

of parallel output, and may employ devices such as are available under the trade designation DIO-32HS, from National Instruments.

[0059] Each one of haptel XY sensors **116(1)-(N)** is coupled via a corresponding one of XY cables **118(1)-(N)** to a corresponding one of XY interface **912(1)-(N)**. Each one of XY interface **912(1)-(N)** digitizes readings from a corresponding one of XY sensors **116(1)-(N)** and provides an interface (e.g., RS-232 serial interface) to this data. XY interfaces **912(1)-(N)** may be implemented using devices such as those under the trade designation CS6000 and available from CyberTouch of Newbury Park, Calif.. The serial port of each of XY interfaces **912(1)-(N)** is coupled to a corresponding serial port on serial cards **910**. Each serial card has eight ports, thus two serial cards are required to support the nine XY interfaces in this embodiment. Serial cards **910** are installed in control system **902** and communicates with control processor **904** via a communication channel such as PCI bus **922** using, for example, devices such as the National Instruments device designated PCI-232/8.

[0060] Control processor **904** is connected via serial link **914** to a computer **916**. Typically, control processor **904** and computer **916** are both appropriately programmed general purpose processors. In one embodiment, computer **916** is a computer system such as a personal computer system. Other embodiments may include different types of computer systems. Computer systems may be found in many forms including but not limited to mainframes, minicomputers, workstations, servers, personal computers, notepads and embedded systems. A typical computer system includes at least one processing unit, associated memory and a number of input/output (I/O) devices. A computer system processes information according to a program and produces resultant output information via the I/O devices. A program is a list of internally stored instructions such as a particular application program and/or an operating system. A software module may include a program. The programs that control the operation of a computer system are commonly referred to as software applications or simply software. Preferably, control processor **904** and computer **916** are implemented using a processor such as an Intel Pentium III operating at 550 MHz.

#### OPERATION

[0061] The operation of a device such as I/O device **900** is now described. The mechanical operation of a haptel is first described, followed by a description of the operation of a proximity sensor and actuator. The operation of control system **902** is then described.

##### Haptel mechanical operation

[0062] In operation, the top of XY sensor **116** is pressed with a pointing element such as a finger or stylus causing moving assembly **100** to move up and down. Constraint pins **200** limit the vertical travel of moving assembly **100** and keep moving assembly **100** from rotating relative to stationary assembly **300**. Spring **312** applies an upward force to moving assembly **100** which returns moving assembly **100** to an upper limit of travel when not depressed.

[0063] When XY sensor **116** is pressed anywhere other than at the exact center, a torque is applied to moving assembly **100**. This torque causes moving assembly **100** to

tilt and applies a normal force to the bearings that increases friction. To minimize this tilt, the gap between the inner and outer bearings is kept small, preferably less than a fifth of a millimeter, for example. The vertical spacing between the upper and lower set of bearings further reduces the tilt angle. Friction is minimized by making the bearings from a material having a very low coefficient of friction (e.g., PTFE). Even in the case of a touch at the far corner of surface **102**, friction is preferably kept below 10% of the applied force. Minimizing off-axis friction ensures that the dynamics of I/O device **900** are kept as independent of touch location as possible.

[0064] Haptel **500** is designed such that moving assembly **100** can move freely with little tilt or rotation. This allows adjacent haptels to be positioned with minimal gaps between the edges of their surfaces and yet avoid contacting one another during use. Small gaps also tend to make the gaps between haptels less noticeable to the user. Preferably, base air hole **302b** is present so air can move more freely in and out of the interior of haptel **500** during use. If not included, motion can be impeded as a result of the air escape between the inner and outer bearings.

[0065] When adjacent haptels are touched simultaneously, the haptels tilt slightly towards one another, but are prevented from touching due in part to the design and manufacturing tolerances selected. The seams between the haptel's surfaces are preferably such that such seams are largely invisible to the user. Grid overlay **606** also helps to make the seams between the haptels less noticeable. The material of grid overlay **606** is preferably somewhat stretchable. This allows adjacent haptel surfaces (e.g., surface **102**) to be at different heights without the material of grid overlay **606** overly restricting their motion. The stretchiness required depends in part on the travel of the haptels and the size of their surfaces (e.g., surface **102**).

[0066] A vertical travel of a few millimeters is adequate to simulate the haptic response of a key press, although the travel of a haptel's surface can vary from on the order of about 0.1 mm to about 2 cm (or more). The size of surface **102** is preferably as small as is feasible. This, in part, allows for more simultaneous touches and a smaller minimum distance between touches. In one embodiment, the size of surface **102** (for each haptel) preferably corresponds to that of a pixel. The mass of moving assembly **100** is preferably minimized in order to maximize the acceleration for a given actuator force and enable a greater range of useful haptic effects.

[0067] Precise manufacture of the haptel is important because the fingertip is very sensitive to shape and texture. The haptel surfaces are preferably well aligned with each other at both extents of their travel. Vertical alignment within 0.1 mm is preferred.

[0068] In general, the haptel surfaces can be of any size, and need not be square or even all of the same shape, so long as they are tiled with minimal gaps between their edges. This includes, for example, rectangular, triangular or hexagonal haptels, but other irregular or non-periodic tilings are possible. The overall shape of the touchable area can be any shape, such a rounded rectangle, an ellipse, or an irregular shape. Depending on the shape of the haptel surfaces and the shape of the touchable area, some portion of the haptels on