Applying Electric Field Sensing to Human-Computer Interfaces

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ABSTRACT

A non-contact sensor based on the interaction of a person with electric fields for human-computer interface is investigated. Two sensing modes are explored: an external electric field shunted to ground through a human body, and an external electric field transmitted through a human body to stationary receivers. The sensors are low power (milliwatts), high resolution (millimeter) low cost (a few dollars per channel), have low latency (millisecond), high update rate (1 kHz), high immunity to noise (>72 dB), are not affected by clothing, surface texture or reflectivity, and can operate on length scales from microns to meters. Systems incorporating the sensors include a finger mouse, a room that knows the location of its occupant, and people-sensing furniture. Haptic feedback using passive materials is described. Also discussed are empirical and analytical approaches to transform sensor measurements into position information.

KEYWORDS: user interface, input device, gesture interface, non-contact sensing, electric field.

INTRODUCTION

Our research on electric field (EF) based human-computer interfaces (HCI) grew out of a project to instrument Yo-Yo Ma's cello [8]. We needed to measure bow position in two axes with minimum impact on the instrument and its playability. In this paper we discuss two types of EF sensing mechanisms: *shunting*, where an external EF is effectively grounded by a person in the field; and *transmitting*, where low frequency energy is coupled into a person, making the entire body an EF emitter. The benefits of each sensing mechanism are presented along with comparisons to other sensing means. We report on several EF systems and applications, designed by arranging the size and location of EF transmitters and receivers, and suggest some future applications.

Since electric fields pass through non-conductors, passive materials that apply force and viscous friction may be incorporated into EF sensing devices, providing haptic feedback. We have constructed a pressure pad and a viscous 3-D workspace based on this principle.

PREVIOUS WORK

The first well-known use of EF sensing for human-machine interface was Leon Theremin's musical instrument. Two omnidirectional antennas were used to control the pitch and amplitude of an oscillator. Body capacitance detunes a resonant tank circuit [7]. The effect of body capacitance on electric circuits was well known to radio's pioneers, who saw the effect as an annoyance rather than an asset.

As the need for electronic security and surveillance increases, there is growing use of remote (non-contact) occupancy and motion detectors. Sensing mechanisms include capacitance, acoustic, optoelectronic, microwave, ultrasonic, video, laser, and triboelectric (detecting static electric charge) [5]. Many of these mechanisms have been adapted to measure the location of body parts in three dimensions, motivated by military cockpit and virtual reality (VR) applications [15].

Acoustic methods are line-of-sight and are affected by echoes, multi-paths, air currents, temperature, and humidity. Optical systems are also line-of-sight, require controlled lighting, are saturated by bright lights, and can be confused by shadows. Infrared systems require significant power to cover large areas. Systems based on reflection are affected by surface texture, reflectivity, and incidence angle of the detected object. Video has a slow update rate (e.g., 60 Hz) and produces copious amounts of data that must be acquired, stored, and processed. Microwaves pose potential health and regulation problems. Simple pyroelectric systems have very slow response times (>100 msec) and can only respond to changing signals. Lasers must be scanned, can cause eye damage, and are line-of-sight. Triboelectric sensing requires the detected object to be electrically charged.

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Mathews [14] developed an electronic drum that detects the 3-D location of a hand-held transmitting baton relative to a planar array of antennas by using near-field signal-strength measurements. Lee, Buxton, and Smith [13] use capacitance measurement to detect multiple contacts on a touch-sensitive tablet. Both systems require the user to touch something.

Capacitive sensors can measure proximity without contact. To assist robots to navigate and avoid injuring humans, NASA has developed a capacitive reflector sensor [22] that can detects objects up to 30 cm away. The sensor uses a driven shield to push EF lines away from grounding surfaces and towards the object. Wall stud finders use differential capacitance measurement to locate wood behind plaster boards by sensing dielectric changes [6]. Linear capacitive reactance sensors are used in industry to measure the proximity of grounded objects with an accuracy of 5 microns [4]. Electrical impedance tomography places electrode arrays on the body to form images of tissue and organs based on internal electric conductivity [21].

Weakly electric fish (e.g., Gymnotiformes, sharks, and catfish) are very sophisticated users of electric fields [1]. These fish use amplitude modulation and spectral changes to determine object size, shape, conductivity, distance, and velocity. They use electric fields for social communication, identifying sex, age, and dominance hierarchy. They perform jamming avoidance when they detect the beating of their field with an approaching fish: the fish with the lower transmit frequency decreases its frequency, and the fish with the higher frequency raises its frequency. Some saltwater weakly electric fish have adapted their sensing ability to detect EF gradients as low as 5nV/cm.

Given this long history of capacitive measurement, one might wonder why EF sensing is not common in human-computer interfaces. But it is only recently that inexpensive electronic components have become available to measure the small signals produced by EF sensors. Also non-uniform electric fields have made it difficult to transform these signals into linear position coordinates. Our research addresses these issues to help make EF sensing more accessible to interface designers.
It will be shown that EF sensors provide ample resolution and that converting the EF signal strength into position is the more challenging task.

MODES OF OPERATION

The Human Shunt

An electrical potential (voltage) is created between an oscillator electrode and a virtual ground electrode (Figure 1). A virtual ground is an electrical connection kept at zero potential by an operational amplifier, allowing current I_R to ground to be measured. The potential difference induces charge on the electrodes, creating an electric field between the electrodes. If the area of the electrodes is small relative to the spacing between them, the electrodes can be modeled as point charges producing dipole fields. The dipole field strength varies inversely with distance cubed. In practice the measurable field strength extends approximately two dipole lengths (distance between the transmitter and receiver electrodes). As the electrodes are moved farther apart, a larger electrode area is required to compensate for the decrease in signal strength.

When a hand, or other body part, is placed in an electric field the amount of displacement current I_R reaching the receiver decreases. This may seem counter-intuitive since the conductive and dielectric properties of the hand should increase the displacement current. However, if an object is much larger than the dipole length, the portion of the object out of the field serves as a charge reservoir, which is what we mean by “ground”. The hand intercepts electric field lines, shunting them to ground, decreasing the amount of displacement current I_R reaching the receiver.

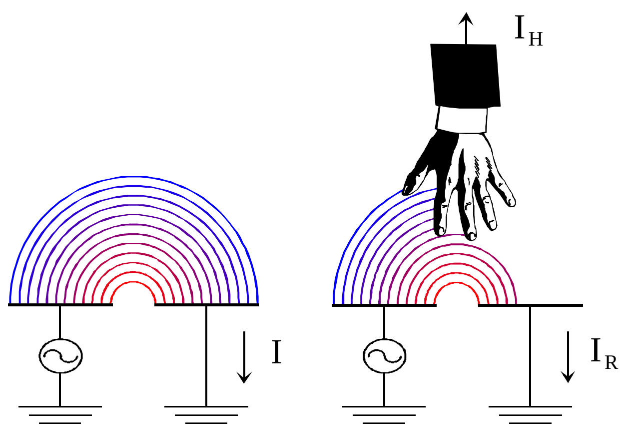

Figure 1. An electric dipole field created between an oscillating transmit electrode and virtual ground receiver electrode is intercepted by a hand. Displacement current to ground I_R decreases as the hand moves further into the dipole field.

The Human Transmitter

Low frequency energy is capacitively coupled into a person’s body, making the entire person an EF emitter (Figure 2). The person can stand on, sit on, touch, or otherwise be near the oscillator electrode. One or more receiver electrodes are placed about the person. The displacement current into a receiver I_R increases as the person moves closer to that receiver. At close proximity, the person and the receiver electrode are modeled as ideal flat plates, where displacement current varies with the reciprocal of distance. At large distances, the person and the receiver electrode are modeled as points, where displacement current varies with the reciprocal of distance squared.

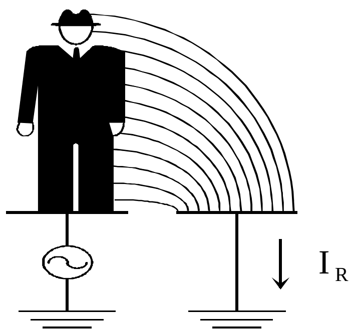

Figure 2. Energy from an oscillator is coupled into a person standing on the transmit electrode making the person an electric field emitter. As the person moves any body part closer to the grounded receive electrode, the displacement current into the receiver I_R increases.

Mode Crossover

When a hand (or any large object relative to the dipole length) approaches the dipole field of Figure 1 (shunt mode), the displacement current I_R decreases. When the hand gets very close (much less than a dipole spacing) the displacement current I_R begins to increase; the system changes from shunt mode to transmit mode. Actually both modes occur simultaneously, the hand is always coupling some field to the receiver (transmit mode) but until the hand is very close to the electrodes, the amount of displacement current shunted away from the receiver exceeds the amount coupled into the receiver.

SYSTEM HARDWARE

Signal Detection Strategy

Many capacitance detection schemes [5, 6, 13] measure the charging time of a resistor-capacitor (RC) network. The capacitance and displacement currents for EF sensing are on the order of picofarads (10^{-12} farad) and nanoamps (10^{-9} amps), requiring more sophisticated detection strategies. A synchronous detection circuit (Figure 3) is used to detect the transmitted frequency and reject all others [10], acting as a very narrow band-pass filter. Other detection methods include frequency-modulation chirps (as used in radar), frequency hopping, and code modulation (e.g., spread spectrum).

The displacement current can be measured with approximately 12 bits accuracy (72 dB) using the components shown in Figure 3. There is a trade-off between update rate (sample rate/number of samples averaged) and accuracy (signal-to-noise ratio). The signal-to-noise ratio increases as the square root of the number of samples averaged. For example, averaging 64 samples increases the signal-to-noise a factor of eight (+18 dB), with a corresponding 1/64 update rate.

Information can be coded in the modulated transmitter signal. A multitude of small EF sensing devices can be scattered about a room, like eels in a murky pond, transmitting measurements to neighboring devices with the same EF used to measure proximity. The jamming avoidance mechanism of weakly electric fish [1] suggests that such devices can adjust their transmission frequencies autonomously when new devices are introduced into the sensing space.

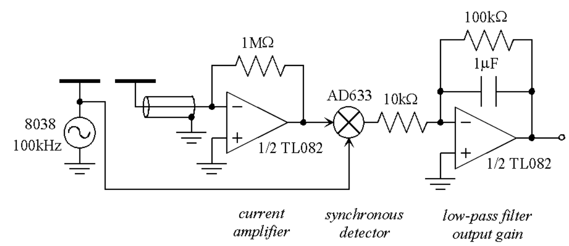

Figure 3. Synchronous detection circuitry.

Small displacement currents require good shielding, however the capacitance of shielded coaxial cable is orders of magnitude greater that the capacitance between electrodes. Cable capacitance low-pass filters the received signal, typically limiting the operating frequency to 30 kHz, and introduces a phase shift that is compensated for in the synchronous detector (not shown). Placing the current amplifier at the receiver electrode allows higher frequencies, limited by the amplifier's slew rate. For example, attaching the receive electrode directly to the TL082 current amplifier allows an operating frequency of 220 kHz.

Transmitter Power

The frequency range we use for EF HCI is 10 kHz to 200 kHz. Below this range, displacement currents and update rates are too small. Above this range FCC power regulations become more stringent [3]. The distance between electrodes is a fraction of a wavelength, so no appreciable energy is radiated. The only power consumed by the transmitter is the energy required to charge the capacitance of the transmitter electrode to the oscillating voltage.

In practice the transmitter power is less than a milliwatt. This allows the design of very low power systems with no radio interference. By adding an inductor, the transmitter can be driven into resonance, decreasing energy dissipation and increasing the transmitter potential, for example 60 volts from a 5 volt supply. A larger transmitter potential increases the strength of the received signal and therefore the signal-to-noise ratio, producing greater spatial resolution. Transmit signal strength can be increased until the current amplifier is saturated.

"Fish" Evaluation Board

To assist researchers in exploring EF HCI, our group has produced a small microprocessor-based EF sensing unit, supporting one transmitter and four receivers (Figure 4). It is called a “fish” after the amazing EF abilities of weakly electric fish, and because fish can navigate three dimensions while a mouse can navigate only two. The evaluation board supports MIDI, RS-232, and RS-485 serial communication protocols. We are currently designing a “smart fish,” a second generation EF evaluation board utilizing a digital signal processor to allow automatic calibration and the exploration of more complex detection strategies, such a spread spectrum. The smart fish also measures the power loading of the transmitter to disambiguate mode crossover. Transmitter loading is monotonic; the current drawn from the transmit electrode always increases as an object approaches the transmit electrode.

ELECTRIC FIELD GEOMETRY

The value returned by a sensor is unfortunately *not* directly proportional to the distance between a hand and the sensor. Recovering information such as the *(x,y,z)* position of a hand from three sensor values *(r,s,t)* is a non-trivial problem. Solving the problem requires a model of the electric field geometry. The absolute signal strength depends on the coupling of the person to a reference (ground for shunt mode and the transmit electrode for transmit mode). This coupling acts as a global system gain. The relative signal strength of the sensors contains the position information. For this reason normalized sensor readings are used to calculate position information.

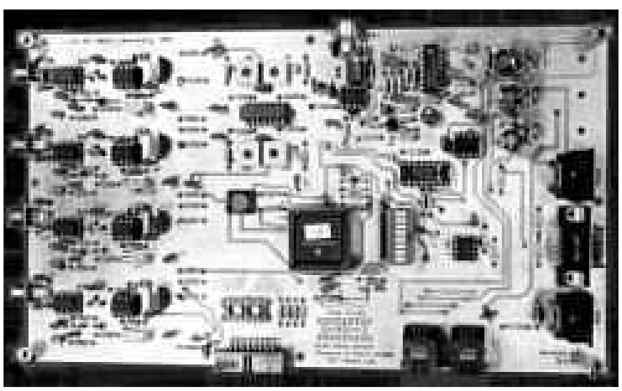

Figure 4. Fish electric field sensing evaluation board.

There are two basic strategies for creating this model. In the analytical approach, knowledge of electrostatics (Laplace equation) is used to derive, for a given sensor geometry, an expression for the signals received as a function of hand position. The expression is then inverted analytically or numerically. In the empirical approach, signals are measured for a variety of known hand positions, and a function (e.g., radial basis function) that converts sensor values to hand positions is fit to the resulting data set. The analytical approach provides insight into the behavior of the sensors and does not require a training phase. However, any given analytical solution is applicable only for a particular sensor geometry, and different sensor geometries require new solutions. The empirical approach is more flexible, because changes in the sensor layout or environment can be accommodated by retraining.

Since our measurements occur within a fraction of a wavelength, we are in the near-field limit where the electric field is the gradient of the potential across the electrodes, so we can treat the situation as an electrostatics problem [12]. The same physics applies for electrode spacing that ranges from microns to meters. Small electrode spacing has been used to measure position with micron resolution [19]; large electrode spacing has been used to measure the location of a person in a room. We are not interested in the absolute values of sensor values; we care only about their functional dependence on the position of the body part we are measuring. Since the human body is covered with conductive, we treat the body as a perfectly conducting object. The hand is treated as a grounded point in space. In practice, the finite area of a hand and its connection to an arm serves to blur or convolve the ideal point response. But this point approximation usually works well as long as the real hand is a constant shape, the same convolution is being applied everywhere, and so the basic functional form of the hand response will be the same as that of the point response.

In-Plane Measurements

Figure 5 shows a contour plot of the predicted received signal, calculated using the classic dipole field expression [12] for a hand moving around a *Z* plane 0.9 dipole units above the dipole axis. A dipole unit is the distance between the transmit electrode and receive electrode. The predicted contour compares well to data collected by moving a grounded cube (2.5 cm on each side) across the plane.

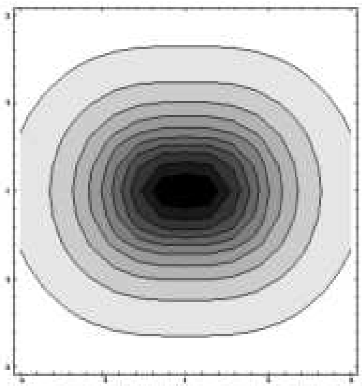

Figure 5. Contours of electric field strength in plane Z = 0.9 (measured in units of the dipole spacing) predicted by analytical model.

Out-Of-Plane Measurements

The relationship between hand proximity Z and displacement current I_R is measured using an electrical equivalent of a hand and arm suspended above the center of a dipole. The term proximity is used to emphasize that EF sensing measures the integrated (convolved) effect of an object in the electric field. When a hand is placed near a dipole, the hand, arm, and body attached to the arm all affect the field, though each contributes less as they are progressively farther away from the dipole.

The surrogate hand and arm combination is an aluminum tube 7.6 cm in diameter and 48.3 cm long and is grounded through a suspending wire for shunt mode and connected to an oscillator for transmit mode. The transmit and receiver electrode, each measuring 2.5 cm x 2.5 cm, are 15.2 cm apart on center. A least squares fit of the data reveals the following functional form for both shunt and transmit modes;

$$I_R = A + \frac{B}{\sqrt{Z}}$$

where A and B are constants determined by electrode geometry, detection circuit gain and bias, oscillator frequency and voltage, and Z is distance above the dipole. For shunt mode B is negative since displacement current I_R decreases as the object moves closer to the dipole.

Proximity resolution is expressed as the change in distance Z that produces a 6 dB change in displacement current I_R over the noise floor (two times the noise floor). The resolution is dependent on the signal-to-noise ratio of the detection system, which is a function of integration time. The longer the data is averaged, the greater the proximity resolution, albeit with a corresponding slower update rate. The fish evaluation board used in these measurements has an integration time constant of 10 milliseconds. Figure 6 plots proximity resolution as a function of distance Z for shunt mode. At 85 mm distance, proximity resolution is 1 mm.

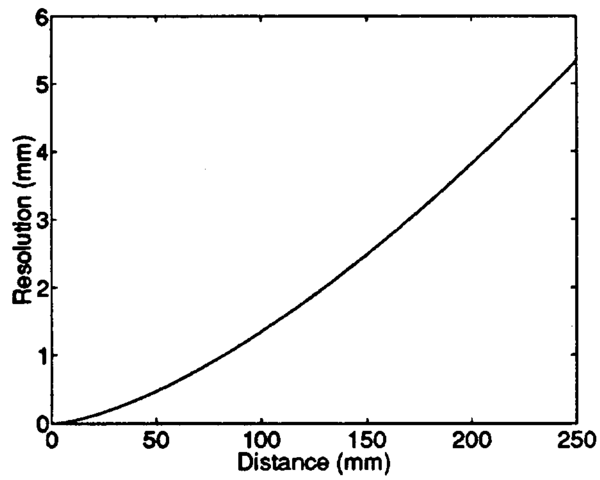

Figure 6. Proximity resolution of a surrogate arm in shunt mode plotted as a function of distance from dipole to arm. Resolution is the change in distance that produces a 6dB change in signal over noise.

Imaging: Converting Signals To Position

Each dipole measures a degree of freedom, either object position or size. A single dipole cannot distinguish a close small object from a large distant object, as both might block the same number of field lines. A second dipole operating on a longer length-scale (greater electrode spacing) can be used to distinguish these two situations, or to measure two spatial coordinates of a single fixed-size object. Three dipoles can measure the 3-D position of an object of fixed size, or determine the 2-D position and size of an object. Four dipoles can determine the size and 3-D position of an object. Five dipoles can determine the 3-D position, size, and elongation of an object. We are working on the continuum limit of adding more dipoles, to perform low-resolution imaging.

Optimal Sensor Placement

Each receiver measurement constrains the position of a small object (relative to dipole spacing) to an ellipsoid centered on the dipole axis (see Figure 5). The dipoles should be oriented orthogonally in order to minimize the sensitivity of the solution (x,y,z) to errors in (r,s,t). The problem of inverting the sensor readings is equivalent to the geometrical problem of finding the intersection points of these ellipsoids. Often additional constraints (prior knowledge) must be imposed to select one solution from the many symmetric cases that are consistent with the data. For example, to make a two-dimensional mouse using only two dipoles, we must impose the constraint that the hand is on one side of the dipoles.

COMPARISON TO OTHER SENSOR TECHNOLOGIES

Electric field sensors detect a bulk effect, integrating the body's interception of EF. Unlike optical system, the effect does not depend on object surface texture and reflectivity. The data from EF sensors is continuous with a resolution limited by transmission strength and noise rejection. There is an economy of data; only three channels are required to locate a hand in 3-D. In comparison, a video camera produces an abundance of data, on the order of 75 megabits per second, while updating at 60 Hz. An EF system operating at 100 kHz can average 100 samples, provide a 1 kHz update rate, with 1 millisecond lag time.

Electric field systems can be extremely small, light-weight and low power, as required by the ever shrinking real estate and energy capacity of lap, palm, and watch based computers. Since electric fields penetrate non-conductors, sensors can be hidden, providing protection from weather and wear, as well as adding an element of magic to the interface.

SYSTEM CONFIGURATIONS AND APPLICATIONS

The transmit method provides large receive signals, operates over large areas, and can distinguish multiple persons. Capacitively coupling energy into a person requires continuous close contact with the person. We have used transmit electrode ranging from 5 to 150 square cm, depending on proximity to the person. The transmit electrode can be incorporated into the seat of a chair, a section of a floor, the back of a palm computer, or a wristwatch band. Direct conductive contact with the person's skin requires a much smaller electrode area (<5 square cm). Asymmetric placement of receiver electrodes helps decouple signal strength from position calculations.

The shunt method does not require close contact with a person. For each dimension, a minimum of one receiver is required. Prototyping interfaces is basically an "arts and crafts" project, consisting of cutting out electrodes, typically aluminum foil and copper tape, taping them down, and wiring them up to the fish evaluation unit.

Figure 7. Two-dimensional finger-pointing mouse.

2-D Finger-Pointing Mouse

We have implemented a two-dimensional finger-pointing mouse on a laptop computer (Figure 7). The input device is activated by touching a small transmitter electrode with the fourth (little) finger of the left hand. Energy is coupled into the person, and the EF emitted from the pointing finger is sensed at two receiving electrodes. A thin uniform copper strip running across the top of the screen senses Y position, and a tapered strip along the side of the screen senses X position. The taper renders the electrode more sensitive to the EF emitted by the pointing finger and less sensitive to the field emitted by the arm. The shaped electrode physically implements an analog spatially varying signal gain. A third small receiving electrode, placed below the spacebar, allows the thumb of the left hand to generate click signals.

The pointing finger does not need to be in contact with, or even close to the screen, thereby avoiding screen smudges and occlusion of the cursor by the pointing finger. Position sensing is easily disabled by lifting the forth finger off the transmitting electrode, the equivalent of lifting and putting down a mouse, facilitating relative position control.

Smart Table

To demonstrate the concept of "smart furniture," a co-linear dipole pair (i.e., receiver, transmitter, receiver) is placed underneath a wooden table to measure hand gestures. A computer screen displays an electronic newspaper whose pages are flipped forward and backward by sweeps of a hand across the table (X-axis). Placing the hand down on the table (Z-axis) advances to the next section, lifting the hand up displays the previous section. Gestures are detected by applying a threshold to the X and Z velocities. Position in the X-axis is approximated by differencing the two receiver signals; position in the Z-axis is approximated by the sum of the receiver signals.

An array of dipoles can turn a table into a multidimensional digitizing and gesture input device. Such an EF sensing matrix may substitute for or augment a video camera for video desk applications [18]. Perhaps visual ambiguities and occlusions could be arbitrated by EF sensing, indicating hand location to the video analysis system.

Person-Sensing Room

In an installation piece at the MIT Media Lab, a single transmitter electrode covers the entire floor of a room, coupling energy into a person walking on the floor. Four receiver electrodes, located on the walls, measure relative signal strength, indicating the location of the person. A computer program, controlling a multitude of synthesizers and sound sources, creates a complex sonic terrain based on the location of the person, allowing navigation of a sonic environment.

Smart Chair

A chair is fitted with one transmitter in the seat and four receivers: two located in the headrest to measure head rotation, and one at each armrest to measure hand proximity. A person in the chair navigates multiple audio channels by head and hand placement [16]. The sensors are mounted underneath the chair fabric, so they are invisible to the user. Smart chairs may be used to control radio functions in a car, home audiovisual equipment, or simply to turn off a computer monitor when a user leaves a workstation.

In another application, a transmitter is installed in a chair to allow the magicians Penn & Teller to perform music by waving their arms near four receivers. Hand position controls various sound parameters produced by computer-controlled sound synthesizers.

Haptic Feedback in 3-D Space

A foam pad is placed on top of a dipole pair. Pressing on the foam produces a force feedback. Since force is proportional to position (Hooke's law), and finger position is measured by EF sensing, finger force is measured. A passive piece of foam on an EF sensor is a pressure sensor.

A plastic box is fitted with electrodes on three sides to measure hand position in 3-D. The box is filled with bird-seed (millet) to provide a viscous medium for haptic feedback. The seed allows users to rest their hand in space, reducing fatigue, and provides something to grab. Slight compression of the seed increases viscosity. Perhaps a computer-controlled piston, bearing on a movable wall of the box, could provide a simple way to simulate an environment with variable viscosity.

FUTURE APPLICATIONS

Researchers are currently exploring direct manipulation of instrumented real objects to facilitate 3-D orientation and manipulation [9, 17]. Electric field sensors may be incorporated in objects to measure object deformation, position, and orientation.

The Tailor project [20] allows disabled individuals to run computer applications by mapping the unique anatomical movement ability of each individual to control signals. Combining EF sensing with such mapping techniques could provide a person in a wheelchair with individually tailored, unobtrusive, invisible, low-power, and low-cost computer and machine interfaces.

Hermetically sealed EF sensors in a palm top could determine when the case is open, when the unit is being held, and could create a large control space around the small device. Foam EF buttons could provide force and tactile feedback, detect finger approach and finger pressure, and distinguish between slow and fast presses.

Multiple transmitters and receivers, multiplexed in time, frequency, or by coding sequence, could be placed under a carpet to determine the number and location of people in a room. When an electrode under a person is activated, that person becomes the EF source. Smart floors can be used for multi-participant VR simulations without the burden of wires or the complexities of video cameras.

Attempts have been made to instrument whiteboards using video cameras [11] and optoelectronics [2]. Both systems require rear imaging to record stylus movement. A conventional plastic whiteboard can be fitted with an array of EF sensing electrodes to measure the location of a metal-cased marker in the hand of a shunting or transmitting person.

Watches have a very small workspace and very little energy capacity. An EF sensor can be used to create a large workspace over a small watch face. Such watch controllers can be used to search through audio databases.

CONCLUSION

We have discussed some HCI systems and future applications of EF based sensing. The near-field nature of low-frequency electric fields allows the same detection scheme to be scaled from microns to meters. EF sensing provides high resolution proximity information. The difficulty is converting proximity to position. We have worked out an analytical method to correct for the non-uniform nature of dipole fields. Empirical methods may be used to compensate for complex field distortion caused by dielectrics or conductors in the field. Some of EF sensing's greatest qualitative appeals are the sense of magic, simplicity, and "naturalness" it brings to an HCI. The abilities of weakly electric fish to perform object detection, communicating, and jamming avoidance demonstrate what is possible with EF sensing. The authors know of no other sensing mechanism or system that can deliver non-contact sensing with millimeter resolution at kilohertz sample rates and millisecond lag times for a few dollars a channel. As computing power leaps off the desk and into a multitude of small battery-powered devices, the need for low-power unobtrusive interfaces grows. It is our belief that EF sensing can make a significant contribution to the sensing abilities of computing machines.

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