ELECTRIC FIELD SENSING FOR GRAPHICAL INTERFACES

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Abstract

Low frequency electric fields provide a means to build contact and non-contact user interfaces that are unobtrusive, responsive, inexpensive, and simple to configure. In this paper, we outline the theory and implementation of such sensing techniques, contrasting them with more familiar alternatives. We then present a range of applications that we have developed for interacting with computer graphics.

1) *Introduction*

The earliest bit-mapped graphical computers have progressed to bring real-time three-dimensional rendering and digital video to the desktop, but the common physical interface remains unchanged from the first workstations, as we are still using the same keyboards and mice. The result is that many applications, such as modeling or navigation in virtual worlds, are often limited not by processing speed but by the users' difficulty in conveying desired actions to the computer.

The range of alternative controllers that have been tried are notable, not just for their diversity, but also for their compromising constraints and/or relatively disappointing overall performance. They can broadly be divided into non-contact approaches and those that require contact with the user. The most familiar non-contact interface is video, using one or more cameras to determine the users' actions [1]. The canonical problems with video are the difficulty in obtaining estimates faster than standard video frame rates, the need for enormous input bandwidth and computational power to process the images, and the requirement to constrain the scene background, activity, and illumination to make the recognition task feasible. Given that the limiting performance of people is on the order of millimeter displacements in milliseconds, there is a large gulf between what people can do and what cameras can reasonably be expected to recognize. Other common, non-contact sensing schemes use ultrasonic or infra-red reflections [2]. These scattering mechanisms depend on surface texture and orientation, and thus can provide only indirect estimates of three-dimensional information. Furthermore, environmental background signals, such as sunlight for IR and mechanical noise for ultrasound, are significant sources of interference for most IR and ultrasound systems to date. Wired interface devices include variants of the Data Glove [3], and families of magnetic position trackers [4]. These have the obvious constraint of encumbering the user with extra hardware, something that can range from inconvenient to impossible for extended or intermittent use.

The ideal interface would be no apparent interface: the users should be able to act as they wish, using either free gestures or manipulating objects that provide tactile cues, and the computer should unobtrusively and continuously know the state of the user, at the limits of their physical performance. This wish-list is not unrealistic: a solution is hinted at by the Theremin [5], one of the earliest and most responsive of electronic instruments. By sensing how the presence of a player's body capacitively loads antennas used to set the pitch and amplitude of an oscillator [6] exquisite control is possible, approaching the lyrical expression of the human voice. A variation of the Theremin is the Radio Baton [7], using a shaped electrode array and wired batons. While it adds wires to the interface, it is able to obtain absolute three-dimensional information.

The Theremin is a very old idea, but the physics and mathematics behind it still pose open questions. There are a number of charge transport pathways that contribute to the observed signal and that have historically been lumped together as "capacitance." These can be separated and measured, posing a new nonlinear inverse problem to go from the measured charges to the conductors perturbing the field. It may be surprising that this inverse problem is non-linear, since the Laplace equation (like the more general Maxwell equations from which it may be derived) is a linear partial differential equation, meaning that for equipotential boundaries at fixed locations, superpositions of solutions are also solutions. However, the electric field strength at the receiver is not a linear function of the location of these equipotential boundaries, and the inference problem is to determine the location of the boundaries from knowledge of the field strength at particular locations. Thus unlike more familiar linear imaging problems that arise in Computed Tomography or

Magnetic Resonance Imaging, this problem occurs in a nonlinear basis requiring a much more difficult search. By multiplexing the transmitter, multiple “projections” can be measured, and we believe this will enable a new form of true three-dimensional imaging. Reference [8] describes our first efforts to infer three-dimensional geometrical information from electric field measurements; further work on this problem is forthcoming

The prospect of extracting three-dimensional images is enticing, but one of the most appealing features of this technology is the continuum that extends from imaging with a large array of electrodes, to position measurement with small numbers of electrodes, all the way down to a single electrode button that can measure distance as well as contact. One of the main difficulties with video is that a camera collects too much information. A sensing modality that allows one to collect as much or as little information as needed in a particular application is appealing and unusual.

The next section describes the basic interaction mechanisms between a body and a field that give rise to these signals, and the instrumentation required to make the required measurements. The following section then describes several implementations of these concepts in building interfaces for different computer graphics applications.

2) *Mechanisms and implementation*

Figure 1 depicts the basic implementations of Electric Field Sensing. The top diagram is a model that describes all sensing modes. This simple hand sensor consists of two electrodes: a transmitter driven by low frequency, low voltage RF (orders of magnitude below FCC and health restrictions), and a receiver that detects the transmitted signal through the capacitive paths given in the figure. In order to reduce interference from ambient electromagnetic background, the receiver usually has a narrowband response centered at the transmit frequency, generally provided by a synchronous detection scheme [6].

Before a hand comes into the region between transmitter and receiver, a signal is received through the intrinsic capacitive coupling C_0 determined by the electrode size and proximity. When the hand enters, the amount of signal detected at the receiver is altered by the capacitive coupling from transmitter into the hand (C_t), hand into receiver (C_r), and body into ground (C_g). The body is essentially perfectly conductive at these frequencies, especially when compared with the picofarad-level capacitances sketched above. If the body is not extremely close to either electrode, C_g dominates, and the body is effectively a grounded shield (electric field lines from the transmitter couple into the hand and are directed through the body to the room, away from the receiver), thus the received signal

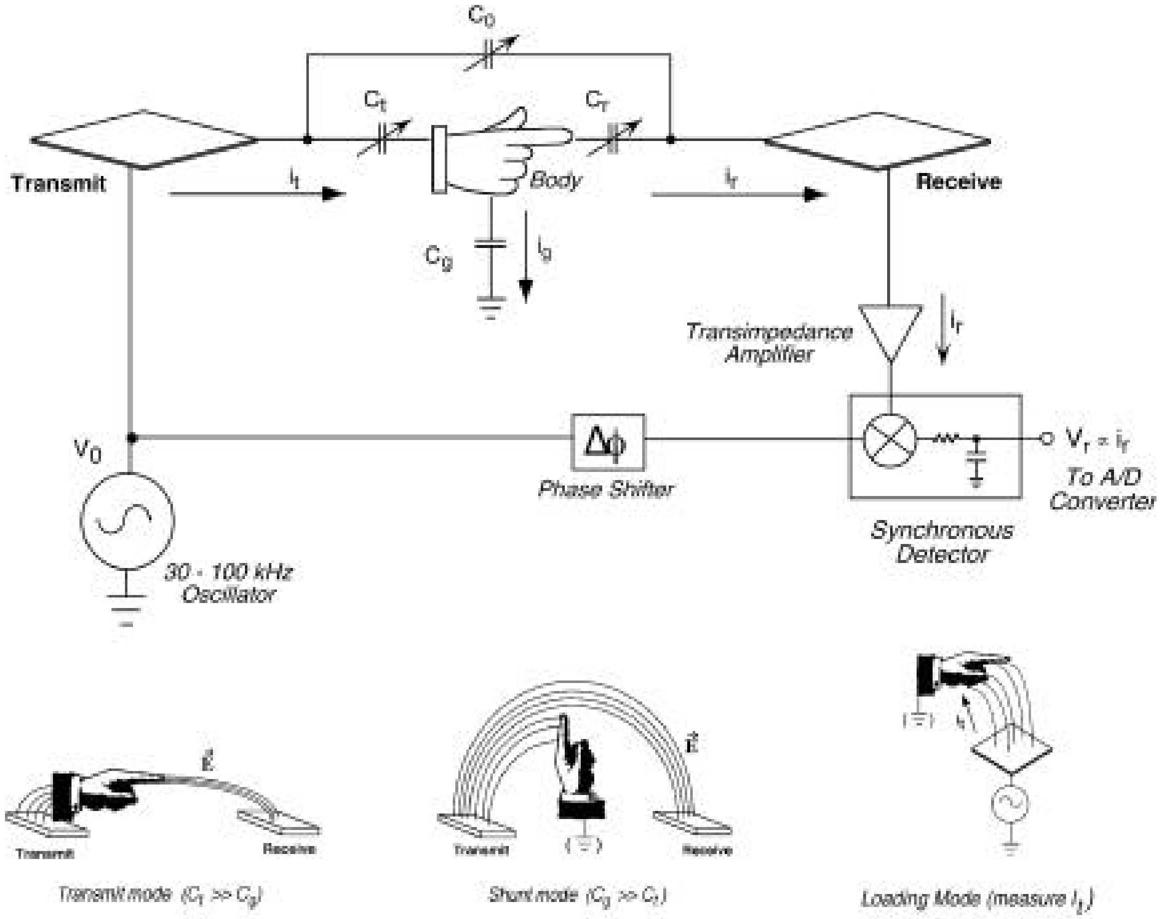


Figure 1: General implementation of Electric Field Sensing (top), and its three primary modes of application (bottom)

decreases as the hand approaches. This is termed "shunt mode", depicted at center in Fig. 1. A related single-electrode "loading mode", depicted at right in Fig. 1 measures the current pulled from the transmitter plate into the body (via C_g), hence needs only a single electrode; this is how the classic Theremin and most other embodiments of "capacitive sensing" work. In "transmit mode", depicted at left in Fig. 1, the body is very close to (or in contact with) the transmitter, hence C_t dominates, and the body becomes an extension of the transmit electrode; the received signal now increases as a function of body proximity to the receiver electrode.

All of our interface implementations use either transmit or shunt mode, which provide measurements that are more informative and robust than those given by loading mode. Loading mode measurements may be likened to images formed without a lens, since only one “end” of each field line is constrained by the measurement. Transmit mode works very well for tracking the motion of a user in contact with a transmitter; as the received signals are only a simple function of the distance between the body and receive electrode, limb position can be easily estimated [6]. Although shunt mode does not require the user to contact a transmitting plate, the nonlinear 3-body coupling (transmitter/body/receiver) is more complicated, thus more mathematics are required to recover detailed position [8], yet simple gestural response can still be easily obtained [9]. The shunt mode example in Fig. 1 shows only a pair of electrodes, one transmitter and one receiver. Most generally, one can use an array of N transceiver electrodes to collect N(N-1)/2 independent numbers. For simple proximity and position measurement, or making constrained decisions about an object's state (as in [10]) N would be chosen small; for more complex imaging applications, N would be chosen large.

The hardware needed to do Electric Field Sensing is very simple and inexpensive. We have designed several generations of electronics, which we term "Fish," since many species of electric fish use electric fields to sense objects in murky waters[11], and because unlike mice, which live on a two-dimensional surface, Fish navigate in three dimensions. Our first device, used in most of the examples given in the next section, contained one transmitter and 4 dedicated receivers employing analog filtering and demodulation, followed by 8-bit digitization and serial communication with a host computer, which ran the gesture tracking algorithms. Our subsequent device, the LazyFish is a minimal implementation of electric field sensing suitable for embedding in handheld devices. The unit has 4 resonant transmit channels, and two receive front end gain stages. The outputs of the receive front end channels feed directly into the onboard microcontroller’s analog-to-digital converter inputs. The received signal is then demodulated in software.

The School of Fish is our most general implementation of Electric Field Sensing. The School is a network of intelligent transceiver electrodes, each with a dedicated 8-bit microcontroller and demodulation circuitry. An arbitrarily large array of such electrodes can be assembled by daisy-chaining them onto a common RS-485 serial bus and placing the electrodes as needed; the electrode parameters (i.e., sensitivity, filtering, response time, transmit/receive mode) are all dynamically downloaded from a host computer, hence this system is highly adaptive and configurable. Since the School of Fish units are transceivers, this hardware is capable of making all N(N-1)/2 independent pairwise capacitance measurements. We are using this platform to develop electrostatic imaging algorithms. By deploying more electrodes, one collects additional geometrical “projections,” or increases the size of the working volume in which the body can be tracked.

Any conductor will suffice for electrodes. We have found copper tape, copper mesh, and aluminized mylar to be very useful for prototyping electrode geometries. When transparent electrodes are desired, mylar metalized with indium tin oxide (a transparent

Figure 2: The "Flying Fish"; navigating through a virtual world by moving hands around a monitor screen. The user sits on a transmitting electrode atop his chair; the receive electrodes can be seen at the edges of the monitor

conductor) may be used. With such materials, interface design becomes "arts and crafts," since one can quickly cut the materials to try a variety of geometries.

The position resolution of an electric field sensor array is a function of the mechanical placement of the electrodes, the background pickup environment, and the amount of noise in the received signal, which is likewise dependent on the demodulation filter bandwidth (hence response time). The gesture sensing systems described in the following section have electrodes spaced from 15-70 cm apart, and are able to resolve mm-level motion on msec timescales at up to a meter in range (by taking particular care in the electrostatic geometry, these techniques are capable of micron-level positioning across cm of range [12]). As the electric fields are unaffected by nonconductive, nondielectric materials, electrodes can be hidden behind furniture or built into other common objects. Ground planes can also be used to selectively confine and shield the sensitive region. The fact that electric fields can be shielded in this way is a significant advantage; because magnetic fields cannot be readily shielded, the effect of large ferromagnetic bodies on magnetic sensors cannot easily be accounted for.

3) *Applications*

Our first position trackers based on Electric Field Sensing technology exploited transmit mode. One of the original devices was a chair [6], with a transmit electrode on the seat (providing excellent coupling into the occupant), 4 receive electrodes to measure hand position mounted at the vertices of a 50 x 70 cm rectangle in front of the chair, and 2 receive electrodes on the floor to measure foot position. This device has been used for many musical applications, e.g. [13], where body motion was mapped in various ways to control electronic sound (see *http://physics.www.media.mit.edu/creative.html*). Shortly thereafter, we adapted this configuration into a computer graphics interface, as shown in Fig. 2. Here, a set of four shaped receive electrodes were affixed to the corners of a computer monitor, and the user was seated atop a transmit electrode placed over a common office chair. The sensors detected the proximity and up/down position of left and right hands; by moving the hands differently in and out, plus collectively up and down (in a pose like that shown in Fig. 2), the user is able to intuitively navigate through a 3-dimensional graphic landscape. The same apparatus is easily scaled down to finger size for applications in which arm fatigue becomes a problem. More details are given in Ref. [14].

Another set of more recent transmit mode implementations were the "Gesture Wall" interfaces (Fig. 3) created for the Brain Opera [15], a large, touring interactive multimedia experience designed for the general public (see also the above URL). As the Gesture Walls were designed more for a transient audience, they do not use a chair, but rather transmit into the body through a plate below the feet (the shoe impedances were first calibrated out by touching a reference sensor before using the device). The gesture sensors consisted of 4 receive electrodes (“budlike” objects on goosenecks in the photo of Fig. 3) placed at the corners of a rear-projection screen. Fig. 4 shows the reconstructed (x,y) hand position in the sensor plane (with arm outstretched) and distance (z) from this plane, as linearly derived from actual Gesture Wall sensor data. In this example, the (x,y) hand position is plotted only when the hand is close to the plane of the sensors, detected from the measured z signal. As the hand moves in and out of the sensor plane, the plotted color changes. These shapes were all made by quickly "drawing in the air" with a hand (the actual hand trajectories taken are shown at the bottom of Fig. 4), and attest to the utility of this interface.

In our actual implementation, the detected body motion controlled a stream of sequenced audio (composed by Tod Machover) and an interactive video clip (designed by videographer Sharon Daniel) using “watery” imagery (emphasizing soft blue and green

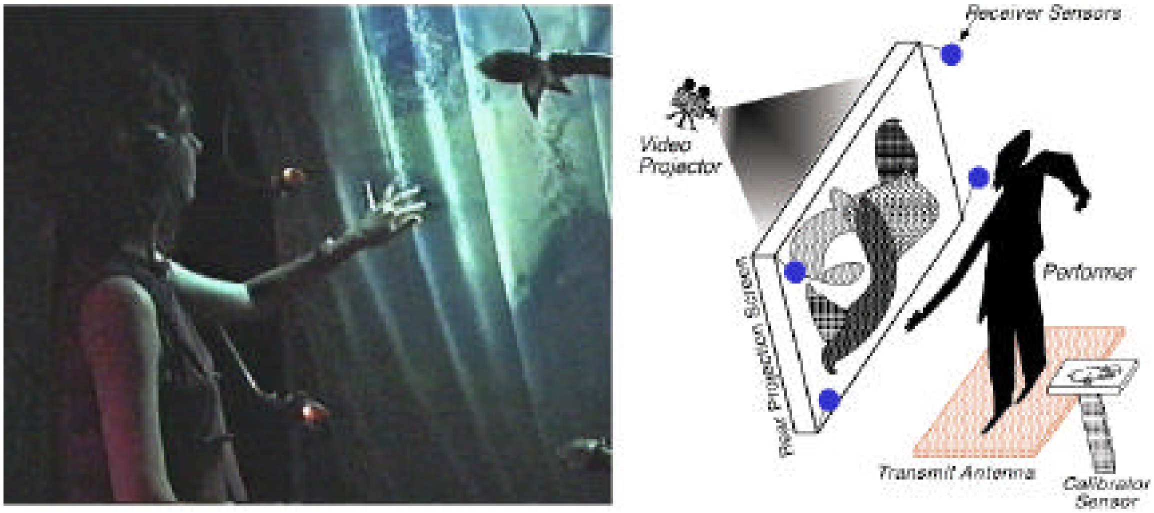
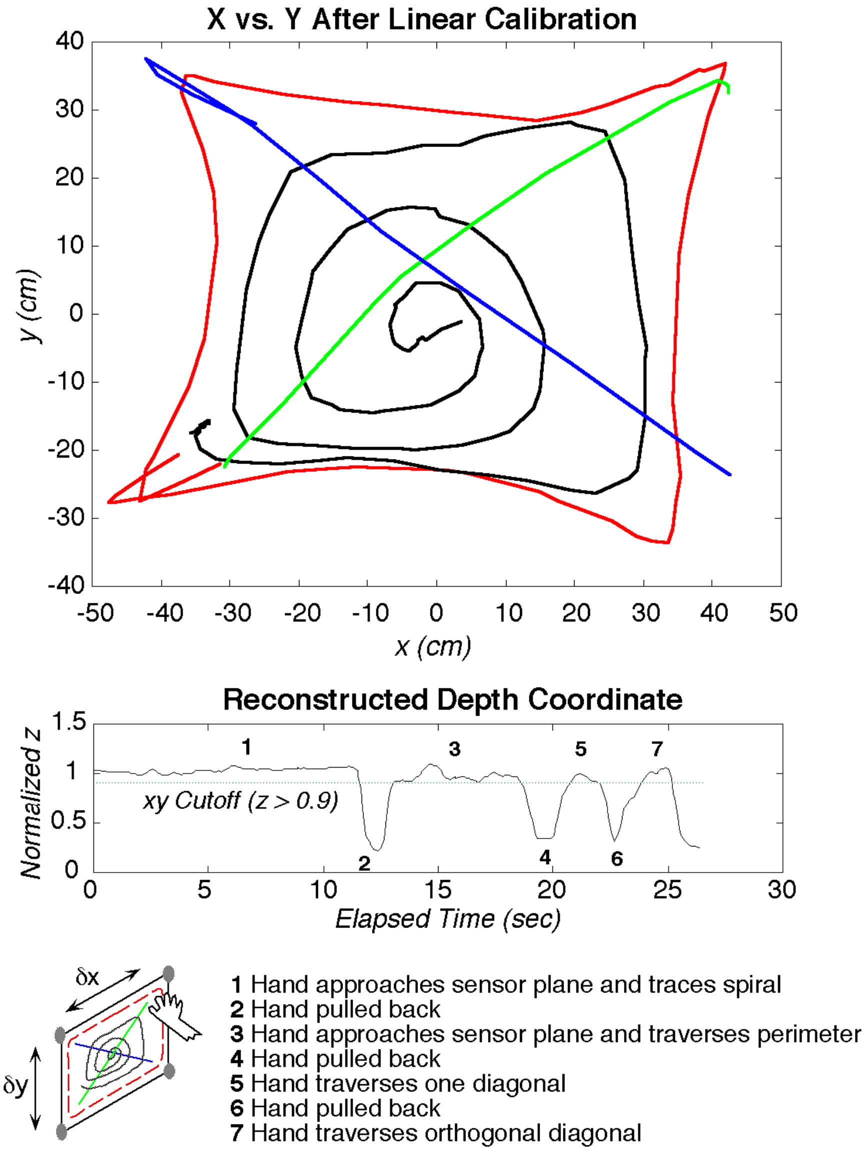


Figure 3: The "Gesture Wall"; schematic (right) and actual installation (left) in the Brain Opera at Lincoln Center, New York, July 1996

colors) as the visual metaphor, making the projections onto the translucent material appear to be filled with water.

The interactive graphics system ran on a Pentium 133, and is described in [16]. Four different interactive systems were built for the *Gesture Walls*. The goal was to create a 'role' for the audience member that was consistent with the general theme of the visual design, the types of information that the Fish sensor yielded, and the 'open' and tetherless manner of interactivity. The interactive design challenge was to link the motions of the participant's hand motions to a light and playful interactive environment. As visual output is such a strong feedback mechanism, participants of interactive visual devices are highly sensitive to cause-and-effect relationships between the his or her actions and the re-action of the system. Therefore, we needed to make both simple visual cues that linked the physical and virtual worlds together, while keeping the experience non-trivial and as engaging as possible.

Three of the four graphical system designs used a simplified particle system in which the video content, short 10 second looped video sequences, is broken into a collection of 76,800 (320 x 240) particle agents. These particle agents are spatially located within the 2D image area and have a set of very simple and highly localized behaviors that are based on simple Newtonian physics. These agents are part of a physical-based model that includes several different 'forces', such as momentum, friction, spring forces, and outside (interactive) forces. When the system is initialized, all of the agents are placed such that the original image sequence appears to be "normal" and the viewer sees the unperturbed video sequence play out. However, as the interactive participant moves his or



1 Hand approaches sensor plane and traces spiral
2 Hand pulled back
3 Hand approaches sensor plane and traverses perimeter
4 Hand pulled back
5 Hand traverses one diagonal
6 Hand pulled back
7 Hand traverses orthogonal diagonal

Figure 4: Position of a hand in the (x,y) plane of the gesture wall sensors (top) and corresponding (z) range (below), as determined from gesture wall data for a user freely “drawing” in the air. The actual hand trajectories that generated this data are diagrammed and summarized at bottom

her hand in the Fish sensor field, the particle agents that are near to the (x,y) coordinates of the hand are “pushed” along the vector of motion. The motion of each particle is the result of four forces: momentum (the particle’s tendency to travel in the same direction), friction (a dampening force), a spring force (to bring the particle back to its original spatial coordinate), and the user stimulus force (e.g., caused by the viewer moving their hand). Out of the simple Newtonian rules comes a swirling flow of pixel elements that float around the screen according to the physical-based model.

Figure 5: A “Smart Table”. Electrodes below (seen under the table in the left figure) sense the position of a hand above, allowing free interaction with a simple virtual environment, visible on the monitor

One of the Gesture Wall systems ran a algorithm called “scatter”, where the particles flew apart like a group of gnats that are scattered when a person swishes his/her hand, reforming themselves back into a group when the outside forces stop. Another ran a “sweep” algorithm, where the particles had a reduced restoring force, causing them to move in the direction of the participant’s motions and then slow down due to friction, hence the user swept the image particles off of the screen like dust. The “swarm” system used an attractive mode of interaction, where the agents would be drawn towards the user’s motion, as if they were a swarm of bees. The fourth Gesture Wall was named “wipe” and, unlike the particle systems described above, it used a spatial-temporal alpha-blend algorithm to allow the participant to gradually clear away one image to reveal another. As the interactive system received the (x,y,z) coordinates of the user’s hands from the Fish sensor, an alpha-blend matrix was updated to correspondingly reveal the underlying image at the place of user stimulus, in proportion to the vigor exerted by the participant (a time-decay system gradually restored the overlaying image, to create the impression that the visual surface was a piece of cold glass that fogged up and could be wiped clean, only to have it fog up once again).

We have also designed several graphics interfaces based around shunt mode sensing. By mounting a transmitter and three receivers underneath a wooden table, we have created an active region above, in which the naked hand can be used to interact with a virtual space. In this demonstration (see Fig. 5), a simple computer graphic image corresponding to the activated region appears on a monitor. The space contains an iconic representation of a hand, and a cubic object. By moving one's hand above the table, one can control the 3D position of the hand in the virtual space. When the virtual hand comes into contact with the cube, the hand closes, and the cube can be moved around the space.

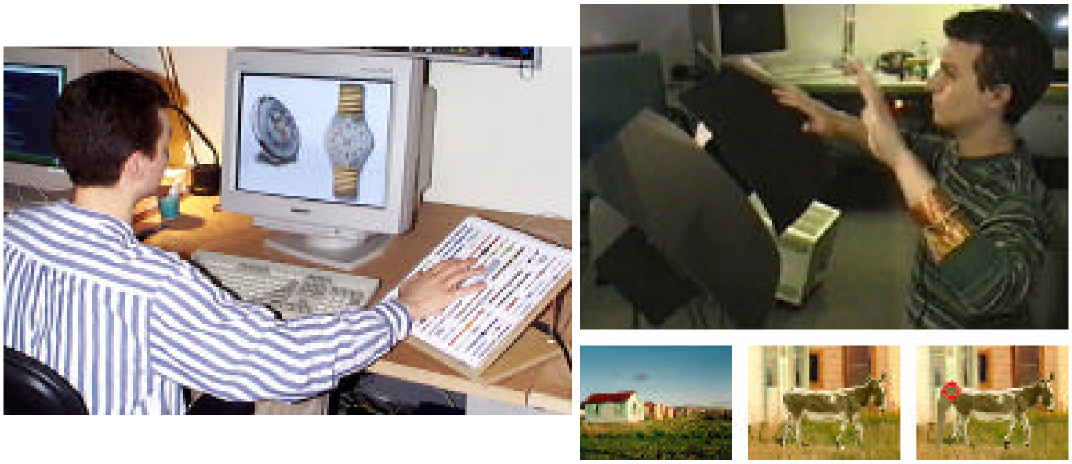


Figure 6: A user interacting with the "FishPad", using the one-handed configuration to browse through a watch catalog (left) and a 2-handed implementation to play virtual "pin-the-tail on the donkey" (right)

When the cube is set down again, the virtual hand opens, and the cube remains. We are currently working on algorithms that use additional electrodes to infer the size and orientation of the user's hand, so that the cube can be picked up or released anywhere in the space.

With the sensors in the same under-the-table configuration, we performed simple gesture recognition on the signals to create a "smart breakfast table" that allows one to turn the pages of an electronic newspaper. Flipping the hand left turns the page forward, right turns back, and moving the hand up or down changes sections. An electronic newspaper is a virtual environment one would like to navigate, but not in an immersive way. An activated breakfast table, which allows the user to flip through the virtual paper without leaving the comfort and convenience of the kitchen, is vastly preferable to a cumbersome immersive solution to the problem.

Another similar gestural interface that we have developed is called the "FishPad": a Fish-based input device used for exploring visual space through arm movements. The FishPad is likewise a flat, shunt-mode array, made from a central transmit electrode, surrounded by four receive electrodes arranged in a north-south-east-west configuration. These detect the 3D location of the hand, which is used to zoom and pan through a high resolution 2D image (Fig. 6, left). The input space of the device is directly mapped onto a selected region of the image. So, unlike a fly-through, the feedback is immediate and moving back to a known point of reference is done simply by returning the hand to the previous position.

FishPads can be used with one or both hands. In the two-handed configuration (see Fig. 6, right), the primary hand is still used for zooming and panning through a space, while the secondary hand is used for meta-operations on the image; separate FishPad arrays are use to track each hand. In one example, one hand zooms into a complex discrete automata program (with many cells on the screen dynamically changing), while the other hand examines the contents of any cell currently in the viewing region. In a more entertaining example (Fig. 6, lower right), a “pin the tail on the donkey” game was made where the primary hand explores the space looking for tailless donkeys, and the secondary hand pins on tails.

The capabilities of the Fish influenced the FishPad design decisions and pointed to areas of further study. As mentioned earlier, the shunt-mode Fish sensors have a non-linear response to distance and, due to slight differences in any one person's body capacitance and grounding, they do not respond equally to everyone. The solution was not to recalibrate for each person, as with the Gesture Walls, but to use reasonable defaults and simple transformations on the input, in order to keep the position updates high. Able to operate upwards of 50 Hz, the Fish had no problem keeping up with a 20 fps frame rate, which was generally fast enough for people to quickly learn the response of the FishPad to their movements.

The two-handed FishPad proved to be much more challenging than using one hand only, suggesting that the hands would work better together instead of decoupled in separate spaces. Fatigue and loss of accuracy was a problem with prolonged use, suggesting a new FishPad design, where the hands could be at rest or supported. It is hoped that a future implementation with the newer Fish hardware and a new physical design will overcome these initial discoveries. The resulting improvements in bandwidth and accuracy would yield themselves to a larger input area that could include both hands in a single sensing region, together with the ability to measure more subtle gestures.

4) Conclusions

Sensing with electric fields is not new, and our understanding is not complete. But we have found that lurking behind what appears to be a trivial exercise in capacitance is a deeper inference problem with significant implications for user interfaces. Given the basic inexpensive instrumentation to make these measurements, physical interface design reduces to shaping electrodes with easily available materials. This lets user actions on and around familiar objects be sensed responsively and reliably, activating the space around the objects without introducing any apparent intrusive technology. A recurring user reaction on encountering such a system is to first marvel at the "magical" causal control without any apparent mechanism for the connection, then to quickly forget about the presence of any intervening technology and focus on the application. This is the ultimate goal of any interface technology: for it to be so good that it becomes invisible.

5) Acknowledgments

It is a pleasure to acknowledge the many colleagues and collaborators who have contributed to the evolution of this work, including Tom Zimmerman, Tod Machover, and John Maeda. This research has been supported by the Things That Think consortium and our other sponsors at the MIT Media Laboratory.

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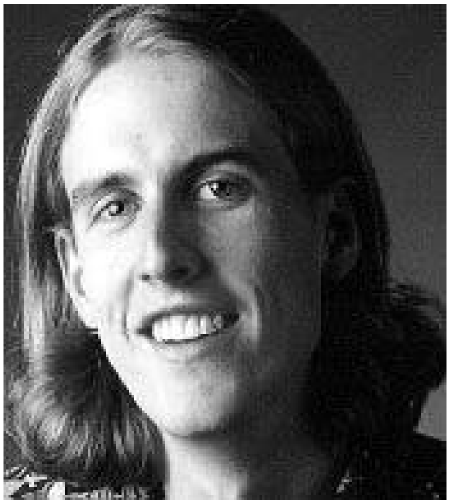
Keywords:

Electric field sensing, capacitive sensing, noncontact gesture sensing, motion capture, hand trackers, input devices



Joshua Smith is a Ph.D. candidate and research assistant in the Physics and Media Group of the MIT Media Laboratory. His central research topic is the problem of inferring body geometry from electric field measurements, but he has also developed new instrumentation and signal processing techniques for electric field sensing, and collaborated on many creative and industrial applications of electric field sensing. He has an M.S. from the Media Laboratory, an M.A. in Physics from Cambridge University, and a double B.A. in Computer Science and Philosophy from Williams College. He has had internships at the Santa Fe Institute, Los Alamos National Lab, the Yale University Department of Computer Science, and NASA's Goddard Institute for Space Studies.

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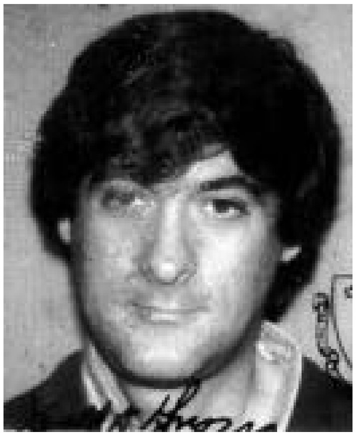
Chris Dodge completed an B.A. from New York University (1991) in an interdisciplinary study of Computer Science, Film/Video, and Music Composition. He has worked several years in the field of Digital Signal Processing software development. He was awarded a two-year Artist/Researcher-In-Residency at the Center for Art and Media Technology (ZKM) in Karlsruhe, Germany. He completed his M.S. at the M.I.T. Media Laboratory (1997), focusing on the development of real-time interactive media environments. As an interactive computer artist, his works have been shown around the world at such festivals as the MultiMediale 4, Ars Electronica '96 and '97, and the ARTEC'97 Media Art Biennial in which he won the Grand Prize. Currently he is an independent real-time interactive media environment producer and software developer in Cambridge, MA.

David Allport received BA in Sanskrit and Pali from Oxford University, England in 1978, and his PhD in Indian Philosophy from Oxford in 1982. After completing his Masters thesis in Artificial Intelligence and Knowledge-Based Systems at Sussex University he spent several years as Research Fellow working on computer natural language understanding. During his seven years at Hewlett-Packard research labs he developed model-based diagnosis systems and computer-human interfaces. He was HP visiting scientist at the MIT Media Lab 1994-1995. He is now Principal Engineer for Java at VSIS, a wholly-owned subsidiary of Mitsubishi Electric America.



Joseph Paradiso is a research scientist at the MIT Media Laboratory, where his activities include the development of new sensing technologies for responsive environments. He is currently the Technology Director for the Things that Think program. He received a B.S. in Electrical Engineering and Physics from Tufts University in 1977 and a Ph.D. in Physics at the Massachusetts Institute of Technology in 1981, after which he developed high-energy physics detectors, spacecraft control algorithms, and sensor systems at the Laboratory for High-Energy Physics at ETH in Zurich and the Draper Laboratory in Cambridge, MA. He is a member of the IEEE, AIAA, APS, and Sigma Xi. He is also active in electronic music, having designed several music synthesizers and electronic musical interfaces.

Prof. Neil Gershenfeld leads the Physics and Media Group at the MIT Media Lab, and co-directs the Things That Think industrial research consortium. His laboratory investigates the interface between the content of information and its physical representation, from building molecular quantum computers to building musical instruments for collaborations ranging from Yo-Yo Ma to Penn & Teller. He has a BA in Physics with High Honors from Swarthmore College, was a technician at Bell Labs using lasers for atomic and nuclear physics experiments, received a Ph.D. from Cornell University studying order-disorder transitions in condensed matter systems, and he was a Junior Fellow of the Harvard Society of Fellows where he organized an international study hosted by the Santa Fe Institute on forecasting the behavior of complex systems.