The Tango:
a tangible tangoreceptive whole-hand human interface

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Abstract

We describe the Tango, a new passive haptic interface for whole-hand interaction with 3D objects. The Tango is shaped like a ball and can be grasped comfortably in one hand. Its pressure sensitive skin measures the contact pressures exerted by the user's hand, and accelerometers within the device measure its motion and attitude. This information can be used for novel modes of interaction with three dimensional objects. We describe the design of the device, and the software for interpreting the sensor data for user interaction.

Accompanying this paper, there will be a demonstration of the device at the Hands-On Demo session of the conference.

1 Introduction

A significant problem facing 3D virtual environments, and more generally, all human-computer interfaces, is the difficulty of manipulating virtual 3D objects in a natural way. The Tango is a new whole-hand computer interface device that addresses this problem for many applications. The Tango looks and feels like a ball that one can pick up and manipulate in a natural fashion. The device measures the configuration of the fingertips, the distribution of pressure applied by the fingers, and also the motion and orientation of the device. This information could be used in a natural, intuitive way to manipulate 3D objects in a virtual environment, 3D graphics, or in CAD/CAM applications. For instance, one can pick up a virtual object, move it around, and deform the object by squeezing it, with the ease of manipulating a real object. In addition, it enables the implementation of "free form buttons," i.e., buttons can be assigned to fingers and not locations on the device, so that users can use any comfortable hand position and avoid repetitive strain injuries.

The remainder of this paper is organized as follows. Section 1.1 describes related work. Section 2 describes the design of the Tango device. Section 3 outlines real-time hand recognition and tracking based on the Tango data. Section 4 describes a simple user interaction testbed. In Section 5 we summarize the results and outline future work.

1.1 Related Work

Glove-based interfaces are currently the most common whole-hand user interfaces; examples include the CyberGlove^{TM} [10] and the Utah/MIT dextrous hand master [18]. These devices indirectly measure the fingertip location by measuring joint angles. Recently, computer vision has also been used for hand tracking, for example with model-based hand tracking [14] and finger tracking using multiple cameras [13].

The lack of force feedback is an important limitation with these interfaces as recent work shows quantifiable evidence that force feedback improves user performance (e.g., surgery [21], steering [3, 7]). Several devices address this by providing active force feedback on individual fingers, for instance, the Rutgers Hand Master [2], the CyberGrasp^{TM} [11], and the multi-finger haptic interface of Springer and Ferrier [19].

While active force feedback has value for many tasks, whole-hand force feedback is expensive and complex. Alternatively, we can provide the user with a passive form of force feedback via a tangible object, such as a ball. Objects that fit conveniently and comfortably in the human hand provide good affordances for 3D manipulation. More importantly, this approach provides a significant improvement over devices with no force feedback at all and does so with greatly reduced complexity. This has been demonstrated with other devices, such as the Fingerball, developed at the University of Toronto [25], a device which provides a similar form factor for grasping and passive force feedback, but does not measure the pressure distribution. The "Squeezables" [22] is a multiplayer musical instrument that provides passive force feedback with a gel ball, and measures forces on a cube within the gel. Passive haptics was also found to significantly enhance immersive virtual environments by Insko et al. [12].

There has been a significant amount of research on tactile sensing; see, for instance, [9] and [5]. Commercial sensors are available from several manufacturers, for example, Pressure Profile Systems, Inc. [16] and Xsensor Technology Corp [23]. In general, these tend to be either small sensors designed for measuring contact at the fingertips (e.g., [16]), or large sensors for biomedical applications [23]. They are generally not designed to conform to curved objects. Reconstruction of hand posture from pressure data is a similar problem to that of reconstructing a full body posture from foot pressure data, addressed by Yin and Pai [24], but the latency requirements are more severe for manual interaction than for animation.

2 Device Design

The Tango (whose name is derived from the old word "tangoreception" meaning "pertaining to the sensation of touch") is a hand-size object in the shape of a ball. In our implementation, there are 256 analog pressure sensors on the device's surface, and a 3-axis accelerometer within (constructed with two ADXL 202 chips from Analog Devices).

See Figure 1 for an external view of the device and Figure 2 for device internals.

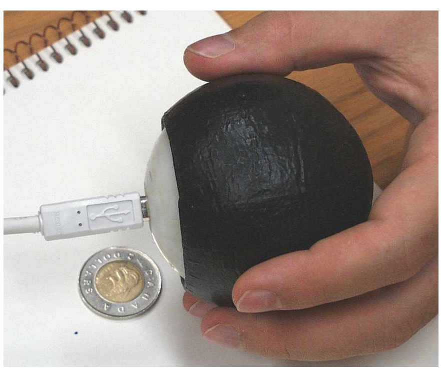

Figure 1: The Tango device

Some important design criteria for the device were:

- The device is of a size that is comfortable to grasp in the hand, and provides passive force feedback which makes virtual objects more tangible (as motivated in Section 1).
- Since the device is meant to be used as comfortably and easily as a mouse, it was important to have a self-contained design, with all analog circuitry on-board and only digital signals leaving the device.

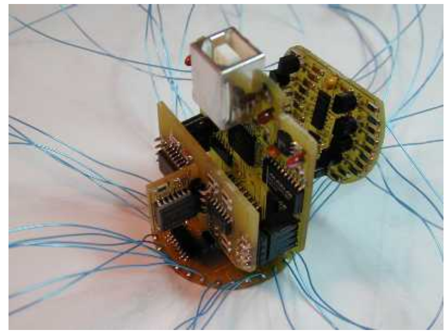

Figure 2: Sensing and communication electronics.

- Capacitance sensing is performed using only digital drive signals. There is no need for demodulation of sensed voltages, as is common in traditional capacitative pressure measurements [5].

The Tango produces an 8x32 tactual image with 8 bits per *taxel* (tactile sensor element), at 100 Hz. Data is gathered at 10 ms intervals by the on-board microcontroller, and transmitted isochronously to the host computer. The pressure and acceleration data can be interpreted by the host computer, and used for user interaction.

The pressure sensing method is as follows. A matrix of pressure sensors is formed by an outer layer of electrically conductive strips, electrically insulated from one another, which run perpendicular to an inner layer of electrically conductive strips, also insulated from one another, with the two layers separated by a compressible dielectric material (foam rubber). At each intersection point between an outer and an inner conductive strip, an individual sensor is formed. Pressure applied at a sensor will cause the dielectric material to compress, thus increasing the capacitance between the inner and outer conductive strips at that point [6].

A simple capacitance sensing method is used, using only digital drive signals. The outer conductive strips, also called driver strips, are driven by low impedance digital signals which serve to shield the inner conductive strips, also called sensor strips, from external electric fields. The voltage on the sensor strips is kept in a measurable range by the use of bias resistors connected from a constant bias voltage to each of the sensor strips. The differential voltages between the bias voltage and each of the sensor strip voltages are the quantities measured by the on-board electronics. Each sensor strip is also connected to two digital drive signals by two separate capacitors of differing, but constant, capacitance. These signals, called 'Calibrate Low' and 'Calibrate High', are used to isolate a particular sensor from the effects of all other sensors on the same sensor strip. Figure 3 shows a typical pressure measurement.

We have built three prototypes of the device. For communication, a high-speed USB interface to the host com-

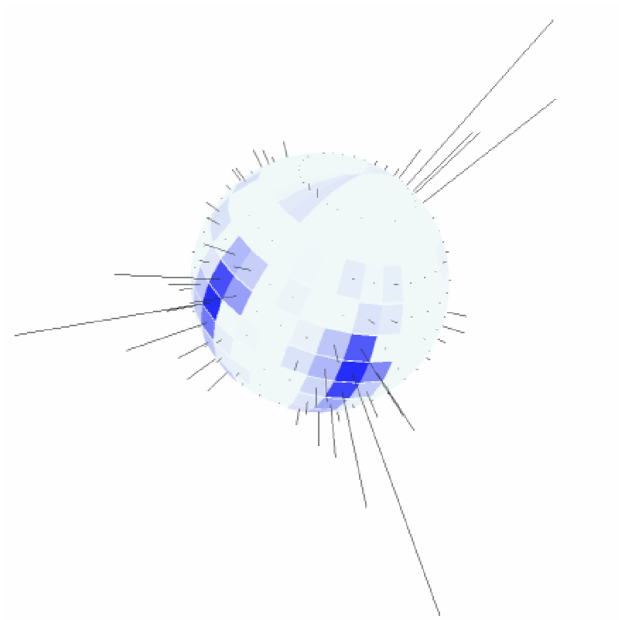

Figure 3: Pressure distribution measurements on the Tango during a three finger grasp. Higher pressures are indicated by darker taxels and longer arrows.

puter has been implemented. No separate power supply is needed when the device is operating using USB power; the power is sufficient for all onboard electronics. The device is hot-pluggable.

The latest version has a Bluetooth communications interface and onboard battery. The battery is rechargeable and is charged when the USB cable is connected. This version solves an important problem: the USB cable is reasonably stiff and makes it difficult to freely manipulate the Tango. We plan to demonstrate this version of the Tango at the symposium.

Figure 4 shows one important complication with the design. Pressure readings are shown, with the device held in a precision grasp with three fingertips. In interpreting the readings, note that the 8 sensor strips are arranged as "latitudes" on the sphere, while the 32 driver strips form "longitudes" or "meridians."

As seen in the figure, the outer driver strips transmit strain from the point of contact to other sensors connected to the same strip. This is corrected in software by measuring the response to a point load on a single sensor (we call this the Meridian Green's Function), and deconvolving the raw readings with this response. The foam rubber's deformation response to pressure is non-linear, but linearity can be assumed for small pressures, and ultimately, nonlinearity at higher pressures is not a significant problem for our application, as we are primarily interested in detecting finger contacts at light pressures, and not accurate pressure readings at higher pressures. The non-linearity makes the sensors sensitive to low pressures and not saturate at relatively high pressures, which is an advantage.

Calibration measurements were collected by probing the surface of the Tango with the WHaT [15] with a modified probe tip (a soft rubber rounded eraser 0.6 cm in diameter) to increase surface area. We applied pressures ranging from zero to approximately 50 gf/cm^2, a range in which the Tango response is quite linear.

For a given taxel on a meridian, we compute the average of several hundred readings, each normalized by the applied pressure as measured by the WHaT. This average response is then further normalized using the Euclidean norm to give a unit length vector, constituting the input response for pressures at the given taxel. The normalized responses of each taxel on a meridian form the columns of our Meridian Green's Function matrix, and deconvolution is simply multiplication of the inverse matrix with the raw pressure measurements from this meridian.

Since all meridians behave similarly, this calibration can be done for one representative meridian. This is shown in Figure 5, where we deconvolve the raw pressures of all the meridians shown in Figure 4 with the same inverse Green's Function matrix. Notice that the the rounded peaks in the raw pressures become sharper, affording better localization of fingertips. Alternatively, at the cost of storing an 8x8 matrix for each meridian, this correction can be applied independently for each meridian.

3 Grasp Recognition and Tracking

To use the Tango as an interface, we developed software to recognize and track the hand grasp configuration. A schematic diagram depicting the various stages for tracking is depicted in Figure 6.

The grasp configuration consists of hand position, orientation and the joint angles of a simplified hand model with respect to the Tango. With more than 20 degrees of freedom in the fingers alone, a full hand model would significantly complicate tracking with only incremental benefits in comparison to our simplified model, which sacrifices less important fingers and joints while enabling realtime tracking. The simplified model hand has 11 degrees of freedom, 6 of which parameterize the position and orientation of the palm relative to the Tango. The remaining degrees of freedom, shown in Figure 7, specify the flexion and abduction of the thumb, index, and middle fingers, where each finger is modeled as a single rigid segment. As such, we restrict grasps to three-finger precision grasps.

Once the raw pressure signal is preprocessed by deconvolution with calibration data (as described above), simple thresholding identifies the active taxels involved in contact. This process is quite robust; we experimented with more sophisticated change detectors [1, 20] but did not observe significant improvements in performance.

The active taxels are then clustered, and three clusters corresponding to the three fingertips are identified. For the initial assignment we use the simple heuristic that the thumb is farthest from the index and middle finger, and assume that the order of fingers is fixed. For each cluster, we compute the total force and the location of the center of pressure. This is then used to match the hand configuration.

3.1 Tracking Hand Configuration with Kalman Filters

We use an extended Kalman filter [8] to track the 11 degress of freedom in our simplified hand model. We also considered particle filters to maintain multiple hypotheses about possible hand configurations but the high dimension of the configuration space, even for the simplified hand, make this approach difficult (but see [4] for a possible solution). The filter first estimates the process state, then obtains feedback in the form of measurements. Let the state of the hand at time k be $x_k = \{\mathbf{p}, \mathbf{q}, \theta\}$ where $\mathbf{p} \in \mathbb{R}^3$ gives the position of the hand in the Tango frame, $\mathbf{q} \in \mathbb{R}^4$ is a quaternion describing the orientation of the hand in the tango frame, and $\theta \in \mathbb{R}^5$ gives the angles of the fingers (see Figure 7). Thus, x_k is a 12 dimension vector depicting the 11 degree of freedom hand model; it is viewed as the state of a stochastic process to be estimated. We use a discrete time control process governed by

$$x_k = f(x_{k-1}, w_{k-1}). \tag{1}$$

where w_k is the process error. The measurements consist of the three fingertip locations, which we write as

$$z_k = h(x_k, v_k). \tag{2}$$

Here h is the forward hand kinematic function used to compute the fingertip position, and v_k is the measurement error. The function h has a well defined matrix of partial derivatives, the hand Jacobian, with respect to the state. Here x_k and z_k form the actual state and measurement vectors. Let $\hat{x}_k^-$ be the *a priori* predicted estimate of the state at time k and $\hat{x}_k$ be the *a posteriori* estimate of the state at time k.

The well known filter equations are then as follows. The time update equation is

$$\begin{aligned} \hat{x}_k^- &= f(\hat{x}_{k-1}), & (3)\\ P_k^- &= A_k P_{k-1} A_k^T + W_k Q_{k-1} W_k^T, & (4) \end{aligned}$$

and the measurement update is given by

$$\begin{aligned} K_k &= P_k^- H_k^T (H_k P_k^- H_k^T + V_k R_k V_k^T)^{-1}, & (5)\\ \hat{x}_k &= \hat{x}_k^- + K_k(z_k - h(\hat{x}_k^-, 0)), & (6)\\ P_k &= (I - K_k H_k) P_k^-, & (7) \end{aligned}$$

where P_k is the error covariance at time k, P_k^- is the *a priori* estimate of the error covariance at time k, and $A, W, H,$ and V are Jacobians of f and h with respect to $x, w,$ and v, as given by

$$\begin{aligned} A_{[i,j]} &= \frac{\partial f_{[i]}}{\partial x_{[j]}}(\hat{x}_{k-1}), & (8)\\ W_{[i,j]} &= \frac{\partial f_{[i]}}{\partial w_{[j]}}(\hat{x}_{k-1}), & (9)\\ H_{[i,j]} &= \frac{\partial h_{[i]}}{\partial x_{[j]}}(\hat{x}_k^-), & (10)\\ V_{[i,j]} &= \frac{\partial h_{[i]}}{\partial v_{[j]}}(\hat{x}_k^-). & (11) \end{aligned}$$

In addition to the configuration of the hand relative to the Tango, for many types of interactions it is useful to estimate the position and orientation (attitude) of the Tango relative to the world. The Tango contains only accelerometers, since at the time it was first constructed small solid state gyroscopes were not available. This situation has now changed, and devices that integrate accelerometers with rate gyros are available from InterSense Inc. and XSens Motion Technologies, though they would add cost and complexity to the design.

We employ a hybrid position and orientation estimation method sufficient for our application as a user interface. At low accelerations, we estimate the attitude of the device based on the algorithm described in [17]; it also tracks the orientation of the accelerometer using a Kalman filter. The rotational drift about the vertical axis is not a major problem for our application, since an approximate orientation can be assumed based on the configuration of the hand. At higher accelerations we estimate the position of the Tango by integrating the accleration.

4 Interaction

The Tango permits intuitive 3D user interaction in several different ways. Figure 8 shows a screen capture of a simple user interface we have implemented to demonstrate user interaction with the Tango. It depicts an artificial 3D world containing various objects with which one can interact, using all or some of the sensing modes of the device. A three-fingered hand is also shown in the scene, and serves as a proxy for the user's hand holding the Tango. A perspective view and three orthographic views are used for visualization of the 3D scene.

The scene can be navigated in three dimensions by moving the Tango using the position estimation described in Section 3. Once the hand is placed on top of a particular object, a gesture (either squeezing harder on the device or shaking) is used to select or deselect the object. The object can then be translated and rotated in three dimensions by moving the Tango.

We determine the nature of the grasp, in terms of the finger tip positions, using the hand tracking method described in Section 3. This information can be used in several ways. The Tango can implement "free form buttons:" we can detect when, say, the index finger is pressing harder than the middle finger, and interpret this state as "left click," regardless of the location of the finger on the device. Similarly, different actions can be triggered by different kinds of grasp, such as a two-finger or three-finger grasp. Finally, the pressure information on the Tango could be used for deforming the object. We are working on manipulation of clay-like deformable objects using the Tango.

5 Conclusions and Future Work

We have developed a novel, graspable, whole-hand input device. The device can measure contact pressure distribution during grasping and manipulation at 100 Hz, as well as the device's acceleration, and transmit these signals to a host computer using USB or Bluetooth. A pressure sensing method using only digital drive signals is used.

We expect the device to form the basis of new computer interfaces for manipulating 3D objects. Some possible applications include:

- Whole-hand sensing of grasping and manipulation of 3D objects (e.g., deformable objects).
- 3D shape sculpting (e.g., to build geometric models for computer animation and free-form CAD surface design). Users can treat the object represented by the Tango as 3D "clay."
- 3D navigation (e.g., to show which direction in 3D to view a virtual environment by touching appropriate points on the Tango).
- 3D mouse (with six degrees of freedom), by combining acceleration readings with locations of fingers on the device.
- Free form "buttons." Buttons can be assigned to fingers, and not locations on the device, so users can use the most comfortable hand position.

In the near future, we plan to track a fully articulated hand model permitting more complex manipulations. Dimension reduction techniques applied to hand-pose space can make the full tracking problem much more cost effective since the space of natural hand poses can be well approximated with relatively few dimensions. Our planned approach of combining tracking with machine learning methods can be further aided through the use of a rotationally invariant representation of the spherical pressure function. Rotational invariance will help reduce both the dimension of the pressure measurement space and the number of training samples that must be collected.

Even though the Tango feels easier and more natural to use than a glove or mouse for 3D manipulation we have not quantified these improvements. We plan to conduct a human subject study to evaluate improvements in task performance with the device.

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References

[1] Michele Basseville and Igor Nikiforov. *Detection of Abrupt Changes: Theory and Applications*. Prentice-Hall, 1993.

[2] Mourad Bouzit, Grigore Burdea, George Popescu, and Rares Boian. The rutgers master ii–new design force-feedback glove. *IEEE/ASME Transactions on Mechatronics*, 7(2), June 2002.

[3] J. T. Dennerlein, D. B. Martin, and C. Hasser. Force-feedback improves performance for steering and combined steering-targeting tasks. In *Proc. of the Conference of Human Factors in Computing Systems (CHI)*, 2000.

[4] J. Deutscher, A. Blake, and I.D. Reid. Articulated body motion capture by annealed particle filtering. In *Int. Conf. Computer Vision and Pattern Recognition (CVPR)*, pages II: 126–133, 2000.

[5] R. S. Fearing. Tactile sensing mechanisms. *The Int. Journal of Robotics Research*, 9(3):3–33, 1990.

[6] R.S. Fearing and J.M. Hollerbach. Basic solid mechanics for tactile sensing. *Int. Journal of Robotics Research*, 4(3), 1985.

[7] B. Forsyth. Intelligen support of interactive manual control: Design, implementation and evaluation of look-ahead haptic guidance. Master's thesis, University of British Columbia, 2004.

[8] Arthur Gelb. *Applied Optimal Estimation*. MIT Press, Cambridge, Mass., 1974.

[9] R. D. Howe. Tactile sensing and control of robotic manipulation. In *The Journal of Advanced Robotics*, 1994.

[10] Immersion Corporation. CyberGlove, http://www.immersion.com/3d/products/cyber_glove.php.

[11] Immersion Corporation. CyberGrasp, http://www.immersion.com/3d/products/cyber_grasp.php.

[12] M. Insko, B.and Meehan, M. Whitton, and F. P. Brooks Jr. Passive haptics significantly enhances virtual environments. Technical report, Computer Science Technical Report 01-010, University of North Carolina, Chapel Hill, NC, 2001.

[13] Cullen Jennings. Robust finger tracking with multiple cameras. In *The International Workshop on Recognition, Analysis, and Tracking of Faces and Gestures in Real-Time Systems*, pages pages 152–160, 1999.

[14] Shan Lu, Gang Huang, Dimitris Samaras, and Dimitris Metaxas. Model-based integration of visual cues for hand tracking. In *WMVC*, 2002.

[15] Dinesh K. Pai and Peter Rizun. The WHaT: a Wireless Haptic Texture Sensor. In *Eleventh Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, March 2003.

[16] Pressure Profile Systems Inc. ConTacts, http://www.pressure-profile.com.

[17] Henrik Rehbinder and Xiaoming Hu. Drift free attitude estimation for accelerated rigid bodies. In *The Proceedings of the 2001 IEEE International Conference on Robotics and Automation*, 2001.

[18] Sarcos. , http://www.sarcos.com/telerobotics.html.

[19] S. Springer and N. Ferrier. Design of a multi-finger haptic interface for teleoperational grasping. In *ASME International Mechanical Engineering Congress and Exposition*, November 1999.

[20] M. Tyler and M. Morari. Change detection using non linear filtering and likelihood ratio testing. Technical report, ETH Institut für Automatic, 1996. AUT96-17.

[21] C. R. Wagner, N. Stylopoulos, and R. D. Howe. The role of force feedback in surgery: Analysis of blunt dissection. In *Tenth Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 73–79, March 2002.

[22] Gil Weinberg and Seum-Lim Gan. The squeezables: Toward an expressive and interdependent multi-player musical instrument. *Computer Music Journal*, 25(2):37–45, Summer 2001.

[23] XSensor Technology Corporation. X2, http://www.xsensor.com/index.htm.

[24] KangKang Yin and Dinesh K. Pai. Footsee: an interactive animation system. In *Proceedings of the ACM SIGGRAPH Symposium on Computer Animation*. ACM, July 2003.

[25] S. Zhai, P. Milgram, and W Buxton. The influence of muscle groups on performance of multiple degree-of-freedom input. In *Proceedings of CHI '96, 308-315*, 1996.

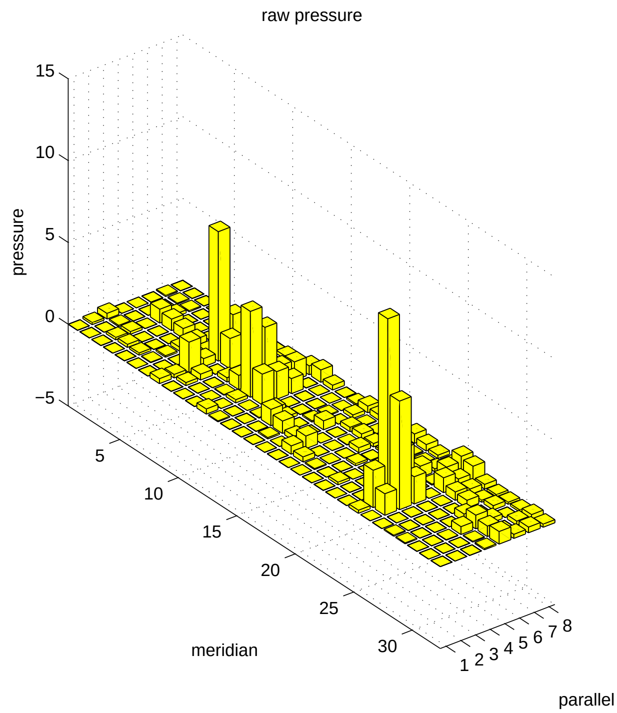

Figure 4: Mechanical coupling along meridians

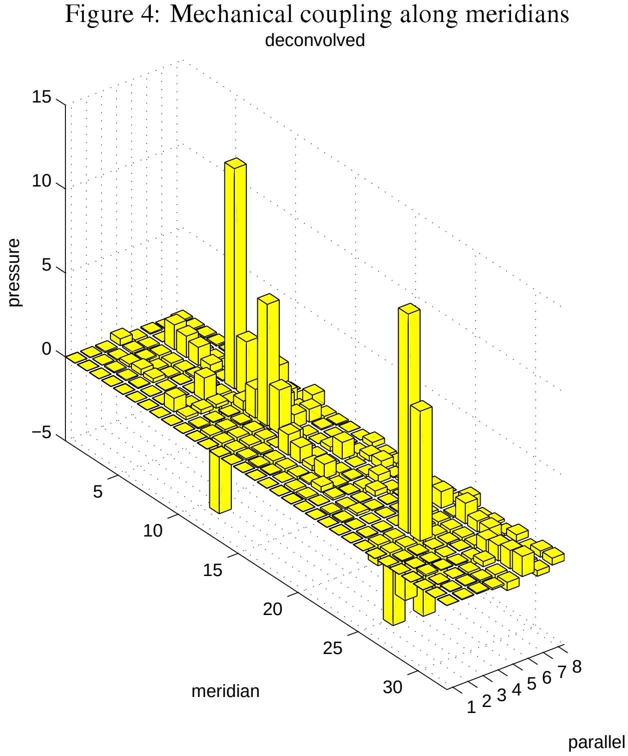

Figure 5: Pressures deconvolved via the inverse Meridian Green's Function

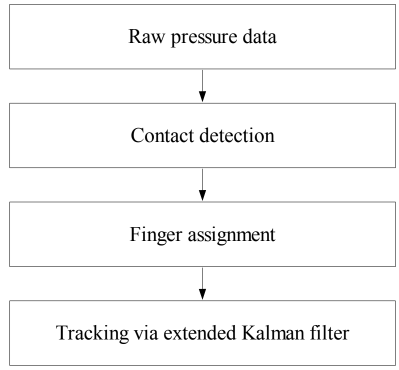

Figure 6: Schematic diagram of hand configuration tracking

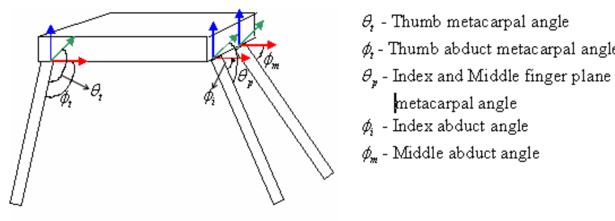

Figure 7: Simplified hand model

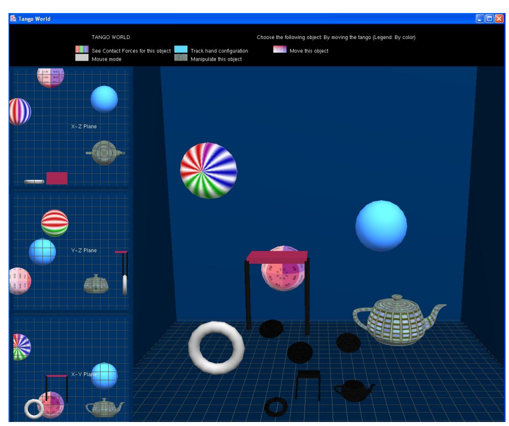

Figure 8: A user interface for demonstration