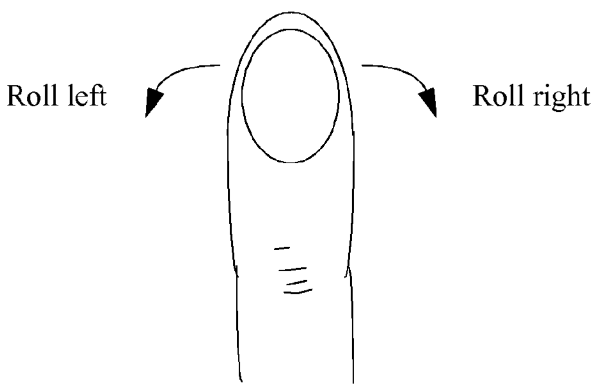


FIG. 34a

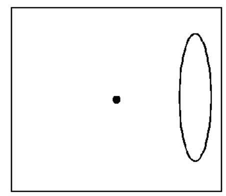


FIG. 34b

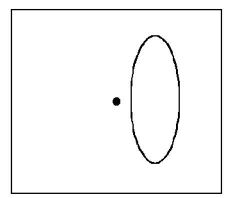


FIG. 34c

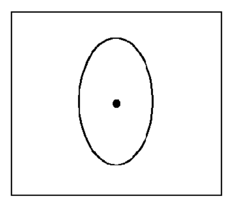


FIG. 34d

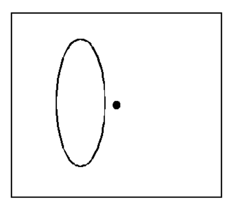


FIG. 34e

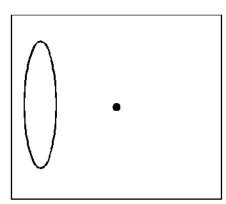


FIG. 34f

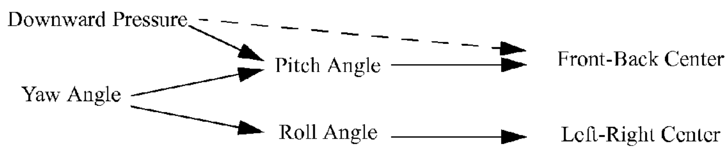


FIG. 35

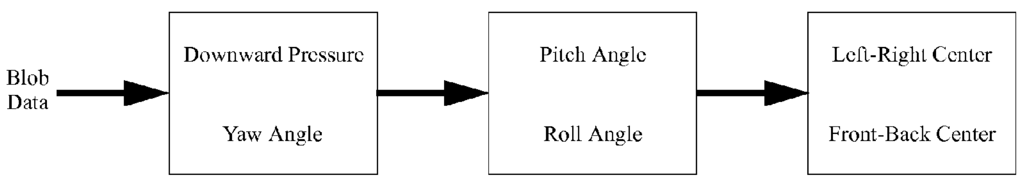


FIG. 36

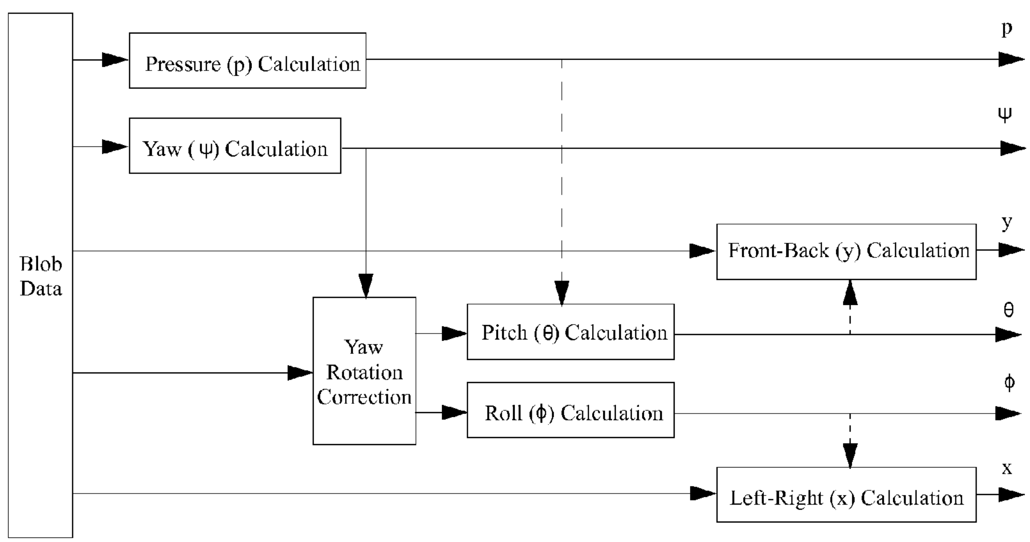


FIG.37

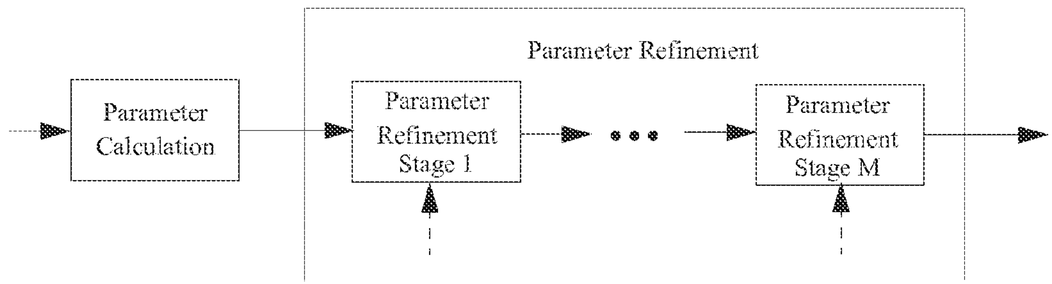


FIG. 38

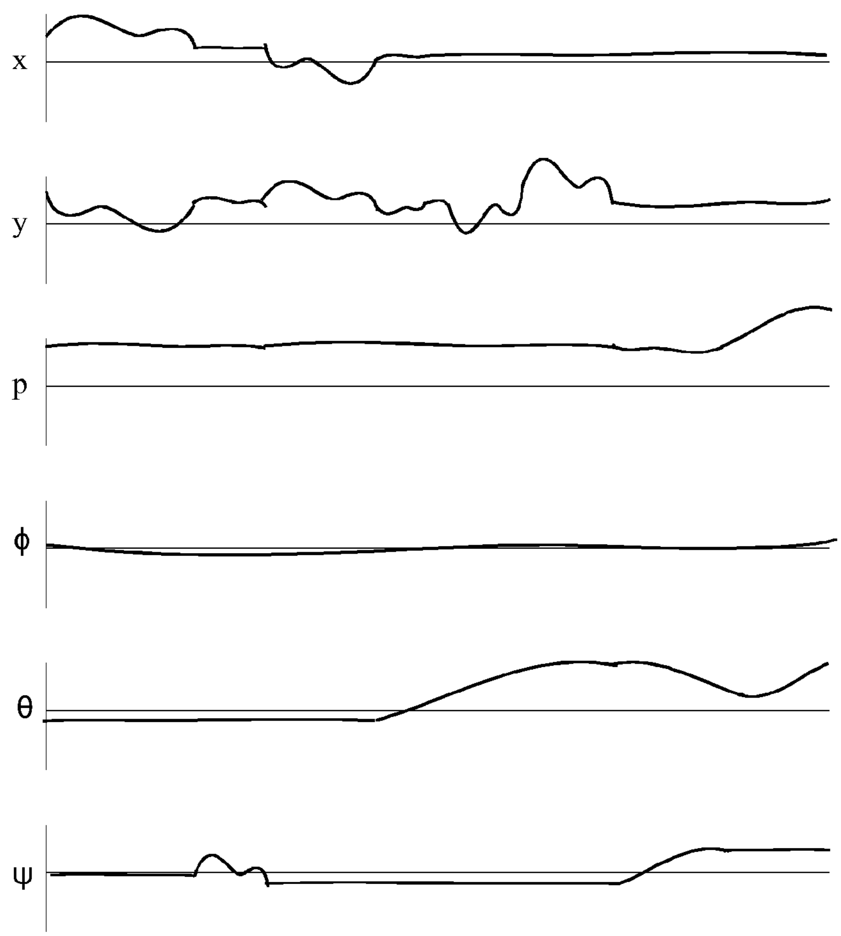


FIG. 39a

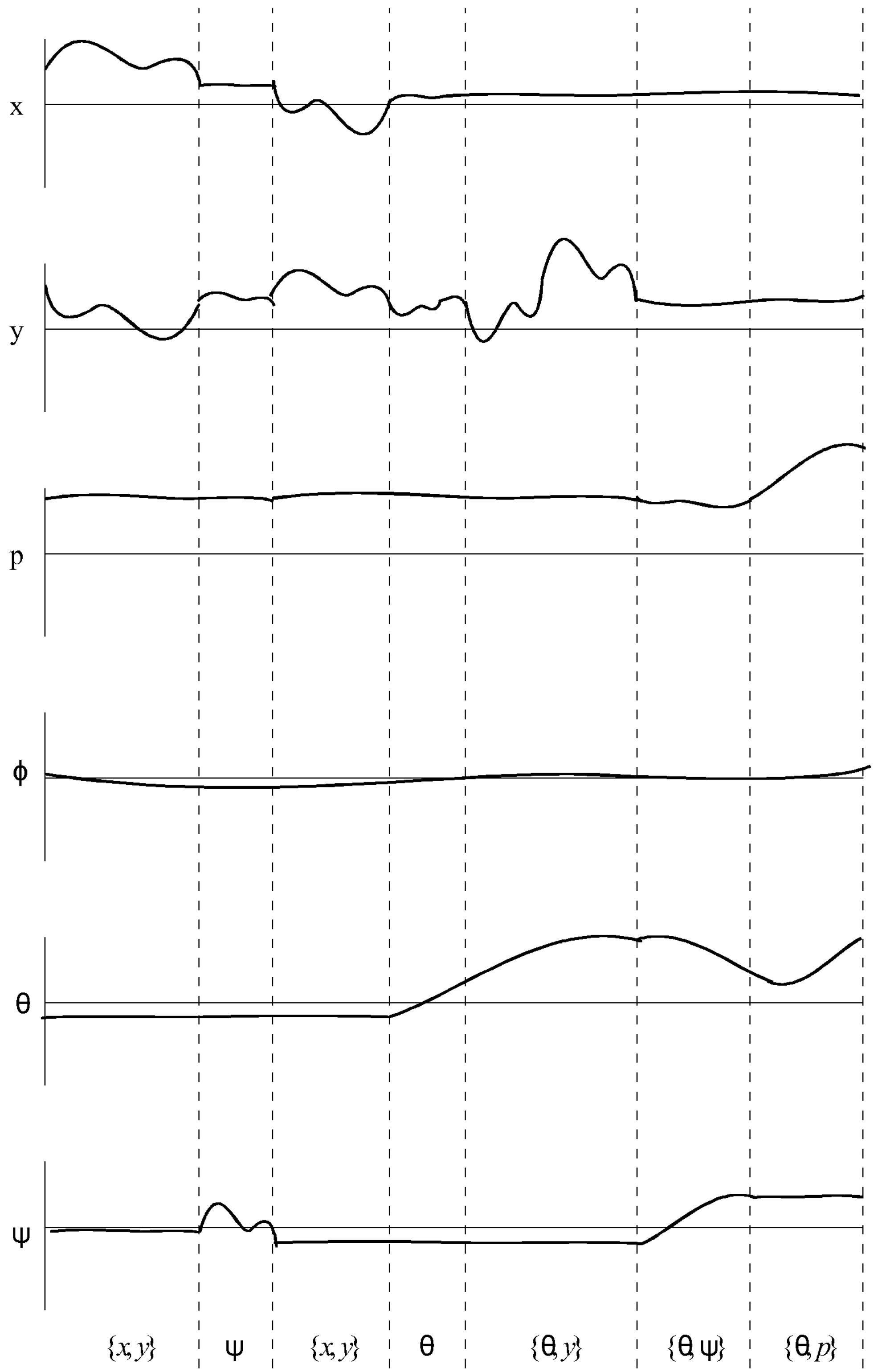


FIG. 39b

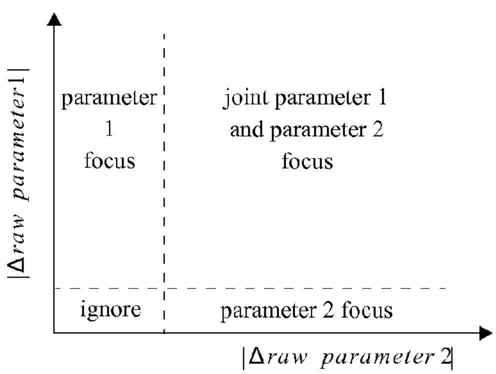


FIG. 40a

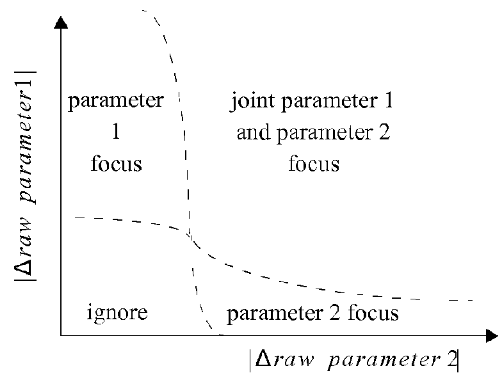


FIG. 40b

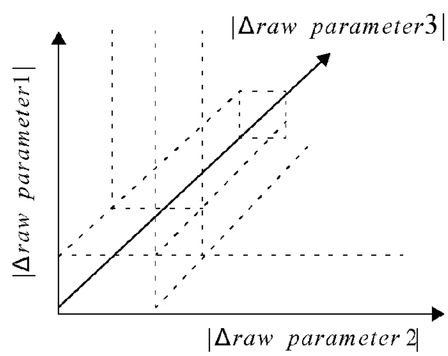


FIG. 40c

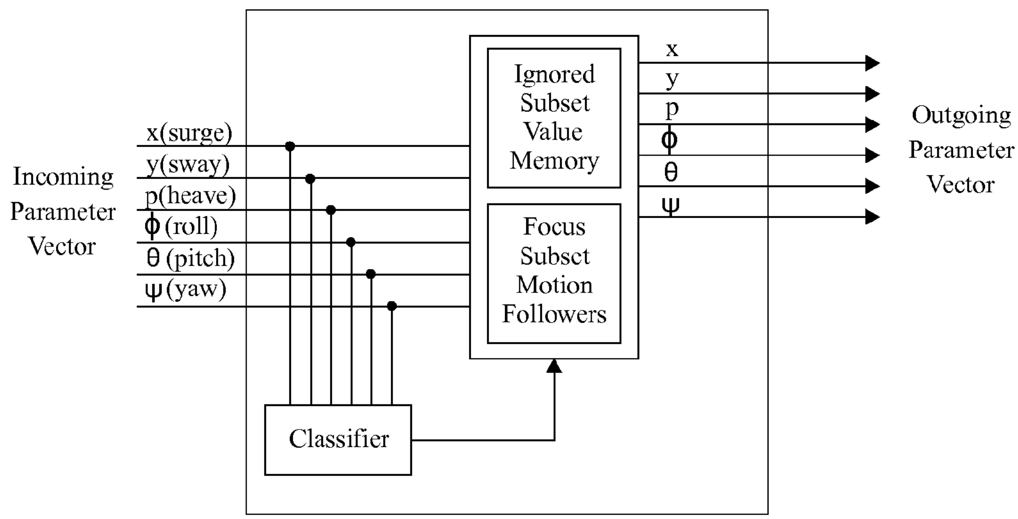


FIG. 41a

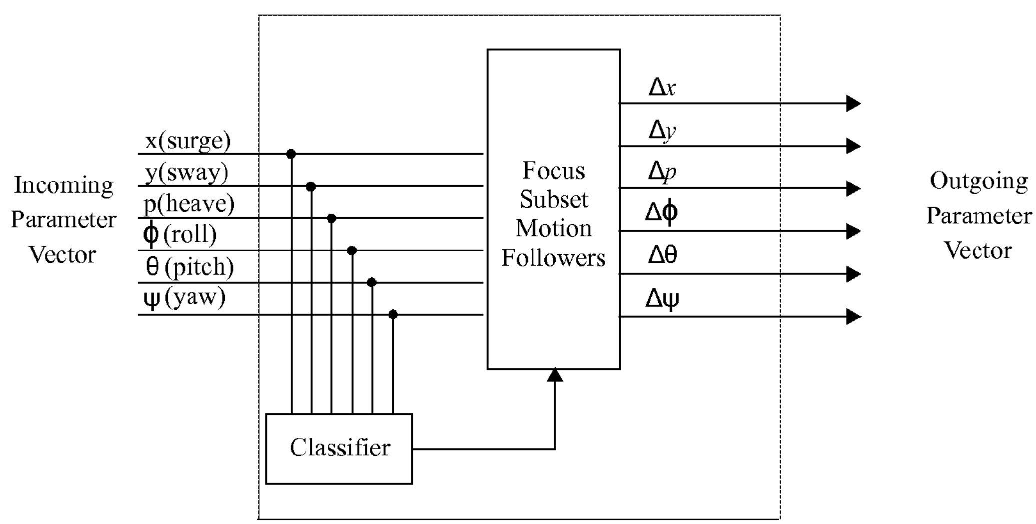


FIG. 41b

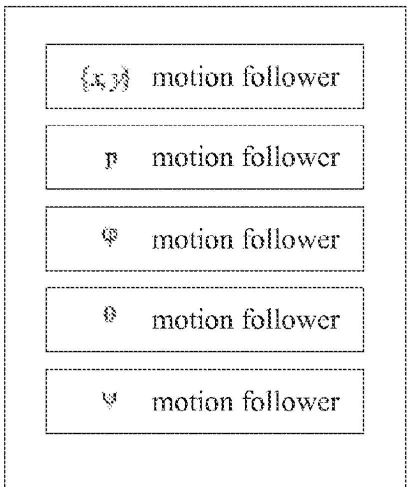


FIG. 42a

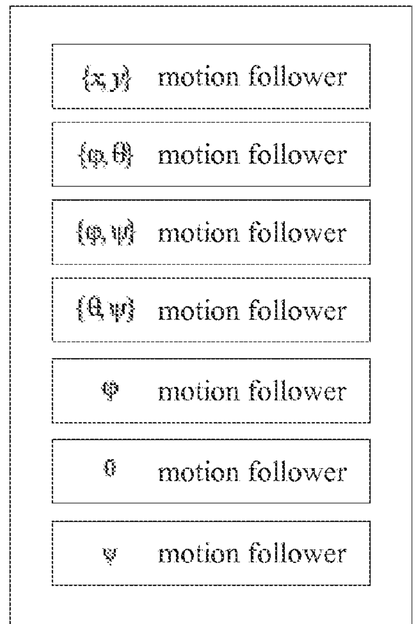


FIG. 42b

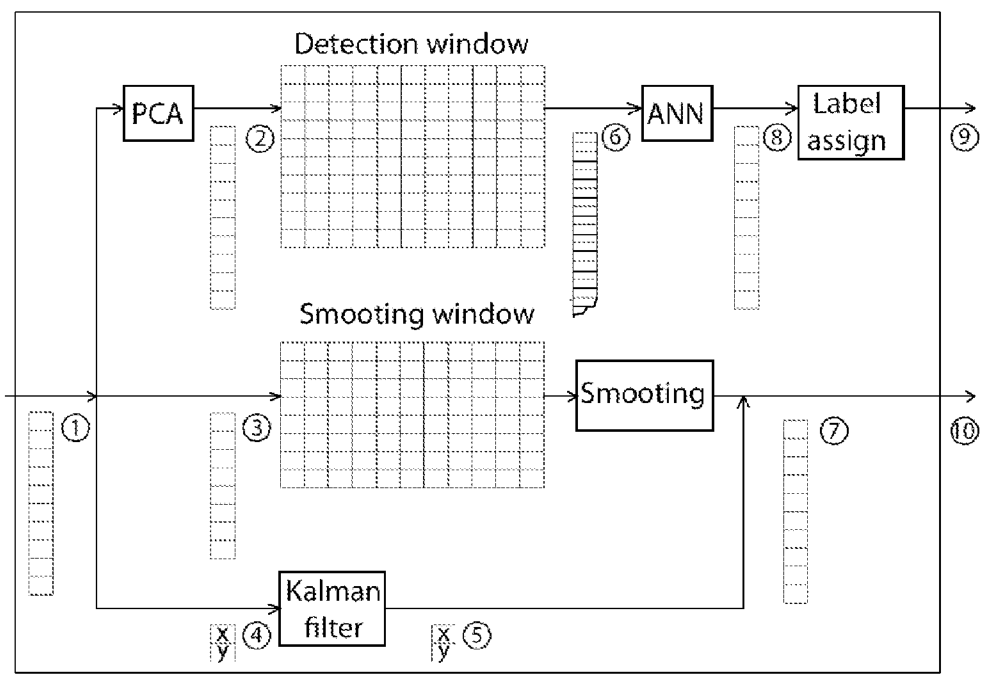


FIG. 43

SEQUENTIAL CLASSIFICATION RECOGNITION OF GESTURE PRIMITIVES AND WINDOW-BASED PARAMETER SMOOTHING FOR HIGH DIMENSIONAL TOUCHPAD (HDTP) USER INTERFACES

CROSS-REFERENCE TO RELATED APPLICATIONS

Pursuant to 35 U.S.C. §119(e), this application claims benefit of priority from Provisional U.S. Patent application Ser. No. 61/363,272, filed Jul. 11, 2010, and Provisional U.S. Patent Application 61/506,096, filed Jul. 9, 2011, the contents of both of which are incorporated by reference.

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BACKGROUND OF THE INVENTION

The invention relates to user interfaces providing an additional number of simultaneously-adjustable interactively-controlled discrete (clicks, taps, discrete gestures) and pseudo-continuous (downward pressure, roll, pitch, yaw, multi-touch geometric measurements, continuous gestures, etc.) user-adjustable settings and parameters, and in particular to the sequential selective tracking of subsets of parameters, and further how these can be used in applications.

By way of general introduction, touch screens implementing tactile sensor arrays have recently received tremendous attention with the addition multi-touch sensing, metaphors, and gestures. After an initial commercial appearance in the products of FingerWorks, such advanced touch screen technologies have received great commercial success from their defining role in the iPhone and subsequent adaptations in PDAs and other types of cell phones and hand-held devices. Despite this popular notoriety and the many associated patent filings, tactile array sensors implemented as transparent touchscreens were taught in the 1999 filings of issued U.S. Pat. No. 6,570,078 and pending U.S. patent application Ser. No. 11/761,978.

Despite the many popular touch interfaces and gestures, there remains a wide range of additional control capabilities that can yet be provided by further enhanced user interface technologies. A number of enhanced touch user interface features are described in U.S. Pat. No. 6,570,078, pending U.S. patent application Ser. Nos. 11/761,978, 12/418,605, 12/502,230, 12/541,948, and related pending U.S. patent applications. These patents and patent applications also address popular contemporary gesture and touch features. The enhanced user interface features taught in these patents and patent applications, together with popular contemporary gesture and touch features, can be rendered by the "High Definition Touch Pad" (HDTP) technology taught in those patents and patent applications. Implementations of the HDTP provide advanced multi-touch capabilities far more sophisticated that those popularized by FingerWorks, Apple, NYU, Microsoft, Gesturetek, and others.

SUMMARY OF THE INVENTION

For purposes of summarizing, certain aspects, advantages, and novel features are described herein. Not all such advantages may be achieved in accordance with any one particular embodiment. Thus, the disclosed subject matter may be embodied or carried out in a manner that achieves or optimizes one advantage or group of advantages without achieving all advantages as may be taught or suggested herein.

The invention provides, among other things, sequential selective tracking of subsets of parameters, the sequence of selections being made automatically by classifications derived from information calculated from data measured by the touchpad sensor.

In one aspect of the invention, the parameters can comprise left-right geometric center ("x"), forward-back geometric center ("y"), average downward pressure ("p"), clockwise-counterclockwise pivoting yaw angular rotation ("ψ"), tilting roll angular rotation ("ϕ"), and tilting pitch angular rotation ("θ") parameters calculated in real time from sensor measurement data.

In one aspect of the invention, the information calculated from data measured by the touchpad sensor can comprise raw parameter values including three or more of left-right geometric center ("x"), forward-back geometric center ("y"), average downward pressure ("p"), clockwise-counterclockwise pivoting yaw angular rotation ("ψ"), tilting roll angular rotation ("ϕ"), and tilting pitch angular rotation ("θ") parameters calculated in real time from sensor measurement data.

In another aspect of the invention, a method is provided for classification recognition of gesture primitives in a touch-based user interface using at least one computational processor, the method comprising:

- receiving tactile image data responsive to data generated from user touch of a user touch interface comprising a sensor array;
- processing the tactile image data with a series of operations to produce a first processed data vector, the series of operations comprising a plurality of numerical values responsive to data generated from the user touch interface; and
- further processing the numerical values with a principle component analysis operation to produce a reduced-dimensionality data vector;
- applying the reduced-dimensionality data vector to a classifier configured to have a plurality of classifier outputs that can be interpreted as probabilities, the classifier further configured to associate the likelihood of user touch comprising the execution of a gesture over an interval of time with a at least one pre-defined gesture from a collection of pre-defined gestures;
- applying the classifier outputs to a decision test, the decision test producing a decision output
- wherein the decision output is associated with user touch as represented by the numerical values responsive to data generated from the user touch interface over the interval of time, and
- wherein decision output is used to specify a gesture outcome.

In another aspect of the invention, the classifications are made from among a collection of predefined gestures or gesture primitives.

In another aspect of the invention, the classifications are made by heuristics.

In another aspect of the invention, the classifications are made by an artificial neural network.

In another aspect of the invention, the classifications are made by a genetic algorithm.

In another aspect of the invention, the classifications are made by combinations of two or more of heuristics, an artificial neural network, and a genetic algorithm,

In another aspect of the invention, a window-based arrangement is used to smooth the numerical values of measured gesture parameters.

In another aspect of the invention, a Kalman filter is used to smooth the numerical values of measured gesture parameters.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other aspects, features and advantages of the present invention will become more apparent upon consideration of the following description of preferred embodiments taken in conjunction with the accompanying drawing figures.

FIGS. **1**a-**1**g depict a number of arrangements and embodiments employing the HDTP technology.

FIGS. **2**a-**2**e and FIGS. **3**a-**3**b depict various integrations of an HDTP into the back of a conventional computer mouse as taught in U.S. Pat. No. 7,557,797 and in pending U.S. patent application Ser. No. 12/619,678.

FIG. **4** illustrates the side view of a finger lightly touching the surface of a tactile sensor array.

FIG. **5**a is a graphical representation of a tactile image produced by contact of a human finger on a tactile sensor array. FIG. **5**b provides a graphical representation of a tactile image produced by contact with multiple human fingers on a tactile sensor array.

FIG. **6** depicts a signal flow in a HDTP implementation.

FIG. **7** depicts a pressure sensor array arrangement.

FIG. **8** depicts a popularly accepted view of a typical cell phone or PDA capacitive proximity sensor implementation.

FIG. **9** depicts an implementation of a multiplexed LED array acting as a reflective optical proximity sensing array.

FIGS. **10**a-**10**c depict camera implementations for direct viewing of at least portions of the human hand, wherein the camera image array is employed as an HDTP tactile sensor array.

FIG. **11** depicts an embodiment of an arrangement comprising a video camera capturing the image of the contact of parts of the hand with a transparent or translucent surface.

FIGS. **12**a-**12**b depict an implementation of an arrangement comprising a video camera capturing the image of a deformable material whose image varies according to applied pressure.

FIG. **13** depicts an implementation of an optical or acoustic diffraction or absorption arrangement that can be used for contact or pressure sensing of tactile contact.

FIG. **14** shows a finger image wherein rather than a smooth gradient in pressure or proximity values there is radical variation due to non-uniformities in offset and scaling terms among the sensors.

FIG. **15** shows a sensor-by-sensor compensation arrangement.

FIG. **16** depicts the comparative performance of a group of contemporary handheld devices wherein straight lines were entered using the surface of the respective touchscreens.

FIGS. **17**a-**17**f illustrate the six independently adjustable degrees of freedom of touch from a single finger that can be simultaneously measured by the HDTP technology.

FIG. **18** suggests general ways in which two or more of these independently adjustable degrees of freedom adjusted at once.

FIG. **19** demonstrates a few two-finger multi-touch postures or gestures from the many that can be readily recognized by HDTP technology.

FIG. **20** illustrates the pressure profiles for a number of example hand contacts with a pressure-sensor array.

FIG. **21** depicts one of a wide range of tactile sensor images that can be measured by using more of the human hand

FIGS. **22**a-**22**c depict various approaches to the handling of compound posture data images.

FIG. **23** illustrates correcting tilt coordinates with knowledge of the measured yaw angle, compensating for the expected tilt range variation as a function of measured yaw angle, and matching the user experience of tilt with a selected metaphor interpretation.

FIG. **24**a depicts an embodiment wherein the raw tilt measurement is used to make corrections to the geometric center measurement under at least conditions of varying the tilt of the finger. FIG. **24**b depicts an embodiment for yaw angle compensation in systems and situations wherein the yaw measurement is sufficiently affected by tilting of the finger.

FIG. **25** shows an arrangement wherein raw measurements of the six quantities of FIGS. **17**a-**17**f, together with multi-touch parsing capabilities and shape recognition for distinguishing contact with various parts of the hand and the touchpad can be used to create a rich information flux of parameters, rates, and symbols.

FIG. **26** shows an approach for incorporating posture recognition, gesture recognition, state machines, and parsers to create an even richer human/machine tactile interface system capable of incorporating syntax and grammars.

FIGS. **27**a-**27**d depict operations acting on various parameters, rates, and symbols to produce other parameters, rates, and symbols, including operations such as sample/hold, interpretation, context, etc.

FIG. **28** depicts a user interface input arrangement incorporating one or more HDTPs that provides user interface input event and quantity routing.

FIGS. **29**a-**29**c depict methods for interfacing the HDTP with a browser.

FIG. **30**a depicts a user-measurement training procedure wherein a user is prompted to touch the tactile sensor array in a number of different positions. FIG. **30**b depicts additional postures for use in a measurement training procedure for embodiments or cases wherein a particular user does not provide sufficient variation in image shape the training. FIG. **30**c depicts boundary-tracing trajectories for use in a measurement training procedure.

FIG. **31** depicts an example HDTP signal flow chain for an HDTP realization implementing multi-touch, shape and constellation (compound shape) recognition, and other features.

FIG. **32**a depicts a side view of an exemplary finger and illustrating the variations in the pitch angle. FIGS. **32**b-**32**f depict exemplary tactile image measurements (proximity sensing, pressure sensing, contact sensing, etc.) as a finger in contact with the touch sensor array is positioned at various pitch angles with respect to the surface of the sensor.

FIGS. **33**a-**33**e depict the effect of increased downward pressure on the respective contact shapes of FIGS. **32**b-**32**f.

FIG. **34**a depicts a top view of an exemplary finger and illustrating the variations in the roll angle. FIGS. **34**b-**34**f depict exemplary tactile image measurements (proximity sensing, pressure sensing, contact sensing, etc.) as a finger in contact with the touch sensor array is positioned at various roll angles with respect to the surface of the sensor.

FIG. **35** depicts an example causal chain of calculation.

FIG. **36** depicts a utilization of this causal chain as a sequence flow of calculation blocks, albeit not a dataflow representation.

FIG. **37** depicts an example implementation of calculations for the left-right ("x"), front-back ("y"), downward pressure ("p"), roll ("φ"), pitch ("θ"), and yaw ("ψ") measurements from blob data.

FIG. **38** depicts an exemplary arrangement wherein the additional parameter refinement processing comprises two or more internal parameter refinement stages that can be interconnected as advantageous.

FIG. **39***a* depicts exemplary time-varying values of a parameters vector comprising left-right geometric center ("x"), forward-back geometric center ("y"), average downward pressure ("p"), clockwise-counterclockwise pivoting yaw angular rotation ("ψ"), tilting roll angular rotation ("φ"), and tilting pitch angular rotation ("θ") parameters calculated in real time from sensor measurement data.

FIG. **39***b* depicts an exemplary sequential classification of the parameter variations within the time-varying parameter vector according to an estimate of user intent, segmented decomposition, etc.

FIG. **40***a* depicts an exemplary simplified arrangement wherein degrees of change per unit time of a pair of parameters can be classified for "no action" (ignore), focusing only on the variation of parameter **1**, focusing only on the variation of parameter **2**, or focusing on the joint variation of parameter **1** and parameter **2**.

FIG. **40***b* depicts another exemplary partition of the state-space according to curved boundaries.

FIG. **40***c* depicts an exemplary simplified arrangement wherein degrees of change per unit time of a triple of parameters can be classified.

FIG. **41***a* illustrates an exemplary arrangement for a type of parameter refinement processing stage as can be advantageously comprised in the exemplary arrangements depicted in FIG. **31** or FIG. **38**.

FIG. **41***b* illustrates an exemplary variation on the exemplary arrangement depicted in FIG. **41***b* wherein the resulting arrangement provides changes in parameter values.

FIG. **42***a* and FIG. **42***b* depict exemplary motion followers that can be employed within the exemplary arrangements of FIG. **41***a* and FIG. **41***b* as well as variations on these and combinations of these.

FIG. **43** depicts an example architecture for gesture recognition and gesture value smoothing.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In the following, numerous specific details are set forth to provide a thorough description of various embodiments. Certain embodiments may be practiced without these specific details or with some variations in detail. In some instances, certain features are described in less detail so as not to obscure other aspects. The level of detail associated with each of the elements or features should not be construed to qualify the novelty or importance of one feature over the others.

In the following description, reference is made to the accompanying drawing figures which form a part hereof, and which show by way of illustration specific embodiments of the invention. It is to be understood by those of ordinary skill in this technological field that other embodiments may be utilized, and structural, electrical, as well as procedural changes may be made without departing from the scope of the present invention.

Despite the many popular touch interfaces and gestures in contemporary information appliances and computers, there remains a wide range of additional control capabilities that can yet be provided by further enhanced user interface technologies. A number of enhanced touch user interface features are described in U.S. Pat. No. 6,570,078, pending U.S. patent application Ser. Nos. 11/761,978, 12/418,605, 12/502,230, 12/541,948, and related pending U.S. patent applications. These patents and patent applications also address popular contemporary gesture and touch features. The enhanced user interface features taught in these patents and patent applications, together with popular contemporary gesture and touch features, can be rendered by the "High Definition Touch Pad" (HDTP) technology taught in those patents and patent applications.

The present patent application addresses additional technologies for feature and performance improvements of HDTP technologies. Specifically, this patent application addresses a curve-fitting approach to HDTP parameter extraction.

Overview of HDTP User Interface Technology

Before providing details specific to the present invention, some embodiments of HDTP technology is provided. This will be followed by a summarizing overview of HDTP technology. With the exception of a few minor variations and examples, the material presented in this overview section is draw from U.S. Pat. No. 6,570,078, pending U.S. patent application Ser. Nos. 11/761,978, 12/418,605, 12/502,230, 12/541,948, 12/724,413, 13/026,248, and related pending U.S. patent applications and is accordingly attributed to the associated inventors.

Embodiments Employing a Touchpad and Touchscreen Form of a HDTP

FIGS. **1***a*-**1***g* (adapted from U.S. patent application Ser. No. 12/418,605) and **2***a*-**2***e* (adapted from U.S. Pat. No. 7,557,797) depict a number of arrangements and embodiments employing the HDTP technology. FIG. **1***a* illustrates an HDTP as a peripheral that can be used with a desktop computer (shown) or laptop) not shown). FIG. **1***b* depicts an HDTP integrated into a laptop in place of the traditional touchpad pointing device. In FIGS. **1***a*-**1***b* the HDTP tactile sensor can be a stand-alone component or can be integrated over a display so as to form a touchscreen. FIG. **1***c* depicts an HDTP integrated into a desktop computer display so as to form a touchscreen. FIG. **1***d* shows the HDTP integrated into a laptop computer display so as to form a touchscreen.

FIG. **1***e* depicts an HDTP integrated into a cell phone, smartphone, PDA, or other hand-held consumer device. FIG. **1***f* shows an HDTP integrated into a test instrument, portable service-tracking device, portable service-entry device, field instrument, or other hand-held industrial device. In FIGS. **1***e*-**1***f* the HDTP tactile sensor can be a stand-alone component or can be integrated over a display so as to form a touchscreen.

FIG. **1***g* depicts an HDTP touchscreen configuration that can be used in a tablet computer, wall-mount computer monitor, digital television, video conferencing screen, kiosk, etc.

In at least the arrangements of FIGS. **1***a*, **1***c*, **1***d*, and **1***g*, or other sufficiently large tactile sensor implementation of the HDTP, more than one hand can be used an individually recognized as such.

Embodiments Incorporating the HDTP into a Traditional or Contemporary Generation Mouse

FIGS. **2***a*-**2***e* and FIGS. **3***a*-**3***b* (these adapted from U.S. Pat. No. 7,557,797) depict various integrations of an HDTP into the back of a conventional computer mouse. Any of these arrangements can employ a connecting cable, or the device can be wireless.

In the integrations depicted in FIGS. **2**a-**2**d the HDTP tactile sensor can be a stand-alone component or can be integrated over a display so as to form a touchscreen. Such configurations have very recently become popularized by the product release of Apple "Magic Mouse™" although such combinations of a mouse with a tactile sensor array on its back responsive to multitouch and gestures were taught earlier in pending U.S. patent application Ser. No. 12/619,678 (priority date Feb. 12, 2004) entitled "User Interface Mouse with Touchpad Responsive to Gestures and Multi-Touch."

In another embodiment taught in the specification of issued U.S. Pat. No. 7,557,797 and associated pending continuation applications more than two touchpads can be included in the advance mouse embodiment, for example as suggested in the arrangement of FIG. **2**e. As with the arrangements of FIGS. **2**a-**2**d, one or more of the plurality of HDTP tactile sensors or exposed sensor areas of arrangements such as that of FIG. **2**e can be integrated over a display so as to form a touchscreen. Other advance mouse arrangements include the integrated trackball/touchpad/mouse combinations of FIGS. **3**a-**3**b taught in U.S. Pat. No. 7,557,797.

Overview of HDTP User Interface Technology

The information in this section provides an overview of HDTP user interface technology as described in U.S. Pat. No. 6,570,078, pending U.S. patent application Ser. Nos. 11/761,978, 12/418,605, 12/502,230, 12/541,948, and related pending U.S. patent applications.

In an embodiment, a touchpad used as a pointing and data entry device can comprise an array of sensors. The array of sensors is used to create a tactile image of a type associated with the type of sensor and method of contact by the human hand.

In one embodiment, the individual sensors in the sensor array are pressure sensors and a direct pressure-sensing tactile image is generated by the sensor array.

In another embodiment, the individual sensors in the sensor array are proximity sensors and a direct proximity tactile image is generated by the sensor array. Since the contacting surfaces of the finger or hand tissue contacting a surface typically increasingly deforms as pressure is applied, the sensor array comprised of proximity sensors also provides an indirect pressure-sensing tactile image.

In another embodiment, the individual sensors in the sensor array can be optical sensors. In one variation of this, an optical image is generated and an indirect proximity tactile image is generated by the sensor array. In another variation, the optical image can be observed through a transparent or translucent rigid material and, as the contacting surfaces of the finger or hand tissue contacting a surface typically increasingly deforms as pressure is applied, the optical sensor array also provides an indirect pressure-sensing tactile image.

In some embodiments, the array of sensors can be transparent or translucent and can be provided with an underlying visual display element such as an alphanumeric, graphics, or image display. The underlying visual display can comprise, for example, an LED array display, a backlit LCD, etc. Such an underlying display can be used to render geometric boundaries or labels for soft-key functionality implemented with the tactile sensor array, to display status information, etc. Tactile array sensors implemented as transparent touchscreens are taught in the 1999 filings of issued U.S. Pat. No. 6,570,078 and pending U.S. patent application Ser. No. 11/761,978.

In an embodiment, the touchpad or touchscreen can comprise a tactile sensor array obtains or provides individual measurements in every enabled cell in the sensor array that provides these as numerical values. The numerical values can be communicated in a numerical data array, as a sequential data stream, or in other ways. When regarded as a numerical data array with row and column ordering that can be associated with the geometric layout of the individual cells of the sensor array, the numerical data array can be regarded as representing a tactile image. The only tactile sensor array requirement to obtain the full functionality of the HDTP is that the tactile sensor array produce a multi-level gradient measurement image as a finger, part of hand, or other pliable object varies is proximity in the immediate area of the sensor surface.

Such a tactile sensor array should not be confused with the "null/contact" touchpad which, in normal operation, acts as a pair of orthogonally responsive potentiometers. These "null/contact" touchpads do not produce pressure images, proximity images, or other image data but rather, in normal operation, two voltages linearly corresponding to the location of a left-right edge and forward-back edge of a single area of contact. Such "null/contact" touchpads, which are universally found in existing laptop computers, are discussed and differentiated from tactile sensor arrays in issued U.S. Pat. No. 6,570,078 and pending U.S. patent application Ser. No. 11/761,978. Before leaving this topic, it is pointed out that these the "null/contact" touchpads nonetheless can be inexpensively adapted with simple analog electronics to provide at least primitive multi-touch capabilities as taught in issued U.S. Pat. No. 6,570,078 and pending U.S. patent application Ser. No. 11/761,978 (pre-grant publication U.S. 2007/0229477 and therein, paragraphs [0022]-[0029], for example).

More specifically, FIG. **4** (adapted from U.S. patent application Ser. No. 12/418,605) illustrates the side view of a finger **401** lightly touching the surface **402** of a tactile sensor array. In this example, the finger **401** contacts the tactile sensor surface in a relatively small area **403**. In this situation, on either side the finger curves away from the region of contact **403**, where the non-contacting yet proximate portions of the finger grow increasingly far **404**a, **405**a, **404**b, **405**b from the surface of the sensor **402**. These variations in physical proximity of portions of the finger with respect to the sensor surface should cause each sensor element in the tactile proximity sensor array to provide a corresponding proximity measurement varying responsively to the proximity, separation distance, etc. The tactile proximity sensor array advantageously comprises enough spatial resolution to provide a plurality of sensors within the area occupied by the finger (for example, the area comprising width **406**). In this case, as the finger is pressed down, the region of contact **403** grows as the more and more of the pliable surface of the finger conforms to the tactile sensor array surface **402**, and the distances **404**a, **405**a, **404**b, **405**b contract. If the finger is tilted, for example by rolling in the user viewpoint counterclockwise (which in the depicted end-of-finger viewpoint clockwise **407**a) the separation distances on one side of the finger **404**a, **405**a will contract while the separation distances on one side of the finger **404**b, **405**b will lengthen. Similarly if the finger is tilted, for example by rolling in the user viewpoint clockwise (which in the depicted end-of-finger viewpoint counterclockwise **407**b) the separation distances on the side of the finger **404**b, **405**b will contract while the separation distances on the side of the finger **404**a, **405**a will lengthen.

In many various embodiments, the tactile sensor array can be connected to interface hardware that sends numerical data responsive to tactile information captured by the tactile sensor array to a processor. In various embodiments, this processor will process the data captured by the tactile sensor array and transform it various ways, for example into a collection of simplified data, or into a sequence of tactile image "frames" (this sequence akin to a video stream), or into highly refined information responsive to the position and movement of one or more fingers and other parts of the hand.

As to further detail of the latter example, a "frame" can refer to a 2-dimensional list, number of rows by number of columns, of tactile measurement value of every pixel in a tactile sensor array at a given instance. The time interval between one frame and the next one depends on the frame rate of the system and the number of frames in a unit time (usually frames per second). However, these features are and are not firmly required. For example, in some embodiments a tactile sensor array can not be structured as a 2-dimensional array but rather as row-aggregate and column-aggregate measurements (for example row sums and columns sums as in the tactile sensor of year 2003-2006 Apple Powerbooks, row and column interference measurement data as can be provided by a surface acoustic wave or optical transmission modulation sensor as discussed later in the context of FIG. **13**, etc.). Additionally, the frame rate can be adaptively-variable rather than fixed, or the frame can be segregated into a plurality regions each of which are scanned in parallel or conditionally (as taught in U.S. Pat. No. 6,570,078 and pending U.S. patent application Ser. No. 12/418,605), etc.

FIG. **5***a* (adapted from U.S. patent application Ser. No. 12/418,605) depicts a graphical representation of a tactile image produced by contact with the bottom surface of the most outward section (between the end of the finger and the most nearby joint) of a human finger on a tactile sensor array. In this tactile array, there are 24 rows and 24 columns; other realizations can have significantly more (hundreds or thousands) of rows and columns. Tactile measurement values of each cell are indicated by the numbers and shading in each cell. Darker cells represent cells with higher tactile measurement values. Similarly, FIG. **5***b* (also adapted from U.S. patent application Ser. No. 12/418,605) provides a graphical representation of a tactile image produced by contact with multiple human fingers on a tactile sensor array. In other embodiments, there can be a larger or smaller number of pixels for a given images size, resulting in varying resolution. Additionally, there can be larger or smaller area with respect to the image size resulting in a greater or lesser potential measurement area for the region of contact to be located in or move about.

FIG. **6** (adapted from U.S. patent application Ser. No. 12/418,605) depicts a realization wherein a tactile sensor array is provided with real-time or near-real-time data acquisition capabilities. The captured data reflects spatially distributed tactile measurements (such as pressure, proximity, etc.). The tactile sensory array and data acquisition stage provides this real-time or near-real-time tactile measurement data to a specialized image processing arrangement for the production of parameters, rates of change of those parameters, and symbols responsive to aspects of the hand's relationship with the tactile or other type of sensor array. In some applications, these measurements can be used directly. In other situations, the real-time or near-real-time derived parameters can be directed to mathematical mappings (such as scaling, offset, and nonlinear warpings) in real-time or near-real-time into real-time or near-real-time application-specific parameters or other representations useful for applications. In some embodiments, general purpose outputs can be assigned to variables defined or expected by the application.

Types of Tactile Sensor Arrays

The tactile sensor array employed by HDTP technology can be implemented by a wide variety of means, for example:

- Pressure sensor arrays (implemented by for example—although not limited to—one or more of resistive, capacitive, piezo, optical, acoustic, or other sensing elements);
- Pressure sensor arrays (implemented by for example—although not limited to—one or more of resistive, capacitive, piezo, optical, acoustic, or other sensing elements);
- Proximity sensor arrays (implemented by for example—although not limited to—one or more of capacitive, optical, acoustic, or other sensing elements);
- Surface-contact sensor arrays (implemented by for example—although not limited to—one or more of resistive, capacitive, piezo, optical, acoustic, or other sensing elements).

Below a few specific examples of the above are provided by way of illustration; however these are by no means limiting. The examples include:

- Pressure sensor arrays comprising arrays of isolated sensors (FIG. **7**);
- Capacitive proximity sensors (FIG. **8**);
- Multiplexed LED optical reflective proximity sensors (FIG. **9**);
- Video camera optical reflective sensing (as taught in U.S. Pat. No. 6,570,078 and U.S. patent application Ser. Nos. 10/683,915 and 11/761,978):
  - direct image of hand (FIGS. **10***a*-**10***c*);
  - image of deformation of material (FIG. **11**);
- Surface contract refraction/absorption (FIG. **12**)

An example implementation of a tactile sensor array is a pressure sensor array. Pressure sensor arrays discussed in U.S. Pat. No. 6,570,078 and pending U.S. patent application Ser. No. 11/761,978. FIG. **7** depicts a pressure sensor array arrangement comprising a rectangular array of isolated individual two-terminal pressure sensor elements. Such two-terminal pressure sensor elements typically operate by measuring changes in electrical (resistive, capacitive) or optical properties of an elastic material as the material is compressed. In typical embodiment, each sensor element in the sensor array can be individually accessed via multiplexing arrangement, for example as shown in FIG. **7**, although other arrangements are possible and provided for by the invention. Examples of prominent manufacturers and suppliers of pressure sensor arrays include Tekscan, Inc. (307 West First Street, South Boston, Mass., 02127), Pressure Profile Systems (5757 Century Boulevard, Suite 600, Los Angeles, Calif. 90045), Sensor Products, Inc. (300 Madison Avenue, Madison, N.J. 07940 USA), and Xsensor Technology Corporation (Suite 111, 319-2nd Ave SW, Calgary, Alberta T2P 0C5, Canada).

Capacitive proximity sensors can be used in various handheld devices with touch interfaces. Prominent manufacturers and suppliers of such sensors, both in the form of opaque touchpads and transparent touch screens, include Balda AG (Bergkirchener Str. 228, 32549 Bad Oeynhausen, DE), Cypress (198 Champion Ct., San Jose, Calif. 95134), and Synaptics (2381 Bering Dr., San Jose, Calif. 95131). In such sensors, the region of finger contact is detected by variations in localized capacitance resulting from capacitive proximity effects induced by an overlapping or otherwise nearly-adjacent finger. More specifically, the electrical field at the intersection of orthogonally-aligned conductive buses is influenced by the vertical distance or gap between the surface of the sensor array and the skin surface of the finger. Such capacitive proximity sensor technology is low-cost, reliable, long-life, stable, and can readily be made transparent. FIG. **8** shows a popularly accepted view of a typical cell phone or PDA capacitive proximity sensor implementation. Capacitive sensor arrays of this type can be highly susceptible to noise and various shielding and noise-suppression electronics and systems techniques can need to be employed for adequate stability, reliability, and performance in various electric field and electromagnetically-noisy environments. In some embodiments of an HDTP, the present invention can use the same spatial resolution as current capacitive proximity touchscreen sensor arrays. In other embodiments of the present invention, a higher spatial resolution is advantageous.

Forrest M. Mims is credited as showing that an LED can be used as a light detector as well as a light emitter. Recently, light-emitting diodes have been used as a tactile proximity sensor array. Such tactile proximity array implementations typically need to be operated in a darkened environment (as seen in the video in the above web link). In one embodiment provided for by the invention, each LED in an array of LEDs can be used as a photodetector as well as a light emitter, although a single LED can either transmit or receive information at one time. Each LED in the array can sequentially be selected to be set to be in receiving mode while others adjacent to it are placed in light emitting mode. A particular LED in receiving mode can pick up reflected light from the finger, provided by said neighboring illuminating-mode LEDs. FIG. **9** depicts an implementation. The invention provides for additional systems and methods for not requiring darkness in the user environment in order to operate the LED array as a tactile proximity sensor. In one embodiment, potential interference from ambient light in the surrounding user environment can be limited by using an opaque pliable or elastically deformable surface covering the LED array that is appropriately reflective (directionally, amorphously, etc. as can be advantageous in a particular design) on the side facing the LED array. Such a system and method can be readily implemented in a wide variety of ways as is clear to one skilled in the art. In another embodiment, potential interference from ambient light in the surrounding user environment can be limited by employing amplitude, phase, or pulse width modulated circuitry or software to control the underlying light emission and receiving process. For example, in an implementation the LED array can be configured to emit modulated light modulated at a particular carrier frequency or variational waveform and respond to only modulated light signal components extracted from the received light signals comprising that same carrier frequency or variational waveform. Such a system and method can be readily implemented in a wide variety of ways as is clear to one skilled in the art.

Use of video cameras for gathering control information from the human hand in various ways is discussed in U.S. Pat. No. 6,570,078 and Pending U.S. patent application Ser. No. 10/683,915. Here the camera image array is employed as an HDTP tactile sensor array. Images of the human hand as captured by video cameras can be used as an enhanced multiple-parameter interface responsive to hand positions and gestures, for example as taught in U.S. patent application Ser. No. 10/683,915 Pre-Grant-Publication 2004/0118268 (paragraphs [314], [321]-[332], [411], [653], both stand-alone and in view of [325], as well as [241]-[263]). FIGS. **10***a* and **10***b* depict single camera implementations, while FIG. **10***c* depicts a two camera implementation. As taught in the aforementioned references, a wide range of relative camera sizes and positions with respect to the hand are provided for, considerably generalizing the arrangements shown in FIGS. **10***a*-**10***c*.

In another video camera tactile controller embodiment, a flat or curved transparent or translucent surface or panel can be used as sensor surface. When a finger is placed on the transparent or translucent surface or panel, light applied to the opposite side of the surface or panel reflects light in a distinctly different manner than in other regions where there is no finger or other tactile contact. The image captured by an associated video camera will provide gradient information responsive to the contact and proximity of the finger with respect to the surface of the translucent panel. For example, the parts of the finger that are in contact with the surface will provide the greatest degree of reflection while parts of the finger that curve away from the surface of the sensor provide less reflection of the light. Gradients of the reflected light captured by the video camera can be arranged to produce a gradient image that appears similar to the multilevel quantized image captured by a pressure sensor. By comparing changes in gradient, changes in the position of the finger and pressure applied by the finger can be detected. FIG. **11** depicts an implementation.

FIGS. **12***a*-**12***b* depict an implementation of an arrangement comprising a video camera capturing the image of a deformable material whose image varies according to applied pressure. In the example of FIG. **12***a*, the deformable material serving as a touch interface surface can be such that its intrinsic optical properties change in response to deformations, for example by changing color, index of refraction, degree of reflectivity, etc. In another approach, the deformable material can be such that exogenous optic phenomena are modulated n response to the deformation. As an example, the arrangement of FIG. **12***b* is such that the opposite side of the deformable material serving as a touch interface surface comprises deformable bumps which flatten out against the rigid surface of a transparent or translucent surface or panel. The diameter of the image as seen from the opposite side of the transparent or translucent surface or panel increases as the localized pressure from the region of hand contact increases. Such an approach was created by Professor Richard M. White at U.C. Berkeley in the 1980's.

FIG. **13** depicts an optical or acoustic diffraction or absorption arrangement that can be used for contact or pressure sensing of tactile contact. Such a system can employ, for example light or acoustic waves. In this class of methods and systems, contact with or pressure applied onto the touch surface causes disturbances (diffraction, absorption, reflection, etc.) that can be sensed in various ways. The light or acoustic waves can travel within a medium comprised by or in mechanical communication with the touch surface. A slight variation of this is where surface acoustic waves travel along the surface of, or interface with, a medium comprised by or in mechanical communication with the touch surface.

Compensation for Non-Ideal Behavior of Tactile Sensor Arrays

Individual sensor elements in a tactile sensor array produce measurements that vary sensor-by-sensor when presented with the same stimulus. Inherent statistical averaging of the algorithmic mathematics can damp out much of this, but for small image sizes (for example, as rendered by a small finger or light contact), as well as in cases where there are extremely large variances in sensor element behavior from sensor to sensor, the invention provides for each sensor to be individually calibrated in implementations where that can be advantageous. Sensor-by-sensor measurement value scaling, offset, and nonlinear warpings can be invoked for all or selected sensor elements during data acquisition scans. Similarly, the invention provides for individual noisy or defective sensors can be tagged for omission during data acquisition scans.

FIG. **14** shows a finger image wherein rather than a smooth gradient in pressure or proximity values there is radical variation due to non-uniformities in offset and scaling terms among the sensors.

FIG. **15** shows a sensor-by-sensor compensation arrangement for such a situation. A structured measurement process applies a series of known mechanical stimulus values (for example uniform applied pressure, uniform simulated proximity, etc.) to the tactile sensor array and measurements are made for each sensor. Each measurement data point for each sensor is compared to what the sensor should read and a piecewise-linear correction is computed. In an embodiment, the coefficients of a piecewise-linear correction operation for each sensor element are stored in a file. As the raw data stream is acquired from the tactile sensor array, sensor-by-sensor the corresponding piecewise-linear correction coefficients are obtained from the file and used to invoke a piecewise-linear correction operation for each sensor measurement. The value resulting from this time-multiplexed series of piecewise-linear correction operations forms an outgoing "compensated" measurement data stream. Such an arrangement is employed, for example, as part of the aforementioned Tekscan resistive pressure sensor array products.

Additionally, the macroscopic arrangement of sensor elements can introduce nonlinear spatial warping effects. As an example, various manufacturer implementations of capacitive proximity sensor arrays and associated interface electronics are known to comprise often dramatic nonlinear spatial warping effects. FIG. **16** depicts the comparative performance of a group of contemporary handheld devices wherein straight lines were entered using the surface of the respective touchscreens. A common drawing program was used on each device, with widely-varying type and degrees of nonlinear spatial warping effects clearly resulting. For simple gestures such as selections, finger-flicks, drags, spreads, etc., such nonlinear spatial warping effects introduce little consequence. For more precision applications, such nonlinear spatial warping effects introduce unacceptable performance. Close study of FIG. **16** shows different types of responses to tactile stimulus in the direct neighborhood of the relatively widely-spaced capacitive sensing nodes versus tactile stimulus in the boundary regions between capacitive sensing nodes. Increasing the number of capacitive sensing nodes per unit area can reduce this, as can adjustments to the geometry of the capacitive sensing node conductors. In many cases improved performance can be obtained by introducing or more carefully implementing interpolation mathematics.

Types of Hand Contact Measurements and Features Provided by HDTP Technology

FIGS. **17***a*-**17***f* (adapted from U.S. patent application Ser. No. 12/418,605 and described in U.S. Pat. No. 6,570,078) illustrate six independently adjustable degrees of freedom of touch from a single finger that can be simultaneously measured by the HDTP technology. The depiction in these figures is from the side of the touchpad. FIGS. **17***a*-**17***c* show actions of positional change (amounting to applied pressure in the case of FIG. **17***c*) while FIGS. **17***d*-**17***f* show actions of angular change. Each of these can be used to control a user interface parameter, allowing the touch of a single fingertip to control up to six simultaneously-adjustable quantities in an interactive user interface.

Each of the six parameters listed above can be obtained from operations on a collection of sums involving the geometric location and tactile measurement value of each tactile measurement sensor. Of the six parameters, the left-right geometric center, forward-back geometric center, and clockwise-counterclockwise yaw rotation can be obtained from binary threshold image data. The average downward pressure, roll, and pitch parameters are in some embodiments beneficially calculated from gradient (multi-level) image data. One remark is that because binary threshold image data is sufficient for the left-right geometric center, forward-back geometric center, and clockwise-counterclockwise yaw rotation parameters, these also can be discerned for flat regions of rigid non-pliable objects, and thus the HDTP technology thus can be adapted to discern these three parameters from flat regions with striations or indentations of rigid non-pliable objects.

These 'Position Displacement' parameters FIGS. **17***a*-**17***c* can be realized by various types of unweighted averages computed across the blob of one or more of each the geometric location and tactile measurement value of each above-threshold measurement in the tactile sensor image. The pivoting rotation can be calculated from a least-squares slope which in turn involves sums taken across the blob of one or more of each the geometric location and the tactile measurement value of each active cell in the image; alternatively a high-performance adapted eigenvector method taught in co-pending provisional patent application U.S. Ser. No. 12/724,413 "High-Performance Closed-Form Single-Scan Calculation of Oblong-Shape Rotation Angles from Binary Images of Arbitrary Size Using Running Sums," filed Mar. 14, 2009, can be used. The last two angle ("tilt") parameters, pitch and roll, can be realized by performing calculations on various types of weighted averages as well as a number of other methods.

Each of the six parameters portrayed in FIGS. **17***a*-**17***f* can be measured separately and simultaneously in parallel. FIG. **18** (adapted from U.S. Pat. No. 6,570,078) suggests general ways in which two or more of these independently adjustable degrees of freedom adjusted at once.

The HDTP technology provides for multiple points of contact, these days referred to as "multi-touch." FIG. **19** (adapted from U.S. patent application Ser. No. 12/418,605 and described in U.S. Pat. No. 6,570,078) demonstrates a few two-finger multi-touch postures or gestures from the hundreds that can be readily recognized by HDTP technology. HDTP technology can also be configured to recognize and measure postures and gestures involving three or more fingers, various parts of the hand, the entire hand, multiple hands, etc. Accordingly, the HDTP technology can be configured to measure areas of contact separately, recognize shapes, fuse measures or pre-measurement data so as to create aggregated measurements, and other operations.

By way of example, FIG. **20** (adapted from U.S. Pat. No. 6,570,078) illustrates the pressure profiles for a number of example hand contacts with a pressure-sensor array. In the case **2000** of a finger's end, pressure on the touch pad pressure-sensor array can be limited to the finger tip, resulting in a spatial pressure distribution profile **2001**; this shape does not change much as a function of pressure. Alternatively, the finger can contact the pad with its flat region, resulting in light pressure profiles **2002** which are smaller in size than heavier pressure profiles **2003**. In the case **2004** where the entire finger touches the pad, a three-segment pattern (**2004***a*, **2004***b*, **2004***c*) will result under many conditions; under light pressure a two segment pattern (**2004***b* or **2004***c* missing) could result. In all but the lightest pressures the thumb makes a somewhat discernible shape **2005** as do the wrist **2006**, edge-of-hand "cuff" **2007**, and palm **2008**; at light pressures these patterns thin and can also break into disconnected regions. Whole hand patterns such the first **2011** and flat hand **2012** have more complex shapes. In the case of the first **2011**, a degree of curl can be discerned from the relative geometry and separation of sub-regions (here depicted, as an example, as **2011**_a_, **2011**_b_, and **2011**_c_). In the case of the whole flat hand **2000**, there can be two or more sub-regions which can be in fact joined (as within **2012**_a_) or disconnected (as an example, as **2012**_a_ and **2012**_b_ are); the whole hand also affords individual measurement of separation "angles" among the digits and thumb (**2013**_a_, **2013**_b_, **2013**_c_, **2013**_d_) which can easily be varied by the user.

HDTP technology robustly provides feature-rich capability for tactile sensor array contact with two or more fingers, with other parts of the hand, or with other pliable (and for some parameters, non-pliable) objects. In one embodiment, one finger on each of two different hands can be used together to at least double number of parameters that can be provided. Additionally, new parameters particular to specific hand contact configurations and postures can also be obtained. By way of example, FIG. **21** (adapted from U.S. patent application Ser. No. 12/418,605 and described in U.S. Pat. No. 6,570,078) depicts one of a wide range of tactile sensor images that can be measured by using more of the human hand. U.S. Pat. No. 6,570,078 and pending U.S. patent application Ser. No. 11/761,978 provide additional detail on use of other parts of hand. Within the context of the example of FIG. **21**:

- multiple fingers can be used with the tactile sensor array, with or without contact by other parts of the hand;
- The whole hand can be tilted & rotated;
- The thumb can be independently rotated in yaw angle with respect to the yaw angle held by other fingers of the hand;
- Selected fingers can be independently spread, flatten, arched, or lifted;
- The palms and wrist cuff can be used;
- Shapes of individual parts of the hand and combinations of them can be recognized.

Selected combinations of such capabilities can be used to provide an extremely rich pallet of primitive control signals that can be used for a wide variety of purposes and applications.

Other HDTP Processing, Signal Flows, and Operations

In order to accomplish this range of capabilities, HDTP technologies must be able to parse tactile images and perform operations based on the parsing. In general, contact between the tactile-sensor array and multiple parts of the same hand forfeits some degrees of freedom but introduces others. For example, if the end joints of two fingers are pressed against the sensor array as in FIG. **21**, it will be difficult or impossible to induce variations in the image of one of the end joints in six different dimensions while keeping the image of the other end joints fixed. However, there are other parameters that can be varied, such as the angle between two fingers, the difference in coordinates of the finger tips, and the differences in pressure applied by each finger.

In general, compound images can be adapted to provide control over many more parameters than a single contiguous image can. For example, the two-finger postures considered above can readily pro-vide a nine-parameter set relating to the pair of fingers as a separate composite object adjustable within an ergonomically comfortable range. One example nine-parameter set the two-finger postures consider above is:

- composite average x position;
- inter-finger differential x position;
- composite average y position;
- inter-finger differential y position;
- composite average pressure;
- inter-finger differential pressure;
- composite roll;
- composite pitch;
- composite yaw.

As another example, by using the whole hand pressed flat against the sensor array including the palm and wrist, it is readily possible to vary as many as sixteen or more parameters independently of one another. A single hand held in any of a variety of arched or partially-arched postures provides a very wide range of postures that can be recognized and parameters that can be calculated.

When interpreted as a compound image, extracted parameters such as geometric center, average downward pressure, tilt (pitch and roll), and pivot (yaw) can be calculated for the entirety of the asterism or constellation of smaller blobs. Additionally, other parameters associated with the asterism or constellation can be calculated as well, such as the aforementioned angle of separation between the fingers. Other examples include the difference in downward pressure applied by the two fingers, the difference between the left-right ("x") centers of the two fingertips, and the difference between the two forward-back ("y") centers of the two fingertips. Other compound image parameters are possible and are provided by HDTP technology.

There are number of ways for implementing the handling of compound posture data images. Two contrasting examples are depicted in FIGS. **22**_a_-**22**_b_ (adapted from U.S. patent application Ser. No. 12/418,605) although many other possibilities exist and are provided for by the invention. In the embodiment of FIG. **22**_a_, tactile image data is examined for the number "M" of isolated blobs ("regions") and the primitive running sums are calculated for each blob. This can be done, for example, with the algorithms described earlier. Post-scan calculations can then be performed for each blob, each of these producing an extracted parameter set (for example, x position, y position, average pressure, roll, pitch, yaw) uniquely associated with each of the M blobs ("regions"). The total number of blobs and the extracted parameter sets are directed to a compound image parameter mapping function to produce various types of outputs, including:

- Shape classification (for example finger tip, first-joint flat finger, two-joint flat finger, three joint-flat finger, thumb, palm, wrist, compound two-finger, compound three-finger, composite 4-finger, whole hand, etc.);
- Composite parameters (for example composite x position, composite y position, composite average pressure, composite roll, composite pitch, composite yaw, etc.);
- Differential parameters (for example pair-wise inter-finger differential x position, pair-wise inter-finger differential y position, pair-wise inter-finger differential pressure, etc.);
- Additional parameters (for example, rates of change with respect to time, detection that multiple finger images involve multiple hands, etc.).

FIG. **22**_b_ depicts an alternative embodiment, tactile image data is examined for the number M of isolated blobs ("regions") and the primitive running sums are calculated for each blob, but this information is directed to a multi-regional tactile image parameter extraction stage. Such a stage can include, for example, compensation for minor or major ergonomic interactions among the various degrees of postures of the hand. The resulting compensation or otherwise produced extracted parameter sets (for example, x position, y position, average pressure, roll, pitch, yaw) uniquely associated with each of the M blobs and total number of blobs are directed to a compound image parameter mapping function to produce various types of outputs as described for the arrangement of FIG. **22**_a_.

Additionally, embodiments of the invention can be set up to recognize one or more of the following possibilities:

Single contact regions (for example a finger tip);

Multiple independent contact regions (for example multiple fingertips of one or more hands);

Fixed-structure ("constellation") compound regions (for example, the palm, multiple-joint finger contact as with a flat finger, etc.);

Variable-structure ("asterism") compound regions (for example, the palm, multiple-joint finger contact as with a flat finger, etc.).

Embodiments that recognize two or more of these possibilities can further be able to discern and process combinations of two more of the possibilities.

FIG. **22***c* (adapted from U.S. patent application Ser. No. 12/418,605) depicts a simple system for handling one, two, or more of the above listed possibilities, individually or in combination. In the general arrangement depicted, tactile sensor image data is analyzed (for example, in the ways described earlier) to identify and isolate image data associated with distinct blobs. The results of this multiple-blob accounting is directed to one or more global classification functions set up to effectively parse the tactile sensor image data into individual separate blob images or individual compound images. Data pertaining to these individual separate blob or compound images are passed on to one or more parallel or serial parameter extraction functions. The one or more parallel or serial parameter extraction functions can also be provided information directly from the global classification function(s). Additionally, data pertaining to these individual separate blob or compound images are passed on to additional image recognition function(s), the output of which can also be provided to one or more parallel or serial parameter extraction function(s). The output(s) of the parameter extraction function(s) can then be either used directly, or first processed further by parameter mapping functions. Clearly other implementations are also possible to one skilled in the art and these are provided for by the invention.

Refining of the HDTP User Experience

As an example of user-experience correction of calculated parameters, it is noted that placement of hand and wrist at a sufficiently large yaw angle can affect the range of motion of tilting. As the rotation angle increases in magnitude, the range of tilting motion decreases as mobile range of human wrists gets restricted. The invention provides for compensation for the expected tilt range variation as a function of measured yaw rotation angle. An embodiment is depicted in the middle portion of FIG. **23** (adapted from U.S. patent application Ser. No. 12/418,605). As another example of user-experience correction of calculated parameters, the user and application can interpret the tilt measurement in a variety of ways. In one variation for this example, tilting the finger can be interpreted as changing an angle of an object, control dial, etc. in an application. In another variation for this example, tilting the finger can be interpreted by an application as changing the position of an object within a plane, shifting the position of one or more control sliders, etc. Typically each of these interpretations would require the application of at least linear, and typically nonlinear, mathematical transformations so as to obtain a matched user experience for the selected metaphor interpretation of tilt. In one embodiment, these mathematical transformations can be performed as illustrated in the lower portion of FIG. **23**. The invention provides for embodiments with no, one, or a plurality of such metaphor interpretation of tilt.

As the finger is tilted to the left or right, the shape of the area of contact becomes narrower and shifts away from the center to the left or right. Similarly as the finger is tilted forward or backward, the shape of the area of contact becomes shorter and shifts away from the center forward or backward. For a better user experience, the invention provides for embodiments to include systems and methods to compensate for these effects (i.e. for shifts in blob size, shape, and center) as part of the tilt measurement portions of the implementation. Additionally, the raw tilt measures can also typically be improved by additional processing. FIG. **24***a* (adapted from U.S. patent application Ser. No. 12/418,605) depicts an embodiment wherein the raw tilt measurement is used to make corrections to the geometric center measurement under at least conditions of varying the tilt of the finger. Additionally, the invention provides for yaw angle compensation for systems and situations wherein the yaw measurement is sufficiently affected by tilting of the finger. An embodiment of this correction in the data flow is shown in FIG. **24***b* (adapted from U.S. patent application Ser. No. 12/418,605).

Additional HDTP Processing, Signal Flows, and Operations

FIG. **25** (adapted from U.S. patent application Ser. No. 12/418,605 and described in U.S. Pat. No. 6,570,078) shows an example of how raw measurements of the six quantities of FIGS. **17***a*-**17***f*, together with shape recognition for distinguishing contact with various parts of hand and touchpad, can be used to create a rich information flux of parameters, rates, and symbols.

FIG. **26** (adapted from U.S. patent application Ser. No. 12/418,605 and described in U.S. Pat. No. 6,570,078) shows an approach for incorporating posture recognition, gesture recognition, state machines, and parsers to create an even richer human/machine tactile interface system capable of incorporating syntax and grammars.

The HDTP affords and provides for yet further capabilities. For example, sequence of symbols can be directed to a state machine, as shown in FIG. **27***a* (adapted from U.S. patent application Ser. No. 12/418,605 and described in U.S. Pat. No. 6,570,078), to produce other symbols that serve as interpretations of one or more possible symbol sequences. In an embodiment, one or more symbols can be designated the meaning of an "Enter" key, permitting for sampling one or more varying parameter, rate, and symbol values and holding the value(s) until, for example, another "Enter" event, thus producing sustained values as illustrated in FIG. **27***b* (adapted from U.S. patent application Ser. No. 12/418,605 and described in U.S. Pat. No. 6,570,078). In an embodiment, one or more symbols can be designated as setting a context for interpretation or operation and thus control mapping or assignment operations on parameter, rate, and symbol values as shown in FIG. **27***c* (adapted from U.S. patent application Ser. No. 12/418,605 and described in U.S. Pat. No. 6,570,078). The operations associated with FIGS. **27***a*-**27***c* can be combined to provide yet other capabilities. For example, the arrangement of FIG. **26***d* shows mapping or assignment operations that feed an interpretation state machine which in turn controls mapping or assignment operations. In implementations where context is involved, such as in arrangements such as those depicted in FIGS. **27***b*-**27***d*, the invention provides for both context-oriented and context-free production of parameter, rate, and symbol values. The parallel production of context-oriented and context-free values can be useful to drive multiple applications simultaneously, for data recording, diagnostics, user feedback, and a wide range of other uses.

FIG. **28** (adapted from U.S. patent application Ser. Nos. 12/502,230 and 13/026,097) depicts a user arrangement incorporating one or more HDTP system(s) or subsystem(s) that provide(s) user interface input event and routing of HDTP produced parameter values, rate values, symbols, etc. to a variety of applications. In an embodiment, these parameter values, rate values, symbols, etc. can be produced for example by utilizing one or more of the individual systems, individual methods, and individual signals described above in conjunction with the discussion of FIGS. **25**, **26**, and **27***a*-**27***b*. As discussed later, such an approach can be used with other rich multiparameter user interface devices in place of the HDTP. The arrangement of FIG. **27** is taught in pending U.S. patent application Ser. No. 12/502,230 "Control of Computer Window Systems, Computer Applications, and Web Applications via High Dimensional Touchpad User Interface" and FIG. **28** is adapted from FIG. 6e of pending U.S. patent application Ser. No. 12/502,230 for use here. Some aspects of this (in the sense of general workstation control) is anticipated in U.S. Pat. No. 6,570,078 and further aspects of this material are taught in pending U.S. patent application Ser. No. 13/026,097 "Window Manger Input Focus Control for High Dimensional Touchpad (HDTP), Advanced Mice, and Other Multidimensional User Interfaces."

In an arrangement such as the one of FIG. **28**, or in other implementations, at least two parameters are used for navigation of the cursor when the overall interactive user interface system is in a mode recognizing input from cursor control. These can be, for example, the left-right ("x") parameter and forward/back ("y") parameter provided by the touchpad. The arrangement of FIG. **28** includes an implementation of this.

Alternatively, these two cursor-control parameters can be provided by another user interface device, for example another touchpad or a separate or attached mouse.

In some situations, control of the cursor location can be implemented by more complex means. One example of this would be the control of location of a 3D cursor wherein a third parameter must be employed to specify the depth coordinate of the cursor location. For these situations, the arrangement of FIG. **28** would be modified to include a third parameter (for use in specifying this depth coordinate) in addition to the left-right ("x") parameter and forward/back ("y") parameter described earlier.

Focus control is used to interactively routing user interface signals among applications. In most current systems, there is at least some modality wherein the focus is determined by either the current cursor location or a previous cursor location when a selection event was made. In the user experience, this selection event typically involves the user interface providing an event symbol of some type (for example a mouse click, mouse double-click touchpad tap, touchpad double-tap, etc). The arrangement of FIG. **28** includes an implementation wherein a select event generated by the touchpad system is directed to the focus control element. The focus control element in this arrangement in turn controls a focus selection element that directs all or some of the broader information stream from the HDTP system to the currently selected application. (In FIG. **28**, "Application K" has been selected as indicated by the thick-lined box and information-flow arrows.)

In some embodiments, each application that is a candidate for focus selection provides a window displayed at least in part on the screen, or provides a window that can be deiconified from an icon tray or retrieved from beneath other windows that can be obfuscating it. In some embodiments, if the background window is selected, focus selection element that directs all or some of the broader information stream from the HDTP system to the operating system, window system, and features of the background window. In some embodiments, the background window can be in fact regarded as merely one of the applications shown in the right portion of the arrangement of FIG. **28**. In other embodiments, the background window can be in fact regarded as being separate from the applications shown in the right portion of the arrangement of FIG. **28**. In this case the routing of the broader information stream from the HDTP system to the operating system, window system, and features of the background window is not explicitly shown in FIG. **28**.

Use of the Additional HDTP Parameters by Applications

The types of human-machine geometric interaction between the hand and the HDTP facilitate many useful applications within a visualization environment. A few of these include control of visualization observation viewpoint location, orientation of the visualization, and controlling fixed or selectable ensembles of one or more of viewing parameters, visualization rendering parameters, pre-visualization operations parameters, data selection parameters, simulation control parameters, etc. As one example, the 6D orientation of a finger can be naturally associated with visualization observation viewpoint location and orientation, location and orientation of the visualization graphics, etc. As another example, the 6D orientation of a finger can be naturally associated with a vector field orientation for introducing synthetic measurements in a numerical simulation.

As another example, at least some aspects of the 6D orientation of a finger can be naturally associated with the orientation of a robotically positioned sensor providing actual measurement data. As another example, the 6D orientation of a finger can be naturally associated with an object location and orientation in a numerical simulation. As another example, the large number of interactive parameters can be abstractly associated with viewing parameters, visualization rendering parameters, pre-visualization operations parameters, data selection parameters, numeric simulation control parameters, etc.

In yet another example, the x and y parameters provided by the HDTP can be used for focus selection and the remaining parameters can be used to control parameters within a selected GUI.

In still another example, x and y parameters provided by the HDTP can be regarded as a specifying a position within an underlying base plane and the roll and pitch angles can be regarded as a specifying a position within a superimposed parallel plane. In a first extension of the previous two-plane example, the yaw angle can be regarded as the rotational angle between the base and superimposed planes. In a second extension of the previous two-plane example, the finger pressure can be employed to determine the distance between the base and superimposed planes. In a variation of the previous two-plane example, the base and superimposed plane are not fixed parallel but rather intersect in an angle responsive to the finger yaw angle. In each example, either or both of the two planes can represent an index or indexed data, a position, a pair of parameters, etc. of a viewing aspect, visualization rendering aspect, pre-visualization operations, data selection, numeric simulation control, etc.

A large number of additional approaches are possible as is appreciated by one skilled in the art. These are provided for by the invention.

Support for Additional Parameters Via Browser Plug-Ins

The additional interactively-controlled parameters provided by the HDTP provide more than the usual number supported by conventional browser systems and browser networking environments. This can be addressed in a number of ways. The following examples of HDTP arrangements for use with browsers and servers are taught in pending U.S. patent application Ser. No. 12/875,119 entitled "Data Visualization Environment with Dataflow Processing, Web, Collaboration, High-Dimensional User Interfaces, Spreadsheet Visualization, and Data Sonification Capabilities."

In a first approach, an HDTP interfaces with a browser both in a traditional way and additionally via a browser plug-in. Such an arrangement can be used to capture the additional user interface input parameters and pass these on to an application interfacing to the browser. An example of such an arrangement is depicted in FIG. **29***a*.

In a second approach, an HDTP interfaces with a browser in a traditional way and directs additional GUI parameters though other network channels. Such an arrangement can be used to capture the additional user interface input parameters and pass these on to an application interfacing to the browser. An example of such an arrangement is depicted in FIG. **29***b*.

In a third approach, an HDTP interfaces all parameters to the browser directly. Such an arrangement can be used to capture the additional user interface input parameters and pass these on to an application interfacing to the browser. An example of such an arrangement is depicted in FIG. **29***c*.

The browser can interface with local or web-based applications that drive the visualization and control the data source(s), process the data, etc. The browser can be provided with client-side software such as JAVA Script or other alternatives. The browser can provide also be configured advanced graphics to be rendered within the browser display environment, allowing the browser to be used as a viewer for data visualizations, advanced animations, etc., leveraging the additional multiple parameter capabilities of the HDTP. The browser can interface with local or web-based applications that drive the advanced graphics. In an embodiment, the browser can be provided with Simple Vector Graphics ("SVG") utilities (natively or via an SVG plug-in) so as to render basic 2D vector and raster graphics. In another embodiment, the browser can be provided with a 3D graphics capability, for example via the Cortona 3D browser plug-in.

Multiple Parameter Extensions to Traditional Hypermedia Objects

As taught in pending U.S. patent application Ser. No. 13/026,248 entitled "Enhanced Roll-Over, Button, Menu, Slider, and Hyperlink Environments for High Dimensional Touchpad (HTPD), other Advanced Touch User Interfaces, and Advanced Mice", the HDTP can be used to provide extensions to the traditional and contemporary hyperlink, roll-over, button, menu, and slider functions found in web browsers and hypermedia documents leveraging additional user interface parameter signals provided by an HTPD. Such extensions can include, for example:

- In the case of a hyperlink, button, slider and some menu features, directing additional user input into a hypermedia "hotspot" by clicking on it;
- In the case of a roll-over and other menu features: directing additional user input into a hypermedia "hotspot" simply from cursor overlay or proximity (i.e., without clicking on it);

The resulting extensions will be called "Multiparameter Hypermedia Objects" ("MHOs").

Potential uses of the MHOS and more generally extensions provided for by the invention include:

- Using the additional user input to facilitate a rapid and more detailed information gathering experience in a low-barrier sub-session;
- Potentially capturing notes from the sub-session for future use;
- Potentially allowing the sub-session to retain state (such as last image displayed);
- Leaving the hypermedia "hotspot" without clicking out of it.

A number of user interface metaphors can be employed in the invention and its use, including one or more of:

- Creating a pop-up visual or other visual change responsive to the rollover or hyperlink activation;
- Rotating an object using rotation angle metaphors provided by the APD;
- Rotating a user-experience observational viewpoint using rotation angle metaphors provided by the APD, for example, as described in pending U.S. patent application Ser. No. 12/502,230 "Control of Computer Window Systems, Computer Applications, and Web Applications via High Dimensional Touchpad User Interface" by Seung Lim;
- Navigating at least one (1-dimensional) menu, (2-dimensional) pallet or hierarchical menu, or (3-dimensional) space.

These extensions, features, and other aspects of the present invention permit far faster browsing, shopping, information gleaning through the enhanced features of these extended functionality roll-over and hyperlink objects.

In addition to MHOS that are additional-parameter extensions of traditional hypermedia objects, new types of MHOS unlike traditional or contemporary hypermedia objects can be implemented leveraging the additional user interface parameter signals and user interface metaphors that can be associated with them. Illustrative examples include:

- Visual joystick (can keep position after release, or return to central position after release);
- Visual rocker-button (can keep position after release, or return to central position after release);
- Visual rotating trackball, cube, or other object (can keep position after release, or return to central position after release);
- A small miniature touchpad).

Yet other types of MHOS are possible and provided for by the invention. For example:

- The background of the body page can be configured as an MHO;
- The background of a frame or isolated section within a body page can be configured as an MHO;
- An arbitrarily-shaped region, such as the boundary of an entity on a map, within a photograph, or within a graphic can be configured as an MHO.

In any of these, the invention provides for the MHO to be activated or selected by various means, for example by clicking or tapping when the cursor is displayed within the area, simply having the cursor displayed in the area (i.e., without clicking or tapping, as in rollover), etc. Further, it is anticipated that variations on any of these and as well as other new types of MHOS can similarly be crafted by those skilled in the art and these are provided for by the invention.

User Training

Since there is a great deal of variation from person to person, it is useful to include a way to train the invention to the particulars of an individual's hand and hand motions. For example, in a computer-based application, a measurement training procedure will prompt a user to move their finger around within a number of different positions while it records the shapes, patterns, or data derived from it for later use specifically for that user.

Typically most finger postures make a distinctive pattern. In one embodiment, a user-measurement training procedure could involve having the user prompted to touch the tactile sensor array in a number of different positions, for example as depicted in FIG. **30***a* (adapted from U.S. patent application

Ser. No. 12/418,605). In some embodiments only representative extreme positions are recorded, such as the nine postures **3000-3008**. In yet other embodiments, or cases wherein a particular user does not provide sufficient variation in image shape, additional postures can be included in the measurement training procedure, for example as depicted in FIG. **30***b* (adapted from U.S. patent application Ser. No. 12/418,605). In some embodiments, trajectories of hand motion as hand contact postures are changed can be recorded as part of the measurement training procedure, for example the eight radial trajectories as depicted in FIGS. **30***a*-**30***b*, the boundary-tracing trajectories of FIG. **30***c* (adapted from U.S. patent application Ser. No. 12/418,605), as well as others that would be clear to one skilled in the art. All these are provided for by the invention.

The range in motion of the finger that can be measured by the sensor can subsequently be re-corded in at least two ways. It can either be done with a timer, where the computer will prompt user to move his finger from position **3000** to position **3001**, and the tactile image imprinted by the finger will be recorded at points **3001.3**, **3001.2** and **3001.1**. Another way would be for the computer to query user to tilt their finger a portion of the way, for example "Tilt your finger ⅔ of the full range" and record that imprint. Other methods are clear to one skilled in the art and are provided for by the invention.

Additionally, this training procedure allows other types of shapes and hand postures to be trained into the system as well. This capability expands the range of contact possibilities and applications considerably. For example, people with physical handicaps can more readily adapt the system to their particular abilities and needs.

Data Flow and Parameter Refinement

FIG. **31** depicts a HDTP signal flow chain for an HDTP realization that can be used, for example, to implement multi-touch, shape and constellation (compound shape) recognition, and other HDTP features. After processing steps that can for example, comprise one or more of blob allocation, blob classification, and blob aggregation (these not necessarily in the order and arrangement depicted in FIG. **31**), the data record for each resulting blob is processed so as to calculate and refine various parameters (these not necessarily in the order and arrangement depicted in FIG. **31**).

For example, a blob allocation step can assign a data record for each contiguous blob found in a scan or other processing of the pressure, proximity, or optical image data obtained in a scan, frame, or snapshot of pressure, proximity, or optical data measured by a pressure, proximity, or optical tactile sensor array or other form of sensor. This data can be previously preprocessed (for example, using one or more of compensation, filtering, thresholding, and other operations) as shown in the figure, or can be presented directly from the sensor array or other form of sensor. In some implementations, operations such as compensation, thresholding, and filtering can be implemented as part of such a blob allocation step. In some implementations, the blob allocation step provides one or more of a data record for each blob comprising a plurality of running sum quantities derived from blob measurements, the number of blobs, a list of blob indices, shape information about blobs, the list of sensor element addresses in the blob, actual measurement values for the relevant sensor elements, and other information. A blob classification step can include for example shape information and can also include information regarding individual noncontiguous blobs that can or should be merged (for example, blobs representing separate segments of a finger, blobs representing two or more fingers or parts of the hand that are in at least a particular instance are to be treated as a common blob or otherwise to be associated with one another, blobs representing separate portions of a hand, etc.). A blob aggregation step can include any resultant aggregation operations including, for example, the association or merging of blob records, associated calculations, etc. Ultimately a final collection of blob records are produced and applied to calculation and refinement steps used to produce user interface parameter vectors. The elements of such user interface parameter vectors can comprise values responsive to one or more of forward-back position, left-right position, downward pressure, roll angle, pitch angle, yaw angle, etc from the associated region of hand input and can also comprise other parameters including rates of change of there or other parameters, spread of fingers, pressure differences or proximity differences among fingers, etc. Additionally there can be interactions between refinement stages and calculation stages, reflecting, for example, the kinds of operations described earlier in conjunction with FIGS. **23**, **24***a*, and **24***b*.

The resulting parameter vectors can be provided to applications, mappings to applications, window systems, operating systems, as well as to further HDTP processing. For example, the resulting parameter vectors can be further processed to obtain symbols, provide additional mappings, etc. In this arrangement, depending on the number of points of contact and how they are interpreted and grouped, one or more shapes and constellations can be identified, counted, and listed, and one or more associated parameter vectors can be produced. The parameter vectors can comprise, for example, one or more of forward-back, left-right, downward pressure, roll, pitch, and yaw associated with a point of contact. In the case of a constellation, for example, other types of data can be in the parameter vector, for example inter-fingertip separation differences, differential pressures, etc.

Example First-Level Measurement Calculation Chain

Attention is now directed to particulars of roll and pitch measurements of postures and gestures. FIG. **32***a* depicts a side view of an exemplary finger and illustrating the variations in the pitch angle. FIGS. **32***b*-**32***f* depict exemplary tactile image measurements (proximity sensing, pressure sensing, contact sensing, etc.) as a finger in contact with the touch sensor array is positioned at various pitch angles with respect to the surface of the sensor. In these, the small black dot denotes the geometric center corresponding to the finger pitch angle associated with FIG. **32***d*. As the finger pitch angle is varied, it can be seen that:

- the eccentricity of the oval shape changes and in the cases associated with FIGS. **32***e*-**32***f* the eccentricity change is such that the orientation of major and minor axes of the oval exchange roles;
- The position of the oval shape migrates and in the cases of FIGS. **32***b*-**32***c* and FIGS. **32***e*-**32***f* have a geometric center shifted from that of FIG. **32***d*, and in the cases of FIGS. **32***e*-**32***f* the oval shape migrates enough to no longer even overlap the geometric center of FIG. **32***d*.

From the user experience viewpoint, however, the user would not feel that a change in the front-back component of the finger's contact with the touch sensor array has changed. This implies the front-back component ("y") of the geometric center of contact shape as measured by the touch sensor array should be corrected responsive to the measured pitch angle. This suggests a final or near-final measured pitch angle value should be calculated first and used to correct the final value of the measured front-back component ("y") of the geometric center of contact shape.

Additionally, FIGS. **33***a*-**33***e* depict the effect of increased downward pressure on the respective contact shapes of FIGS. **32***b*-**32***f*. More specifically, the top row of FIGS. **33***a*-**33***e* are the respective contact shapes of FIGS. **32***b*-**32***f*, and the bottom row show the effect of increased downward pressure. In each case the oval shape expands in area (via an observable expansion in at least one dimension of the oval) which could thus shift the final value of the measured front-back component ("y"). (It is noted that for the case of a pressure sensor array, the measured pressure values measured by most or all of the sensors in the contact area would also increase accordingly.)

These and previous considerations imply:

- the pitch angle as measured by the touch sensor array could be corrected responsive to the measured downward pressure. This suggests a final or near-final measured downward pressure value should be calculated first and used to correct the final value of measured downward pressure ("p");
- the front-back component ("y") of the geometric center of contact shape as measured by the touch sensor array could be corrected responsive to the measured downward pressure. This suggests a final or near-final measured pitch angle value could be calculated first and used to correct the final value of measured downward pressure ("p").

In one approach, correction to the pitch angle responsive to measured downward pressure value can be used to correct for the effect of downward pressure on the front-back component ("y") of the geometric center of the contact shape.

FIG. **34***a* depicts a top view of an exemplary finger and illustrating the variations in the roll angle. FIGS. **34***b*-**34***f* depict exemplary tactile image measurements (proximity sensing, pressure sensing, contact sensing, etc.) as a finger in contact with the touch sensor array is positioned at various roll angles with respect to the surface of the sensor. In these, the small black dot denotes the geometric center corresponding to the finger roll angle associated with FIG. **34***d*. As the finger roll angle is varied, it can be seen that:

- The eccentricity of the oval shape changes;
- The position of the oval shape migrates and in the cases of FIGS. **34***b*-**34***c* and FIGS. **34***e*-**34***f* have a geometric center shifted from that of FIG. **34***d*, and in the cases of FIGS. **34***e*-**34***f* the oval shape migrates enough to no longer even overlap the geometric center of FIG. **34***d*.

From the user experience, however, the user would not feel that the left-right component of the finger's contact with the touch sensor array has changed. This implies the left-right component ("x") of the geometric center of contact shape as measured by the touch sensor array should be corrected responsive to the measured roll angle. This suggests a final or near-final measured roll angle value should be calculated first and used to correct the final value of the measured left-right component ("x") of the geometric center of contact shape.

As with measurement of the finger pitch angle, increasing downward pressure applied by the finger can also invoke variations in contact shape involved in roll angle measurement, but typically these variations are minor and less significant for roll measurements than they are for pitch measurements. Accordingly, at least to a first level of approximation, effects of increasing the downward pressure can be neglected in calculation of roll angle.

Depending on the method used in calculating the pitch and roll angles, it is typically advantageous to first correct for yaw angle before calculating the pitch and roll angles. One source reason for this is that (dictated by hand and wrist physiology) from the user experience a finger at some non-zero yaw angle with respect to the natural rest-alignment of the finger would impart intended roll and pitch postures or gestures from the vantage point of the yawed finger position. Without a yaw-angle correction somewhere, the roll and pitch postures and movements of the finger would resolve into rotated components. As an extreme example of this, if the finger were yawed at a 90-degree angle with respect to a natural rest-alignment, roll postures and movements would measure as pitch postures and movements while pitch postures and movements would measure as roll postures and movements. As a second example of this, if the finger were yawed at a 45-degree angle, each roll and pitch posture and movement would case both roll and pitch measurement components. Additionally, some methods for calculating the pitch and roll angles (such as curve fitting and polynomial regression methods as taught in pending U.S. patent application Ser. No. 13/038,372) work better if the blob data on which they operate is not rotated by a yaw angle. This suggests that a final or near-final measured yaw angle value should be calculated first and used in a yaw-angle rotation correction to the blob data applied to calculation of roll and pitch angles.

Regarding other calculations, at least to a first level of approximation downward pressure measurement in principle should not be affected by yaw angle. Also at least to a first level of approximation, for geometric center calculations sufficiently corrected for roll and pitch effects in principle should not be affected by yaw angle. (In practice there can be at least minor effects, to be considered and addressed later).

The example working first level of approximation conclusions together suggest a causal chain of calculation such as that depicted in FIG. **35**. FIG. **36** depicts a utilization of this causal chain as a sequence flow of calculation blocks. FIG. **36** does not, however, represent a data flow since calculations in subsequent blocks depend on blob data in ways other than as calculated in preceding blocks. More specifically as to this, FIG. **37** depicts an example implementation of a real-time calculation chain for the left-right ("x"), front-back ("y"), downward pressure ("p"), roll ("ϕ"), pitch ("θ"), and yaw ("ψ") measurements that can be calculated from blob data such as that produced in the exemplary arrangement of FIG. **31**. Examples of methods, systems, and approaches to downward pressure calculations from tactile image data in a multi-touch context are provided in pending U.S. patent application Ser. No. 12/418,605 and U.S. Pat. No. 6,570,078. Examples methods, systems, and approaches to yaw angle calculations from tactile image data are provided in pending U.S. patent application Ser. No. 12/724,413; these can be applied to a multi-touch context via arrangements such as the depicted in FIG. **31**. Examples methods, systems, and approaches to roll angle and pitch angle calculations from tactile image data in a multi-touch context are provided in pending U.S. patent application Ser. No. 12/418,605 and Ser. No. 13/038,372 as well as in U.S. Pat. No. 6,570,078 and include yaw correction considerations. Examples methods, systems, and approaches to front-back geometric center and left-right geometric center calculations from tactile image data in a multi-touch context are provided in pending U.S. patent application Ser. No. 12/418,605 and U.S. Pat. No. 6,570,078.

The yaw rotation correction operation depicted in FIG. **37** operates on blob data as a preprocessing step prior to calculations of roll angle and pitch angle calculations from blob data (and more generally from tactile image data). The yaw rotation correction operation can, for example, comprise a rotation matrix or related operation which internally comprises sine and cosine functions as is appreciated by one skilled in the art. Approximations of the full needed range of yaw angle values (for example from nearly −90 degrees through zero to nearly +90 degrees, or in a more restricted system from nearly −45 degrees through zero to nearly +45 degrees) can therefore not be realistically approximated by a linear function. The need range of yaw angles can be adequately approximated by piecewise-affine functions such as those to be described in the next section. In some implementations it will be advantageous to implement the rotation operation with sine and cosine functions in the instruction set or library of a computational processor. In other implementations it will be advantageous to implement the rotation operation with piecewise-affine functions (such as those to be described in the next section) on a computational processor.

FIG. **37** further depicts optional data flow support for correction of pitch angle measurement using downward pressure measurement (as discussed earlier). In one embodiment this correction is not done in the context of FIG. **37** and the dashed signal path is not implemented. In such circumstances either no such correction is provided, or the correction is provided in a later stage. If the correction is implemented, it can be implemented in various ways depending on approximations chosen and other considerations. The various ways include a linear function, a piecewise-linear function, an affine function, a piecewise-affine function, a nonlinear function, or combinations of two or more of these. Linear, piecewise-linear, affine, and piecewise-affine functions will be considered in the next section.

FIG. **37** further depicts optional data flow support for correction of front-back geometric center measurement using pitch angle measurement (as discussed earlier). In one embodiment this correction is not done in the context of FIG. **37** and the dashed signal path is not implemented. In such circumstances either no such correction is provided, or the correction is provided in a later stage. If the correction is implemented, it can be implemented in various ways depending on approximations chosen and other considerations. The various ways include a linear function, a piecewise-linear function, an affine function, a piecewise-affine function, a nonlinear function, or combinations of two or more of these.

FIG. **37** further depicts optional data flow support for correction of left-right geometric center measurement using roll angle measurement (as discussed earlier). In one embodiment this correction is not done in the context of FIG. **37** and the dashed signal path is not implemented. In such circumstances either no such correction is provided, or the correction is provided in a later stage. If the correction is implemented, it can be implemented in various ways depending on approximations chosen and other considerations. The various ways include a linear function, a piecewise-linear function, an affine function, a piecewise-affine function, a nonlinear function, or combinations of two or more of these.

FIG. **37** does not depict optional data flow support for correction of front-back geometric center measurement using downward pressure measurement (as discussed earlier). In one embodiment this correction is not done in the context of FIG. **37** and either no such correction is provided, or the correction is provided in a later stage. In another embodiment this correction is implemented in the example arrangement of FIG. **37**, for example through the addition of downward pressure measurement data flow support to the front-back geometric center calculation and additional calculations performed therein. In either case, if the correction is implemented, it can be implemented in various ways depending on approximations chosen and other considerations. The various ways include a linear function, a piecewise-linear function, an affine function, a piecewise-affine function, a nonlinear function, or combinations of two or more of these.

Additionally, FIG. **37** does not depict optional data flow support for the tilt refinements described in conjunction with FIG. **24***a*, the tilt-influent correction to measured yaw angle described in conjunction with FIG. **24***b*, the range-of-rotation correction described in conjunction with FIG. **23**, the correction of left-right geometric center measurement using downward pressure measurement (as discussed just a bit earlier), the correction of roll angle using downward pressure measurement (as discussed just a bit earlier), or the direct correction of front-back geometric center measurement using downward pressure measurement. There are many further possible corrections and user experience improvements that can be added in similar fashion. In one embodiment any one or more such additional corrections are not performed in the context of FIG. **37** and either no such correction is provided, or such corrections are provided in a later stage after an arrangement such as that depicted in FIG. **37**. In another embodiment one or more such corrections are implemented in the example arrangement of FIG. **37**, for example through the addition of relevant data flow support to the relevant calculation step and additional calculations performed therein. In either case, any one or more such corrections can be implemented in various ways depending on approximations chosen and other considerations. The various ways include use of a linear function, a piecewise-linear function, an affine function, a piecewise-affine function, a nonlinear function, or combinations of two or more of these.

In one approach, one or more shared environments for linear function, a piecewise-linear function, an affine function, a piecewise-affine function, or combinations of two or more of these can be provided. In an embodiment of such an approach, one or more of these one or more shared environments can be incorporated into the calculation chain depicted in FIG. **37**.

In another or related embodiment of such an approach, one or more of these one or more shared environments can be implemented in a processing stage subsequent to the calculation chain depicted in FIG. **37**. In these circumstances, the output values from the calculation chain depicted in FIG. **37** can be regarded as "first-order" or "unrefined" output values which, upon further processing by these one or more shared environments produce "second-order" or refined" output values.

Additional Parameter Refinement

Additional refinement of the parameters can be obtained by additional processing. As an example, FIG. **38** shows an arrangement of FIG. **31** wherein each raw parameter vector is provided to additional parameter refinement processing to produce a corresponding refined parameter vector. The additional parameter refinement can comprise a single stage, or can internally comprise two or more internal parameter refinement stages as suggested in FIG. **38**. The internal parameter refinement stages can be interconnected in various ways, including a simple chain, feedback and/or control paths (as suggested by the dash-line arrows within the Parameter Refinement box), as well as parallel paths (not explicitly suggested in FIG. **38**), combinations, or other topologies as may be advantageous. The individual parameter refinement stages can comprise various approaches systems and methods, for example Kalman and/or other types of statistical filters, matched filters, artificial neural networks (such as but not limited to those taught in pending U.S. provisional patent application 61/309,421), linear or piecewise-linear transformations (such as but not limited to those taught in pending U.S. Provisional Patent Application 61/327,458), nonlinear transformations, pattern recognition operations, dynamical systems, etc. In an embodiment, the parameter refinement can be provided with other information, such as the measured area of the associated blob, external shape classification of the associated blob, etc.

Segmented Classification of Parameters and Parameter Subsets

FIG. **39***a* depicts exemplary time-varying values of a parameters vector comprising left-right geometric center ("x"), forward-back geometric center ("y"), average downward pressure ("p"), clockwise-counterclockwise pivoting yaw angular rotation ("ψ"), tilting roll angular rotation ("ϕ"), and tilting pitch angular rotation ("θ") parameters calculated in real time from sensor measurement data. These parameters can be aggregated together to form a time-varying parameter vector.

FIG. **39***b* depicts an exemplary sequential classification of the parameter variations within the time-varying parameter vector according to an estimate of user intent, segmented decomposition, etc. Each such classification would deem a subset of parameters in the time-varying parameter vector as effectively unchanging while other parameters are deemed as changing. Such an approach can provide a number of advantages including:

- suppression of minor unintended variations in parameters the user does not intend to adjust within a particular interval of time;
- suppression of minor unintended variations in parameters the user effectively does not adjust within a particular interval of time;
- utilization of minor unintended variations in some parameters within a particular interval of time to aid in the refinement of parameters that are being adjusted within that interval of time;
- reduction of real-time computational load in real-time processing.

Accordingly, the invention provides, among other things, sequential selective tracking of subsets of parameters, the sequence of selections being made automatically by classifications derived from information calculated from data measured by the touchpad sensor. In one aspect of the invention, the parameters tracked at any particular moment include one or more of left-right geometric center ("x"), forward-back geometric center ("y"), average downward pressure ("p"), clockwise-counterclockwise pivoting yaw angular rotation ("ψ"), tilting roll angular rotation ("ϕ"), and tilting pitch angular rotation ("θ") parameters calculated in real time from sensor measurement data.

Typically the left-right geometric center ("x"), forward-back geometric center ("y") measurements are essentially independent and these can be tracked together if none of the other parameters only undergo minor spurious variation. An exemplary classification under such conditions could be {x,y}. For example, FIG. **39***b* depicts two exemplary intervals of time wherein the {x,y} classification is an estimated outcome.

Other motions of the finger or parts of the hand can invoke variations of not only the intended parameter but also variation in one or more other "collateral" parameters as well. One example of this is tilting roll angular rotation ("ϕ"), where rolling the finger from a fixed left-right position nonetheless causes a correlated shift in the measured and calculated left-right geometric center ("x"). In an embodiment, the classification system discerns between a pure tilting roll angular rotation ("ϕ") with no intended change in left-right position (classified for example as {ϕ}) from a mixed tilting roll angular rotation with an intended change in left-right position (classified for example as {ϕ,x}). A similar example is the tilting pitch angular rotation ("θ"), where pitching the finger from a fixed forward-back position nonetheless causes a correlated shift in the measured and calculated forward-back geometric center ("y"). In an embodiment, the classification system discerns between a pure tilting pitch angular rotation ("θ") with no intended change in forward-back position (classified for example as {θ}) from a mixed tilting roll angular rotation with an intended change in forward-back position (classified for example as {θ,y}). FIG. **39***b* depicts an exemplary interval of time wherein the {θ} classification is an estimated outcome and an exemplary interval of time wherein the {y} classification is an estimated outcome.

In a similar fashion, the invention provides for embodiments to include classifications for isolated changes in pressure {p} and isolated changes in yaw angle {ψ}. (Should it be useful, the invention also provides for embodiments to include classifications pertaining to isolated changes in left-right position {x} and/or isolated changes in forward-back position {y}.)

Also in a similar fashion, the invention provides for embodiments to include classifications pertaining to other pairs of simultaneous parameter variations, for example such as but not limited to {x,p}, {y,p}, {θ,ψ}, {θ,p}, {θ x}, {ϕ, θ}, {ϕ, ψ}, {θ, ψ}, {ϕ,p}, {ϕ, y}, {ψ, x}, {ψ, y}, etc.

FIG. **40***a* depicts an exemplary simplified arrangement wherein degrees of change per unit time of a pair of parameters can be classified for "no action" (ignore), focusing only on the variation of parameter **1**, focusing only on the variation of parameter **2**, or focusing on the joint variation of parameter **1** and parameter **2**. Here the two orthogonal axes represent the magnitude (absolute value) of the change per unit time each of the pair of parameters. In this simplified example, the resulting state-space is partitioned into the four aforementioned regions according to straight-line boundaries. FIG. **40***b* depicts another exemplary partition of the state-space according to curved boundaries. The invention provides for straight-line boundaries, curved boundaries, a mix of these, static boundary locations, conditional or controllable boundary locations, adaptive control of boundary locations, hysteretic boundary locations, etc. In an embodiment, the boundary for moving from classification A to classification B within the state-space can be different from boundary for moving from classification B to classification A within the state-space. In an embodiment, one or more boundary locations can be changed according to values and or variations in parameters other than parameter **1** and parameter **2**. In an embodiment, the boundary locations can be changed according to values and or variations in other quantities, such as the measured area of the associated blob, external shape classification of the associated blob, etc. In an aspect of the invention, the classifications are made by an artificial neural network.

Also in a similar fashion, the invention provides for embodiments to include classifications pertaining to other triples of parameter variations, for example such as but not limited to {x,y,p}, {ϕ,θ,ψ}, {θ,p}, {θ,x,p}, {ϕ,θ,p}, {ϕ,ψ p}, {θ,ψ}, {ϕ,p}, {ϕ, y, p}, {ψ, x, p}, {ψ, y, p}, etc. FIG. **40***c* depicts an exemplary simplified arrangement wherein degrees of change per unit time of a triple of parameters can be classified for:

- "no action" (ignore),
- focusing only on the variation of parameter **1**,
- focusing only on the variation of parameter **2**,
- focusing only on the variation of parameter **3**,
- focusing only on the joint variation of parameter **1** and parameter **2**.
- focusing only on the joint variation of parameter **1** and parameter **3**.
- focusing only on the joint variation of parameter **2** and parameter **3**.
- focusing only on the joint variation of parameter **1**, parameter **2**, and parameter **3**.

Here the three orthogonal axes represent the magnitude (absolute value) of the change per unit time each of the pair of parameters. In this simplified example, the resulting state-space is partitioned into the eight aforementioned regions according to straight-line boundaries. However, this is merely exemplary; the invention provides for straight-line boundaries, curved boundaries, a mix of these, static boundary locations, conditional or controllable boundary locations, adaptive control of boundary locations, hysteretic boundary locations, etc. In an embodiment, the boundary for moving from classification A to classification B within the state-space can be different from boundary for moving from classification B to classification A within the state-space. In an embodiment, one or more boundary locations can be changed according to values and or variations in parameters other than parameter **1**, parameter **2**, and parameter **3**. In an embodiment, the boundary locations can be changed according to values and or variations in other quantities, such as the measured area of the associated blob, external shape classification of the associated blob, etc.

In an embodiment the invention provides for including classifications pertaining to four parameter variations. The four dimensional present/nonpresent state-space would comprise $2^4=16$ classification regions.

The boundaries between such classification regions can comprise straight-line boundaries, curved boundaries, a mix of these, static boundary locations, conditional or controllable boundary locations, adaptive control of boundary locations, hysteretic boundary locations, etc. In an embodiment, the boundary for moving from classification A to classification B within the state-space can be different from boundary for moving from classification B to classification A within the state-space. In an embodiment, one or more boundary locations can be changed according to values and or variations in parameters other than the four associated with the state-space. In an embodiment, the boundary locations can be changed according to values and or variations in other quantities, such as the measured area of the associated blob, external shape classification of the associated blob, etc. In various approaches to this provided for by the invention, the classifications can be made by one or more of heuristics, an artificial neural network, a genetic algorithm.

In an embodiment the invention provides for including classifications pertaining to five parameter variations. The five dimensional state-space would comprise 32 classification regions. The boundaries between classification regions can comprise straight-line boundaries, curved boundaries, a mix of these, static boundary locations, conditional or controllable boundary locations, adaptive control of boundary locations, hysteretic boundary locations, etc. In an embodiment, the boundary for moving from classification A to classification B within the state-space can be different from boundary for moving from classification B to classification A within the state-space. In an embodiment, one or more boundary locations can be changed according to values and or variations in parameters other than the four associated with the state-space. In an embodiment, the boundary locations can be changed according to values and or variations in other quantities, such as the measured area of the associated blob, external shape classification of the associated blob, etc. In an aspect of the invention, the classifications are made by an artificial neural network.

In an embodiment the invention provides for including classifications pertaining to all six parameter variations. The five dimensional state-space would comprise 64 classification regions. The boundaries between classification regions can comprise straight-line boundaries, curved boundaries, a mix of these, static boundary locations, conditional or controllable boundary locations, adaptive control of boundary locations, hysteretic boundary locations, etc. In an embodiment, the boundary for moving from classification A to classification B within the state-space can be different from boundary for moving from classification B to classification A within the state-space. In an embodiment, the boundary locations can be changed according to values and or variations in other quantities, such as the measured area of the associated blob, external shape classification of the associated blob, etc. In an aspect of the invention, the classifications are made by an artificial neural network.

More generally, design consideration can include the number of gestures and parts of gestures (or "gesture primitives") to be discerned. For example:

- For recognition of each of the individual 6D actions of a single finger, there are six cases to recognize {x, y, pressure, roll, pitch, yaw}
- For recognition of pairs of the individual 6D actions of a single finger, there are

$$\binom{6}{2} = 15 \text{ possibilities;}$$

- For recognition of triples of the individual 6D actions of a single finger, there are

$$\binom{6}{3} = 20 \text{ possibilities;}$$

- For recognition of groups of 4 of the individual 6D actions of a single finger, there are

$$\binom{6}{4} = 15 \text{ possibilities;}$$

- For recognition of groups of 4 of the individual 6D actions of a single finger, there are

$$\binom{6}{5} = 6 \text{ possibilities;}$$

- For recognition of groups of 4 of the individual 6D actions of a single finger at once, there is 1 possibility.

In general there can be up to 6+15+20+15+6+1=63 types of potentially discernable motions, and if these are to be further distinguished by direction, there can be considerably more.

FIG. **41***a* illustrates an exemplary arrangement for a type of parameter refinement processing stage as can be advantageously comprised in the exemplary arrangements depicted in FIG. **31** or FIG. **38**. In this exemplary parameter refinement processing stage architecture, an incoming parameter vector is presented to a classifier element. The output from the classifier element controls the selection of motion followers, each associated with one or more classifications. In this exemplary arrangement, the resulting arrangement provides current values of outgoing parameters rather than changes in them. Accordingly, the output from the classifier element also controls the selection of memory arrangements for retaining the values of parameters that are not currently being tracked so as to provide smooth operation.

FIG. **41**b illustrates an exemplary variation on the exemplary arrangement depicted in FIG. **41**b wherein the resulting arrangement provides changes in parameter values. In this exemplary arrangement, no ignored parameter value memory arrangements are employed. In an alternate embodiment, ignored parameter value memory arrangements can be included. The invention also provides for parameter value memory within the classifier element. The invention also provides for various combinations and adaptations of the aforedescribed arrangements.

FIG. **42**a and FIG. **42**b depict exemplary motion followers that can be employed within the exemplary arrangements of FIG. **41**a and FIG. **41**b as well as variations on these and combinations of these. In general there can be up to 6+15+20+15+6+1=63 types of potentially discernable motions, and if these are distinguished by direction, there can be considerably more.

The arrangements discussed thus far can be used for a variety of purposes in a HDTP system, for example:

- to suppress spurious "noise" in user interface output
- to aid in identifying user intent and accordingly suppressing some changes in gesture parameter outputs
- as "symbol" outputs of a HDTP system
- as primitive elements used in the recognition of and parameter extractions from larger, longer, and/or more complex gestures

A more detailed example is now provided.

Example Sequential Classification Recognition of Gesture Primitives

In an example implementation, the detection of entire gestures and/or components of gestures ("gesture primitives") from a sequence of frames of sequential tactile image data is treated as a real-time sequential pattern recognition problem. This type of pattern recognition problem is formally referred as "sequence labeling" [1] and in this context is often employed in speech recognition. For purposes here, a formalization of real-time sequence labeling relevant to the present invention is:

Given an input observation sequence (which can result from a window operation imposed on in a longer observation sequence) of T elements:

$$X=\{x^1, \ldots, x^T\}$$

and a set of distinct classifications

$$C=\{C^1, \ldots, C^m\}$$

perform a multiclass classification operation to produce an output label sequence of T elements:

$$Y=\{y^1, \ldots, y^T\}$$

Here C serves as the set of gestures to be recognized.

Note in an alternate formulation the output label sequence need not have the as many elements in it as the input observation sequence. For example, the output label sequence need not be produced with the same frequency as the input sequence. Thus, more generally

Given an input observation sequence (which can result from a window operation imposed on in a longer observation sequence) of Tin elements:

$$X=\{x^1, \ldots, x^{Tin}\}$$

and a set of distinct classifications

$$C=\{C^1, \ldots, C^m\}$$

perform a multiclass classification operation to produce an output label sequence of T elements:

$$Y=\{y^1, \ldots, y^{Tout}\}$$

Although there are a wide variety of possible positions and gestures a user can perform on the HDTP, it is instructive to consider a few of the most basic gesture involving variation over a (typically short) duration of time of single individual finger orientations from the list below:

- Sway: User changes x coordinate of centroid position by swiping finger in left to right or in right to left direction;
- Surge: User changes y coordinate of centroid position by swiping finger towards or away from the user;
- Heave: User changes avgp (average pressure) by varying the pressure applied to or removed from otherwise static finger on HDTP touch surface;
- Yaw: User changes yaw angle ψ by varying the ψ Euler angle [2] of the figure orientation with respect to the plane of the HDTP touch surface;
- Roll: User changes the roll angle ϕ by varying the ϕ Euler angle of the figure orientation with respect to the plane of the HDTP touch surface;
- Pitch: User changes the pitch angle θ by varying the θ Euler angle of the figure orientation with respect to the plane of the HDTP touch surface;

As a simple example, if each of these six gestures is allowed two states of existence, one for each direction of variation:

Sway left, Sway right
Surge forward, Surge back
Heave decrease, Heave increase
Yaw CCW, Yaw CW
Roll left, Roll right
Pitch down, Pitch up

A null symbol (indicating that none of these cases were recognized) can be added to give a total of 13 possible classes comprised by C for the multiclass classification operation. As another example, if each of these six gestures is allowed only one state of existence, and a null symbol (indicating that none of these cases were recognized) is added, there are a total of 7 possible classes comprised by C for the multiclass classification operation.

Conditions that are candidates for the null symbol can include the following three conditions:

1. No finger in contact with the HDTP surface;
2. A finger is in contact with the HDTP surface but there is no significant variation;
3. A finger is in contact with the HDTP surface and there is variation, but the variation is not recognized.

Thus suggests opportunities for creating more than one type of null classification, especially since some of the conditions can be used for other purposes. For example, for at least condition 3 it may be advantageous to direct the surge and sway measurements for use in cursor control ("tracking") directed to a user interface mouse driver function or equivalent. If such a user interface mouse driver function or equivalent operates robustly, all three of the above conditions may be lumped together into a single classification. In other implementations, condition 1 can be of interest as it can be used to signify the need for attention, a gesture execution delimited ("such as "lift-off" and "finger-down"), etc. As another example, condition 2 may be used as part of a gesture, as a grammatical delimiter within sequence of gestures, etc. In some situations it is likely useful to have separate labels for at least two (if not all) of conditions 1-3 and logical "OR" operations can be done upon these for various consumers of this status information.

Using the raw parameter calculations for each of the six parameters (as well as other possible derived quantities such as contact image area, yaw eigensystem eigenvectors, etc.) on the tactile image data comprised by each sensor system provided tactile image frame, at a given time t each tactile image frame could be represented in the next portion of the HDTP system by a vector of signals. As example of such a vector of signal:

$$s_t=\{M_{0,0},avgp,bcx,bcy,cx,cy,eigv1,eigv2,\phi,\psi,\theta\}$$

wherein the discrete Cartesian moments (sometimes referred as image moments [3]) for a gray scale image of size M by N with pixel intensities I(x,y) are defined as:

$$\tilde{M}_{p,q} = \sum_{x=1}^{M}\sum_{y=1}^{N} x^p y^q I(x, y)$$

and for its thresholded binary-valued (silhouette) image:

$$I_{step}(x, y) = \begin{vmatrix} 1 & \text{if } I(x, y) \geq \text{threshold} \\ 0 & \text{if } I(x, y) < \text{threshold} \end{vmatrix}$$

$$M_{p,q} = \sum_{x=1}^{M}\sum_{y=1}^{N} x^p y^q I_{step}(x, y)$$

$$avgp = \frac{\tilde{M}_{0,0}}{M_{0,0}}$$

The notation $\tilde{M}_{p,q}$ signifies a moment of original image I(x,y), while the notation $M_{p,q}$ signifies a moment of thresholded binary-valued image I_{step}(x,y). The two first order moments are used to find the geometric center of the frame image. If applied to a binary image and the results are then normalized with respect to the total area ($M_{0,0}$), the result

$$bcx = \frac{M_{1,0}}{M_{0,0}}$$

$$bcy = \frac{M_{0,1}}{M_{0,0}}$$

provides the centroid (bcx, bcy) whose physical meaning amounts to the "geometric center" of the thresholded binary-valued image. A similar pair of signals calculated on the original image (cx, cy):

$$cx = \frac{\tilde{M}_{1,0}}{M_{0,0}}$$

$$cy = \frac{\tilde{M}_{0,1}}{M_{0,0}}$$

amounts to the "weighted center."

As an example, consider a "sliding window" implementation wherein the classification of a sample at time t is made based on a set comprising w current and previous observations s_τ:

$$\{s_t, s_{t-1}, \ldots, s_{t-(w-1)}\}.$$

The number w will be called the "window size." In an implementation, choice of a specific value for the window size w can be based on one or more factors such as sampling rate, average gesture duration, shortest gesture duration, longest allowed gesture duration, etc. The value for the window size w can selected by a priori design or experimentally.

To make the HDTP more responsive and limit computational complexity and real-time computational loading it can be desirable to keep the window smaller. Note that for example, in responding to transients in touch the system can include a delay of up to w observation times. Note that the classifications can be structured to include more responsive initial classifications at the beginning of a variation. Such an arrangement, however, can in many circumstances create erratic behavior. In a typical implementation it is reasonable to consider a window size value in the range of 10 to 30, depending on attributes of the sensor, sampling times, and aspects of the desired user experience.

In an example implementation, at every associated time step in the system the input to a "classifier" (performing multiclass classification operations) is the concatenation x_t comprising the w most recent signal vectors:

$$x_t=\{s_t, s_{t-1}, \ldots, s_{t-(w-1)}\}.$$

At each time step t this "sliding window" concatenation of observations x_t is presented to a classifier.

In an example implementation, an Artificial Neural Network ("ANN") can be used as a classifier. Alternatively, a heuristic-based classifying implementation can be used. As another alternative, a genetic algorithm classifying implementation can be used. As another example, a classifying implementation can comprise two or more of an ANN, heuristic-based, and genetic algorithm aspects or components. Yet other approaches are possible and are provided for by the invention.

Example Use of Artificial Neural Network as a Classifier

Here an example implementation is presented employing an Artificial Neural Network ("ANN") as a classifier. As mentioned above, other approaches are possible and are provided for by the invention, and thus this illustrative is example is in no way limiting.

In one approach to an implementation, the input of the classifier at time step t is the "sliding window" of observations x_t. The associated output label sequence produced by a classifier could be interpreted as a vector of probabilities for each label from set C.

In an example ANN implementation, a simple back-propagation ANN with two hidden layers can be used as a classifier (for example the FANN library [4]. Hidden layers can be implemented for example using a hyperbolic tangent (tan h) activation function. The ANN output layer can be implemented for example using a logistic activation function.

In an example ANN implementation, a separate output is associated with each of the labels in the set C. Use of logistic activation functions to produce the ANN outputs is advantageous as it produces outputs in [0,1] interval which is naturally applicable for probabilistic interpretation of the likelihood of each of these labels. All of the above can be readily implemented in other ways with a wide range of variation and these are provided for by the invention.

In one approach to an implementation, the ANN outputs are used to select a label by next applying accept and reject thresholds to each of the ANN outputs. For example, a "One-of-N with Confidence Thresholds" [5] can be used wherein the label whose associated ANN output is maximal is chosen if (a) its probability is above the acceptance threshold and (b) all other label probabilities are below the rejection threshold. In an implementation, if no single label passes this composite "One-of-N with Confidence Thresholds" test, a null or tracking label can be applied. Alternatively, a "Winner-Takes-All" test can be used in place of the "One-of-N with Confidence Thresholds" test. Other types of tests can be used to select a best candidate outcome and these are provided for by the invention. All of the above can be readily implemented in other ways with a wide range of variation and these are provided for by the invention.

For training of such an ANN, a variation [6] of the Rprop learning algorithm can be used (although other training methods and ANN configuration approaches can also be used and are provided for by the invention). As an example training procedure, the ANN can be trained by providing recorded a datasets of representative users performing various representative renderings of selected gestures accompanied by manually transcribed indications of the intended gesture label for each frame in the recorded dataset. As an example cross-validation process for ANN training, the ANN can first be provided a first collection of recorded datasets for use in training and later be provided a second collection of recorded datasets for use in validation of ANN performance.

In a robust system design, provisions are included for the handling of situations where of the individual touch parameter signals (for example here, sway, surge, heave, yaw, roll, and pitch) cannot be reliably calculated. For example, in such a case, a special value outside the range of the permitted signal variation can be placed of the signal at that point. In some implementations should this special value be presented to the ANN, the ANN could be come confused, so provisions can be included to block such special values from being used as inputs to the ANN portion of the classifier.

Further as to provisions included for handling of situations where of the individual touch parameter signals cannot be reliably calculated, an implementation can be configured to distinguished two missing value cases:

- A particular signal is undefined for all frames within a given window;
- A particular signal is undefined for only some frames within a given window.

Various implementations can be configured to act on these two missing-value cases in various ways as can be advantageous for desired performance. For example:

- If a particular signal is undefined for all frames within a given window, one or more of these actions can be taken:
  - Values for this signal are not included in the "sliding window" of observations x_t presented to the ANN portion of the classifier;
  - Under such conditions it is deemed that no gesture is present.
- If a particular signal is undefined for only some frames within a given window, an interpolation can be used to synthesize those missing signal values:
  - Missing values can be replaced with the mean value for the respective signal across the window;
  - Missing values can be replaced with the value of a localized moving average of the signal across a local subset of observation values within the window in the sequential neighborhood of the missing value;
  - Missing values can be replaced with the value of calculated by a predictor for the signal across a observation values within the window;
  - Missing values can be replaced with the value of calculated by a Kalman filter for the signal across an observation values within the window.

Design and Performance Improvement Leveraging Principal Component Analysis

All the signals discussed thus far have a physical meaning and it is clear, intuitively, how they can contribute to gesture classification. Alternatively, other forms of moments, as well as some higher order moments, can also be used in gesture detection. Since it is difficult to guess which items of information will become useful, it is tempting to feed as much information as possible to the ANN classifier and let it decide (brute force approach). Unfortunately this brute force approach quickly is encumbered by limitations as feeding large numbers of inputs and irrelevant inputs to ANN makes it more difficult to converge on correct weights during training. Also, the overall number of ANN inputs have a significant impact on ANN size, ANN training time, ANN training CPU usage, and real-time CPU resource usage.

In an implementation, Principal Component Analysis (PCA) can be used to reduce the dimensionality of the information applied as inputs to the ANN. PCA performs a linear orthogonal projection of vector data into a lower-dimensional linear space, known as principal subspace, such that the variance of the projected data is maximized [7]. In an implementation, a PCA projection can be applied to a vector of signal and/or moment information; for example in addition to those signals defined in s_t, additional moments can be added. Also since some signals and moments are linearly related to each other and PCA is a linear transformation, some signals defined in s_t and moments identified earlier can be excluded to a priori reduce the task of the PCA operation. In an implementation, some of the moment signals can be mean-centered, for example as in the central moments [8] defined as:

$$\tilde{\mu}_{p,q} = \sum_{x=1}^{M} \sum_{y=1}^{N} (x - \overline{x})^p (y - \overline{y})^q I(x, y)$$

$$\mu_{p,q} = \sum_{x=1}^{M} \sum_{y=1}^{N} (x - \overline{x})^p (y - \overline{y})^q I_{step}(x, y)$$

In an implementation, each some of the moment signals can be scaled to unit variance. In an implementation, each some of the moment signals can be both mean-centered and scaled to unit variance.

As one example, the signal set operated on by PCA could comprise:

$$\{\tilde{M}_{0,1}, \tilde{M}_{1,0}, \tilde{M}_{0,0}, \tilde{M}_{0,1}, \tilde{M}_{1,0}, \tilde{\mu}_{1,1}, \tilde{\mu}_{2,0}, \tilde{\mu}_{0,2}, \tilde{\mu}_{2,1}, \tilde{\mu}_{1,2}, \tilde{\mu}_{2,2}, \text{eigv1}, \text{eigv2}, \phi, \psi, \theta\}$$

As another example, the signal set operated on by PCA could alternatively comprise:

$$\{\tilde{M}_{0,1}, \tilde{M}_{1,0}, \tilde{M}_{0,0}, \tilde{M}_{0,1}, \tilde{M}_{1,0}, \tilde{\mu}_{1,1}, \tilde{\mu}_{2,0}, \tilde{\mu}_{0,2}, \tilde{\mu}_{2,1}, \tilde{\mu}_{1,2}, \tilde{\mu}_{2,2}, \text{eigv1}, \text{eigv2}, \phi, \psi, \theta\text{avgp}, \text{bcx}, \text{bcy}, \text{cx}, \text{cy}\}$$

Alternatively, a shorter vector can be used.

The PCA operation produces a dimensionally-reduced vector comprising only principal components, each corresponding to dimension in a new vector space. In an implementation, the various principle components can be ordered by decreasing variance.

In an implementation, the dimensionally can be reduced yet further by omitting those principle components which have standard deviations significantly lower than the first component. In one approach, the threshold for omission can be determined manually based on high-level design. In another approach, the threshold for omission can be determined manually based on analysis of empirical data. In yet another approach, the threshold for omission can be

automatically determined after ANN training and measuring how choice of various threshold values affect miss rate.

Based on training data the PCA procedure calculates a vector of scaling factors P_S, a vector of offsets P_0 and transformation matrix P_t (a matrix of basis vectors, each column corresponding to an eigenvector). These are later used to convert the vector of signals corresponding to PCA inputs to a vector of principal components:

$$s_{pca}=((s_t-P_0)P_S)P_t$$

In an implementation, the PCA operation is performed as a first step to produce inputs to the ANN, and the input and training of the ANN employs only PCA data (rather than the earliear-described vector of signals as ANN classifier input, using the same sliding window approach as described earlier, i.e., replacing vector s_t with vector of principal components, calculated based on s_{pca}.

Example Gesture Recognition and Gesture Parameter Value Smoothing Architecture

An example architecture for gesture recognition employing the techniques described and other aspects provided for by the invention is shown in FIG. **43**. It is noted that variations of this and alternative implementations are possible, and these are anticipated by the invention. Accordingly, the arrangement depicted in FIG. **43** is not limiting.

In an example implementation, a PCA operation, trained ANN, Kalman filter, "One-of-N with Confidence Thresholds" test, vector partition, vector merge, and two moving window vector "shift register" accumulators are arranged in a "gesture recognition and gesture value smoothing module." For example, a vector of signals s_t (**1**) is provided by earlier signal extraction stages and serves as the input of the module FIG. **43**. A PCA operation is applied to this vector of signals s_t and produces the s_{pca} vector (**2**). A window of last s_{pca} are retained for future reference in a "detection window". The content of this detection window is then concatenated into a vector (**6**) which is provided as the input to the ANN. The output of the ANN (**8**) is a vector of label probabilities. This output is interpreted by the label assigning module which, using a "One-of-N with Confidence Thresholds" test, decides what label to assign to the current frame. This sequence of labels (**9**) provides a "symbol" (or label") output of the "gesture recognition and gesture value smoothing module."

Example Gesture Recognition and Gesture Parameter Value Smoothing Architecture

Parallel to the "symbol" or "label" data flow depicted in the upper portion of FIG. **43**, the original signal inputs (**1**) can also be used to obtain smoothed numerical values responsive to the amount of variation of finger orientation. In an example embodiment, the original signal input is partitioned into two smaller vectors: a first vector of centroid signals (**4**) and a second vector of remaining signals from s_t. The centroid signals in the first vector is smoothed using a Kalman filter, resulting in a vector of smoothed centroid coordinates (**5**). The remaining input signal values are smoothed using LOWESS [9] based on several previous remaining input signal vectors that are accumulated in the "smoothing window." These smoothed remaining input signals are reunited back with the smoothed centroid signals to produce a composite vector (**7**) which serves as a smoothed version of s_t (**10**) and which is the "numerical values" output of the "gesture recognition and gesture value smoothing module." In a prototype implementation, the performance of this arrangement is sufficient to perform gesture recognition in real-time on a regular consumer-level PC at a frame rate of 100 frames per second with gesture recognition accuracy above 99%.

CLOSING REMARKS

The terms "certain embodiments", "an embodiment", "embodiment", "embodiments", "the embodiment", "the embodiments", "one or more embodiments", "some embodiments", and "one embodiment" mean one or more (but not all) embodiments unless expressly specified otherwise. The terms "including", "comprising", "having" and variations thereof mean "including but not limited to", unless expressly specified otherwise. The enumerated listing of items does not imply that any or all of the items are mutually exclusive, unless expressly specified otherwise. The terms "a", "an" and "the" mean "one or more", unless expressly specified otherwise.

While the invention has been described in detail with reference to disclosed embodiments, various modifications within the scope of the invention will be apparent to those of ordinary skill in this technological field. It is to be appreciated that features described with respect to one embodiment typically can be applied to other embodiments.

The invention can be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The present embodiments are therefore to be considered in all respects as illustrative and not restrictive, the scope of the invention being indicated by the appended claims rather than by the foregoing description, and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

Although exemplary embodiments have been provided in detail, various changes, substitutions and alternations could be made thereto without departing from spirit and scope of the disclosed subject matter as defined by the appended claims. Variations described for the embodiments may be realized in any combination desirable for each particular application. Thus particular limitations and embodiment enhancements described herein, which may have particular advantages to a particular application, need not be used for all applications. Also, not all limitations need be implemented in methods, systems, and apparatuses including one or more concepts described with relation to the provided embodiments. Therefore, the invention properly is to be construed with reference to the claims.

[9] Wikipedia, "Local regression", 2011, http://en.wikipedia.org/w/index.php?title=Local_regression&oldid=4167622 87, (accessed 28 Jun. 2

I claim:

1. A method for recognition of user gesture primitives in a touch-based user interface using at least one computational processor, the method comprising:

receiving tactile image data responsive to user touch of a user touch interface comprising a tactile sensor array, the user touch comprising a user touch gesture primitives executed over an interval of time;

processing the tactile image data with at least one analysis processing operation to produce a processed data vector comprising a plurality of numerical values responsive to data generated from the tactile image data, the at least one analysis processing operation comprising calculations including deriving first and second moments from the tactile image data and producing the processed data vector based on a centroid calculation on the derived first and second moments; and

further processing the numerical values with a principle component analysis operation to produce a reduced-dimensionality data vector;

applying the reduced-dimensionality data vector to a classifier, the classifier configured to selectively provide a plurality of classifier outputs, the plurality of classifier outputs selectively provided responsive to the reduced-dimensionality data vector, each classifier output representing an associated pre-defined gesture from a set of pre-defined gestures, the classifier further configured to provide an associated probability value for each classifier output;

applying the classifier outputs and the associated probability value for each provided classifier output to a decision test, the decision test producing a decision output,

wherein the plurality of classifier outputs provided by the classifier and the associated probability value for each provided classifier output are responsive to the tactile image data;

wherein the decision output is responsive to the user touch gesture primitives, and

wherein the decision output is used to specify an identified gesture to an external system, the external system comprising software.

2. The method of claim **1** wherein the classifier comprises an artificial neural network.

3. The method of claim **1** wherein the classifier comprises a heuristic.

4. The method of claim **1** wherein the classifier comprises a genetic algorithm.

5. The method of claim **1** wherein the decision output is used as a user interface signal.

6. The method of claim **1** wherein the collection of pre-defined gestures includes the roll angle change of a single finger on the user touch interface.

7. The method of claim **1** wherein the collection of pre-defined gestures includes the pitch angle change of a single finger on the user touch interface.

8. The method of claim **1** wherein the collection of pre-defined gestures includes the yaw angle change of a single finger on the user touch interface.

9. The method of claim **1** wherein the collection of pre-defined gestures includes the simultaneous change in the sway ("x") of the position of a single finger on the user touch interface.

10. The method of claim **1** wherein the numerical values with a principle component analysis operation comprise moments calculated from the tactile image data.

11. The method of claim **1** wherein the numerical values with a principle component analysis operation comprise a roll angle measurement derived from the tactile image data.

12. The method of claim **1** wherein the numerical values with a principle component analysis operation comprise a pitch angle measurement derived from the tactile image data.

13. The method of claim **1** wherein the numerical values with a principle component analysis operation comprise a yaw angle measurement derived from the tactile image data.

14. The method of claim **2** wherein the output layer of the artificial neural network comprises a logistics function element.

15. The method of claim **1** wherein the at least one analysis processing operation produces a plurality of processed data vectors during the time used execution of the intended touch gesture.

16. The method of claim **1** wherein the collection of pre-defined gestures includes the simultaneous change in the surge ("y") of the position of a single finger on the user touch interface.

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