Pervasive Activity Detection with Capacitive Sensing

Raphael Wimmer, Matthias Kranz, Albrecht Schmidt
Embedded Interaction Research Group, University of Munich
Amalienstrasse 17, 80333 Munich, Germany
{raphael,matthias,albrecht}@hcilab.org

Sebastian Boring
Fluidum Research Group, University of Munich
Amalienstrasse 17, 80333 Munich, Germany
sebastian.boring@ifi.lmu.de

Abstract

This paper presents a toolkit for realizing capacitive sensing applications for human-computer interaction in pervasive computing systems. We describe the CapSenseToolkit, a complete toolkit for prototyping and implementing systems for detecting presence of humans and objects and for integrating 3D interaction with everyday objects. This allows to acquire data and develop sophisticated algorithms for e.g. gesture recognition using capacitive sensing. We systematically measured the range, resolution and reliability of the hardware to show possibilities and limitations of capacitive sensing. This hasn't been done so far. We illustrate the capabilities of the toolkit by presenting several applications realized with the system. In particular we built a table augmented with capacitive sensors to capture activities. An instrumented shelf senses where the user puts his hand and can thus infer what he's grasping. Adding capacitive sensing capabilities to an ordinary computer keyboard enhances scrolling in documents and switching between screens. By putting sensors on a tablet PC we built an intuitive touchscreen replacement. The complete system, including all hardware and software components, is released as open source.

1. Introduction

Capacitive sensors in everyday objects, e.g. touch light switches, touch lamps, are common place. Research for systems in pervasive computing suggests the use of capacitive sensing in user interfaces - they are frequently used to detect an approaching user, the presence of users, or the act of grasping a prototype before interaction Ready-to-use sensors with simple detection mechanisms, e.g. the QT100 from QProx [6], can be bought off the shelf. Capacitive sensors not only detect touch events, but are also used for e.g. fluid level sensing [2], in research as well as in commercial products.

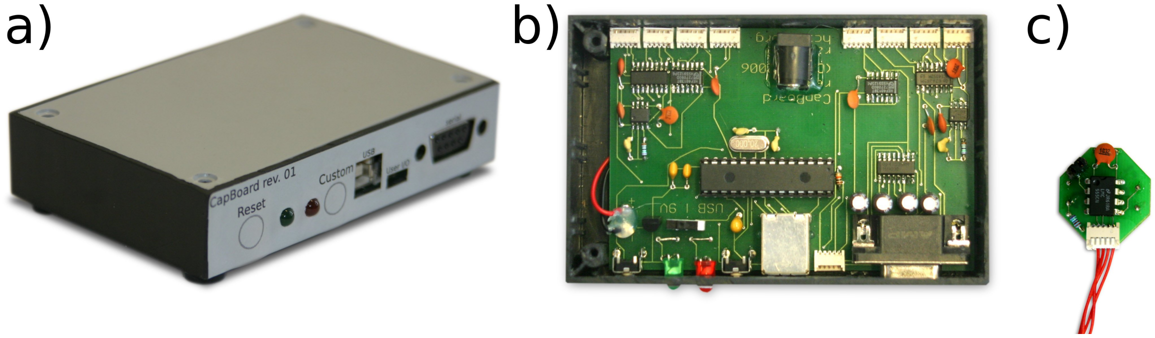

Figure 1. CapBoard (a, b) is a newly developed hardware platform for capacitive sensing. It features eight sensor channels, four custom I/O ports, built-in pre-filtering, communication and power supply via USB and a user-customizable firmware. Small and cheap sensors (c) allow augmenting many different objects with capacitive sensing.

In this paper we report our experience in creating a capacitive sensing toolkit (hardware and software, Fig. 1) and initial experiences in augmenting everyday environments with capacitive sensing. In contrast to other research our approach will use the potential of capacitive sensing for embedded interaction in augmented environments. We concentrate on coarse detection of 3-dimensional input, and in particular we focus on gesture input, activity recognition, and presence detection.

Capacitive sensing is a quite old technology. It was used first in 1919 in a musical instrument called Theremin, where pitch and volume of the sound were controlled by the distance of the musicians hands to two antennas. While utilized for industrial measuring applications (e.g. fluid level sensing [2]), and in art projects for many years, only recently the potential of capacitive sensors for human computer interaction has been explored.

Exemplarily, several research systems as the School of Fish [9], the DiamondTouch Table [1] or the SmartSkin [7] project show new and interesting applications and significant advances in human computer interaction based on capacitive sensing. Our view is that embedding capacitive sensing into everday objects, and providing toolkit support for this, can open a new field for interactive pervasive applications. Hardware and software for the toolkit is open source, easy to connect to different PC-backends, and the hardware cost in prototype quantities is very low (less than 100 Euro for an 8 channel system).

A central in concern in our research project was to create a system that is easily deployable, and where the sensors can be integrated into environments, furniture, and every day objects. This provided the motivation for us to design a modular system, where sensor modules and antennas can be easily tailored to specific settings and host environment. To support the setup of new systems, tools to log data and graphical sensor data viewers are provided.

The paper is organized as follows. We first discuss the basics of capacitive sensing in Section 2 to give researchers the required basic understanding of the technology used. We related our research to recent work in the field of capacitive and electric field sensing and highlight the differences of the proposed system in Section 3. We present our vision of a capacitive sensing toolkit along with the required and working hard- and software systems which are readily available in Section 4. We also encourage researchers to use our system for their research. All details, including schematics and source code, will freely be available on our webpage. We show several appliances realized with the described toolkit. We conclude our paper with a discussion of the taken approach and an outlook for future research in Section 6.

2. Capacitive Sensing

2.1 Basics of Capacitive Sensing

The simplest capacitor consists of two metal plates put close together without touching each other. When current is placed on those plates energy is stored. When the current is removed and the plates are connected through a circuit, the stored energy initiates a current. Thus, a capacitor works like a small accumulator. The capacity (capacitance) of this simplest capacitor depends on the size of the plates and their distance. The principle holds true for all sophisticated capacitors as well.

Various other technologies are used to realize capacitive electric elements, like electrolytic capacitor or tantalum capacitors. Similarly, there are various ways to measure the capacity of a capacitor. A simple option is to use an electric circuit consisting of a resistor and a capacitor, a so-called RC circuit. Measuring the time till a certain voltage is reached (charging) can be used to calculate the capacity if the voltage and the value of the resistor are known. The formulas can be found in any basic text book in physics or electronics.

Using the effect described above, one can infer and track the distance between a sensor and an object from the capacitance they provide. For this, one of the two plates of a capacitor is replaced by the object to be tracked. The object to be tracked has to provide enough positive charges to counter the negative charges at the sensor plate.

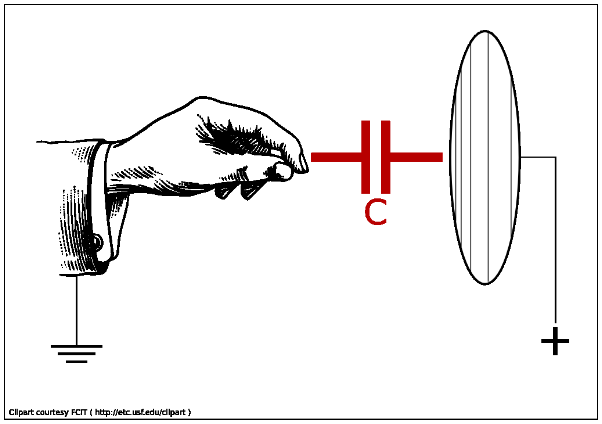

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Figure 2. A human hand and a metal plate form a capacitor. The hand or body does not have to be connected to ground because the human body provides a sufficient charge reservoir. From the capacitance of this capacitor the distance between hand and sensor plate can be estimated.

Objects partially consisting of conducting materials like metal or water are very well suited for tracking. Ideally the object is grounded, as ground provides a quasi endless charge reservoir. Often the object itself provides a sufficient charge reservoir. Especially the human body does not need to be grounded in order to act as a good capacitor plate. When the object gets closer to the plate, the capacitance of the so formed capacitor increases. One can measure the capacitance and from this calculate or estimate the distance between sensor plate and object.

The most common way to measure the capacitance of a capacitor is to use a resonant circuit. Depending on the capacitor's capacitance, the resonant circuit resonates faster or slower. This technique of measuring distances between a sensor and an object is called capacitive sensing.

Such sensors allow measurement of microscopic displacements in the range of micrometers. They are the industry standard for ultra-high precision measurements in many application areas. But they can also be used for large-scale tracking, featuring sensing ranges up to three meters. However, for such distances to be covered, special measures like virtual grounds (see Section 4.1) have to be taken.

While the principle of capacitive sensing described above is used in the Theremin and most industrial sensors, there are other means to use quasi-static electric fields for tracking conductive objects. Smith [10] describes three different modes of electric field sensing: Loading Mode, Transmit Mode and Shunt Mode. Loading mode is equivalent to "traditional" capacitive sensing. In Transmit Mode the user is coupled to an antenna and prolongs its electric field. Thus the capacitance between his hand and a non-emitting sensor plate can be measured. This mode requires the user to be connected to an electrode. Shunt mode utilizes the effect that a conducting object near a emitter-receiver plate combo shunts part of their electric field to ground, acting as a shield. Thus the electric field measured at the receiving electrodedecreases as the object approaches. Shunt mode offers the advantage of getting $\frac{n*(n-1)}{2}$ measurements from n sensor plates. For details see [9].

2.2. Limitations of Capacitive Sensing

2.2.1 Exponential Decrease of Capacity with Distance

A major hurdle for implementing capacitive sensing into pervasive applications is its limited range. The generic equation for the capacitance of a capacitor, $C \approx \frac{\epsilon A}{d}$, implies that capacitance is inversely proportional to the distance between the plates. However, this is not the case for greater distances between the plates. The farther apart the two plates are, the smaller their overlapping area gets relatively to their surrounding (Fig. 3).

Thus a more realistic model is $C \approx \frac{\epsilon A}{d^x}$; whereas x is between $1 - 3$, depending on the environment. This rapid decrease of capacitance with increasing distance poses a problem when trying to track objects at distances greater than $\approx 10cm$. The lower resolution has to be accounted for, e.g. by placing another sensor opposite of the first , so that the object is always close to one sensor. Additional sensor data and sophisticated filtering can be useful, too. Some systems incorporate the inherent limits described above into the application's design ("it's not a bug, it's a feature").

2.2.2 Blind Sensor

Capacitive sensors can only measure a capacitance. What is causing this capacitance remains unknown to the sensor. Thus a capacitive sensor cannot discriminate different objects which generate the same capacitance. Discerning e.g. the hands of different users is nearly impossible. However, e.g. DiamondTouch infers the user's identity from time-slicing the electric field and detecting which user is exposed to it at a certain time.

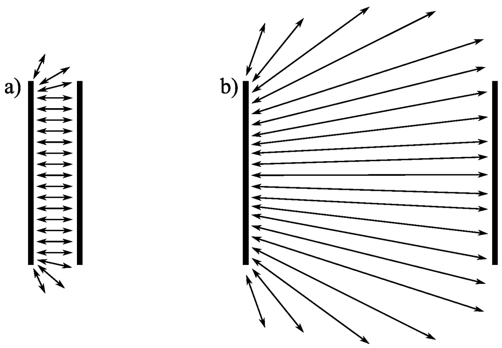

Figure 3. With increasing distance (a, b) between the capacitor plates the stray capacitance and self capacitance (not shown) of the plates increases. This behaviour heavily limits the range of capacitive sensors.

2.2.3 Inferring Objects

Capacitive sensing hardware is prone to external distortions. Other objects passing the sensor can spoil the measurement. E.g. when a person walks past closely to the system, this interferes with the sensor measurements. This makes it hard to provide reliable capacitive sensing for heavily populated environments. The indifferent recognition behavior poses a challenge when integrating capacitive sensing hardware in handheld devices. Though, for specific scenarios, e.g. a dinner table, this problems can be handled by algorithms to some extent. Also, for non-changing scenarios like a workpiece workplace, as we present in the Future Work (Sect. 6 CHANGE) this can be detected and recognized and thus be neglected. Even if the interfering object does not move, it dampens the signals and reduces the tracking resolution. This can only partly be compensated by shielding. As capacitances to a certain degree accumulate, like for example weight or load on a load sensitive surface [8], this can to some extend be discriminated by extensive measurement of objects that are to be used in conjunction with the system. In a few tests, we could e.g. discriminate which one of four different empty coffee mugs was placed on the CapTable (described in detail in Sect. 5.1.1), as all four cups were different in size and thickness. By measuring these objects in advance, an easier discrimination of desired and undesired objects can be made.

2.2.4 Limited and Ambiguous Data

The only information a capacitive sensor returns is its capacitance and the change of capacitance over time. A certain capacitance can result from one person standing in front of the sensor or from two persons standing a little farther away. Disambiguation can sometimes be achieved by using additional sensors and filtering as discussed above.

3. Related Work

The technology of capacitive sensing itself is already part of today's computers, e.g. in the touchpads of current laptops. There, input is limited to a very small range of sensor to hand, typically less then half an inch. We extend the sensing range to explore the impacts on the way input to a system can be generated. However, using capacitive sensing for medium-scale position tracking has not been pursued so far.

3.1 Electric Field Sensing

Smith et Al. [10] and Zimmerman et Al.[11] explored the potentials of electric field sensing (EFS) as input modality. Especially Joshua R. Smith implemented many systems using shunt mode electric field sensing. Some systems allow gesture tracking in two dimensions. A mobile phone with an integrated EFS module measured the distance between phone and head. This was used to determine radiation exposure of the user's brain. This research on electric field sensing, unfortunately, was discontinued after Joshua R. Smith left the MIT Media lab.

3.2 iSphere

Jacky Lee et al. [5] developed a 3D interface device for CAD workstations which uses capacitive sensing. This device (iSphere) only measures three different states (distant, close, pressure). The user needs to touch the iSphere for interaction. Interaction at a distance is not supported.

3.3 DiamondTouch

The DiamondTouch table proposed by Dietz et al. [1] uses a grid of metal strips below a tabletop to sense finger position. A digital projector projects a computer screen onto the table. The strips of the grid emit - time-multiplexed - an electric field. This design is practically a huge touchpad, very similar in principle to those used in notebooks or the Apple iPod. While touchpads implement loading mode electric field sensing, DiamondTouch utilizes the transmit mode. Two features make DiamondTouch special: Its ability to track more than one finger (which is also possible with recent touchpads). And its ability to discriminate different user's hands. This is made possible by seating all users on metal chairs which are capacitively coupled to the user sitting in them. The user in turn is capacitively coupled to the DiamondTouch grid. By determining which grid strips are active when an electric field is sensed in the chair the system can detect where each user is touching the display. Thus DiamondTouch allows intuitive collaborative interaction on a computer screen. The emitted field of the DiamondTouch table though is only capable of detecting direct touch events. The user has to directly have contact to the table.

3.4 SmartSkin

The SmartSkin project by Rekimoto et al. [7] also uses capacitive measurement for user-surface interaction. Again, a fine array of emitters is placed below the surface for achieving the sufficient resolution which is needed for intuitive human-surface interaction. The measuring range in the Z axis is about 5 cm.

SmartSkin is only capable of detecting touch or tagged objects. Untagged objects as they are common and natural are hard to use with the SmartSkin.

3.5 EtherTouch IC

EtherTouch [3] is a commercial electric field sensing IC for mobile devices like PDAs or mobile phones. It is connected to X, Y, and Z electrodes all together on a thin plastic board. As Ethertouch implements transmit mode electric field sensing, the user has to be capacitively coupled to the emitter. With handheld devices this is very easy to accomplish. The manufacturer claims to reach a sensitivity of $4\frac{aF}{\sqrt{Hz}}$. As no actual devices with this chip are available the usefulness of the IC for pervasive computing applications can not be estimated. Initial measurings suggest that CapBoard sensitivity is about in the same magnitude as the EtherTouch. In close ranges up to 10 cm either solution should provide sufficient resolution.

3.6 Problems with current systems

While the mentioned systems show highly interesting applications for capacitive sensing, current research still lacks some aspects.

- Most systems known to us focus on explicit interaction with the device. Only some art installations use capacitive sensing to trigger events if someone approaches. Capacitive sensing for implicit interaction - as desired in ubicomp and pervasive scenarios - has not been researched in depth.
- While capacitive sensing is basically a very primitive technology, many researchers have seen the need to design complex specialized hardware in order to overcome some of the limitations of capacitive sensing. As a consequence other researchers have difficulty adapting those systems to their needs.
- A lack of data on sensor performance discourages new designs and makes it difficult to determine the quality of a capacitive sensing solution. Most publications and technical datasheets omit hands-on figures regarding sensor range, resolution and reliability. Often no actual evaluation of the proposed system has been conducted. Regularly research papers describe actions which can be performed without mentioning resolution and error rate. Discussing the system's problems and limitations often is not regarded necessary, either. On the other hand, several students trying their hand on capacitive sensing projects often report failure in building sensors with sufficient resolution for useful applications. The lack of reliable data, together with the fact that only renowned researchers seem to be able to build working systems, appears to us as the main drawback of research in capacitive sensing.

4. The CapSenseToolkit

Capacitive sensing systems have a high potential for human-computer interaction in pervasive computing systems. However, due to the aforementioned problems concerning research and implementation of such systems, we see the need for ready-to-use hardware and software to quickly evaluate and integrate capacitive sensing into new prototypes.

Therefore, we release our complete system, comprising hardware and software, to the community to support research in this field. We hope we thereby enable researchers to use a out-of-the-box system to realize their ideas and projects using capacitive sensing technology.

The CapSenseToolkit was designed to support

- sensing interaction in 3D
- recognizing activities
- detecting and discriminating objects

Our main goals with the toolkit are to

- provide cheap, easy to build and to use hardware
- provide open-source, cross-platform tools to analyze and visualize the data
- put down hands-on tips and guidelines for implementing custom systems
- enable researchers to improve and extend the system to fit their needs
- make it easy for non-engineers to build new sensing applications
- offer reliable data on range, resolution and error of the hardware, allowing other systems to be compared to this hardware

We will now describe the toolkit components and some example applications we so far built with our system.

4.1. Toolkit Hardware

In this section, we in detail present our capacitive sensing hardware, the so-called CapBoard (Fig. 4). It aims to provide a cheap, flexible, and open-source hardware design, device firmware and host software for capacitive sensing interfaces.

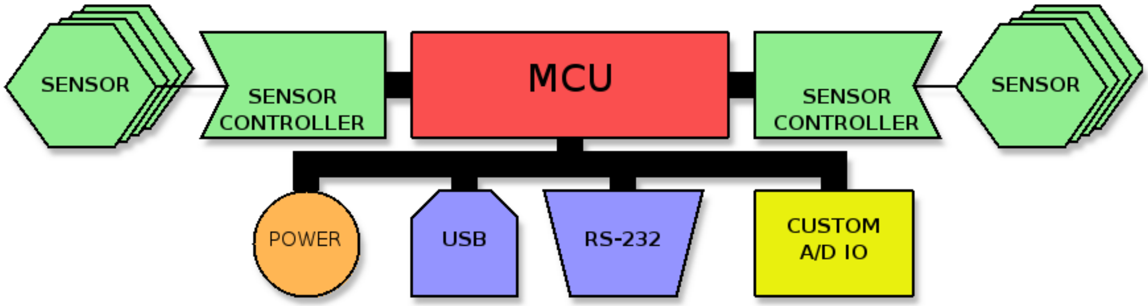

Figure 4. The CapBoard is assembled from standard parts. A PIC 18F2550 IC controls the two sensor circuits and sends measurement data via USB or RS-232. A connector for an external power supply and four freely programmable I/O pins enable stand-alone operation.

Each CapBoard allows up to 8 capacitive sensors to be read out at a frequency of 25 to 100 Hz. The data is acquired by a PIC microcontroller and published via USB. Additional complementary sensors can be connected to four analog/digital I/O ports. Acquisition time, filtering, and output format can be easily adjusted.

The control and communication part of CapBoard is based on a Microchip PIC 18F2550 microcontroller. A USB port directly connected to the microcontroller is used for bi-directional communication, and provides the system with power. This reduces the necessity for additional power supply and therefore facilitates easy installation.

A USB bootloader firmware allows the user to upload custom firmware via USB, and makes fast iteration cycles possible. USB communication is currently using a custom protocol, but support for e.g the Human Interface Device (HID) Class is planned.

The communication protocol is kept deliberately simple and straightforward, following the KISS principle: keep it simple, stupid. For example 'A' and 'Z' start and stop measuring, 'E2' enables sensor channel 2, and 'L21' lights the second LED on CapBoard. Measuring data can be output in various formats, depending on the needs of the connected application. Everything can be configured and altered during run-time of the system.

The sensor part is based on the ThereminVision-II hardware by Terry Fritz (thereminvision.com). A sensor consists of a sensor board and an antenna or sensor plate. Core of each sensor board is a LMC555 timer IC. Depending on the capacitance of a connected capacitor the LMC555 outputs a non-linear frequency up to 3 MHz. A rapidly changing, quasi-electrostatic field is generated around the antenna. As two electrostatic fields distort each other, no two sensors should be active near each other at a time. Thus each sensor can be enabled and disabled via a digital signal. As our sensor boards consist only of one IC and some resistors and capacitors, they are very cheap (less than one Euro per sensor) and small-size. Current sensor boards are about 2 cm by 2 cm. Using only SMD parts a sensor size of 1 cm by 1 cm is easily possible. The sensor board is depicted in Fig. 1.

The capacitance provided by a small antenna plate of 10 by 10 cm is between 30 pF (empty room) and 46 pF (hand in a few millimeters distance). The frequency of the LMC555 is set to about 3 MHz and changes to about 2 MHz when a hand is placed almost on top of the plate. Capacitance and frequency vary depending on antenna size and shape, circuit design, sensor placement and environmental conditions. An additional capacitor can be added in parallel to decrease the frequency.

To each of the 8 sensor channels provided by CapBoard, one of those sensors can be connected. A four-wire-connector provides power to the sensor, controls its state and is used for data transmission. The sensor puts a square-wave signal with a variable frequency onto one wire. In the CapBoard the frequency of a reference timer (2 MHz) is subtracted from the measured frequency. This is done by a D-type flip-flop. Thus small absolute frequency changes result in rather large relative changes. In four measurement passes two sensors are activated and read out at a time. This reduces cumulative acquisition time but requires the concurrently active sensors to be placed some distance apart. When measuring the frequency of a signal the resolution depends linear on the acquisition time. If the signal is read for 10 ms the smallest frequency change that can be detected is 100 Hz. When measuring a channel for 100 ms frequency changes of 10 Hz can be detected. So there is always a tradeoff between resolution and update rate when measuring frequencies. The easiest way for measuring a frequency with a microcontroller is using the signal to drive an in-built counter. At fixed intervals the counter value is read out and the counter is resetted. With a 16bit counter a frequency of 1 MHz results in a counter overflow every 65 milliseconds. The update rate of CapBoard can therefore be adjusted from 25 to 100 Hz, depending on the factors mentioned above.

4.2 Integrating CapBoard into existing hardware

The antenna can be arbitrarily shaped to accommodate for size constraints. However, antenna size and shape define the sensor's range and sensitivity: the larger the antenna the greater the sensing range. A metal plate as antenna provides high sensitivity (and range) in the orthogonal axis. Objects in the other two axes have only very limited influence on the sensor's capacitance.

On the other hand a spherical antenna can be used for omnidirectional sensing, e.g. to provide simple proximity detection. Spherical antennas also simplify data extraction from measurement data as they can be described as single points instead of planes. However, it is often difficult to integrate a sphere into hardware designs. In scenarios like gesture tracking spherical antennas may introduce more noise than simple bi-directional plates.

A common problem of capacitive sensors is that they are generally more or less omnidirectional. In order to shield one side of a sensor plate against other objects a 'guard' may be added to one side of the antenna. A 'guard' is a shielding that is not grounded but kept at the same voltage level as the antenna (principle of a 'virtual ground'), thus preventing an electric field from building up in its direction. CapBoard sensors do not yet have 'guards'. Those will be added in the next iteration of the hardware.

4.3 Loading Mode and Frequency Measuring

Most electric field sensing systems implement transmit mode (DiamondTouch, SmartSkin) or shunt mode (School of Fish). Those are expected to provide better resolution than the loading mode electric field sensing implemented in CapBoard. For our Toolkit we have chosen loading mode for three reasons:

- placement of sensors less complex than in shunt mode
- users / objects don't have to be connected to an electrode as in transmit mode
- simplest implementation

Most commercial sensors output their measurements as a voltage level instead of signal frequency as CapBoard sensors do. Using signal frequency has advantages and disadvantages.

High-frequency signals are more prone to noise than voltage levels. However, our measurements do not indicate any influence of external signals on the measured frequency. Another drawback of our method is that precisely measuring a frequency takes more time than measuring voltage levels. We argue that for most pervasive computing applications an update rate of 25 Hz - 100 Hz is quite sufficient.

Measuring a frequency avoids two D-A (sensor) and A-D (microcontroller) conversions. Thus no conversion errors can occur. Additionally, signal frequency stays the same even when transmitted over long cabling. Voltage levels drop, however, with distance.

Therefore believe that CapBoard provides ample resolution and range for most applications.

4.4 Range, Resolution, Reliability

We are currently in the process of evaluating and optimizing our toolkit. Nevertheless we can provide preliminary minimal specs for the hardware.

Measuring Range depends on the size of the sensor antenna and the acquisition time. Using a metal plate of 10 cm x 10 cm and a acquistion time of 25 ms CapBoard reliably detects hand movements at a distance of 70 cm. A smaller plate of 2 cm x 2 cm still yields a reliable measuring range of 30 cm.

Spatial Resolution greatly depends on the distance between object and sensor plate. Using the same 10 cm x 10 cm plate, the same hand and the same acquisition time of 25 ms, CapBoard provides a resolution of about 1 cm at a distance of 60 cm. At a distance of 30 cm one millimeter displacements can be detected.

Reliability of CapBoard is high. Due to the low complexity, open source firmware and modular design the hardware will work reliably and unattended. However, environmental factors like temperature or humidity have a measurable influence on capacitive sensors. Thus the system should be re-calibrated if these factors change. We are considering an auto-calibration feature and/or temperature compensation for the next version of the toolkit.

5. Toolkit Software

The software for the CapSenseToolkit comprises software for accessing the the CapBoard via USB and additional tools to visualize the sensor data. This software uses libusb on Linux for transferring the data by interrupt read and writes on the USB endpoints. We plan to provide a Windows driver, too.

We provide two interfaces for accessing the CapBoard data. The first one publishes the data over a TCP socket which allows the integration of the CapBoard in every system that can send and receive data over sockets. While this bridging software needs to be run on the computer the CapBoard is connected to, applications that process the data can be run on any networked computer.

The second interface uses the sensor/actuator middleware Player/Stage and publishes the sensor data via the analog i/o interface (AIO). This open source middleware is widely used in the robotics domain and well supported. The data can be accessed with a great variety of programming languages as well. By providing these two interfaces we hope that every researcher interested in using the system can easily access the data and use it for his research. Both tools allow the capture and logging of the desired sensor values and to use it in any other application, e.g. for activity recognition.

We also developed several tools for visualizing the sensor data. The CapBoard Analyzer (Fig. 5) is a Java-based GUI that displays the values of the desired sensors in real-time. It connects to a TCP socket and plots sensor values over time. The tool also allows to control several parameters of the CapBoard firmware as acquisition time, channels enabled or filtering.

Another application that builds on the toolkit is the CapTable Visualizer (Fig. 6). It allows to display live video or a captured video stream overlayed with the sensor data from the CapTable mentioned in Section 5.1.1. The purpose of this tool is to combine sensor data and video as starting point for activity recognition. The tool helps the research view all relevant data at once in a very convenient human-understandable format.

CapBoard uses a plain-text protocol to send and receive data. Starting the bridging software and connecting to the TCP socket with HyperTerminal or netcat is everything needed to view sensor data. Thus CapBoard makes rapid development of prototypes and troubleshooting easy.

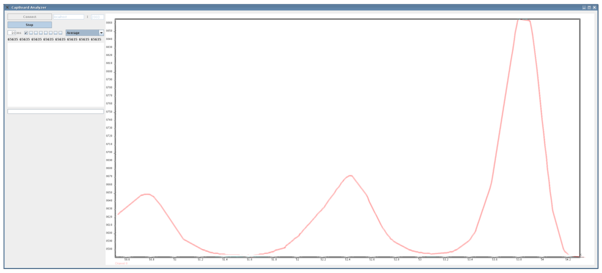

Figure 5. CapBoard Analyzer displays capacitance values for each sensor in real-time and plots it over time. A GUI enables the user to quickly enable and disable sensors, select filters, or adjust the acquisition time. The data can be logged to a file for further review.

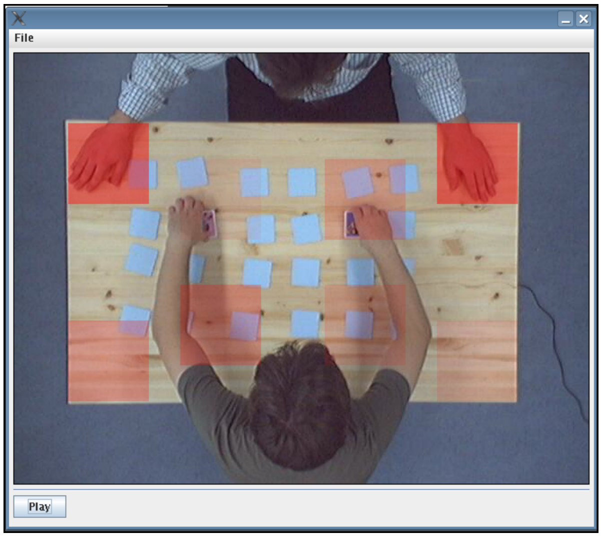

Figure 6. CapTable Visualizer displays a video of the scene with capacitive sensing data overlayed. In this screenshot the unprocessed sensor values are shown as saturation of squares.

5.1. Toolkit Examples

In this section, we present several example applications we realized with the toolkit presented above.

5.1.1 CapTable

We present a example scenario where all aspects of the system can be highlighted. Of course, the scenario from a first glance looks similar to the related work discussed in detail above. But we think we can illustrate e.g. the explicit context recognition and activity detection which is not possible with DiamondTouch and SmartSkin.

The CapTable is a wooden table of ca. 70 cm height. The plate is 120 by 75 cm. Below the plate, there are eight metal plates of each 20 by 20 cm installed. The plates are made of ordinary 1mm steel. In each edge of the table, there is one plate. The reaming four plates are arranged as smaller rectangle in the middle of the table (see Fig. 7).

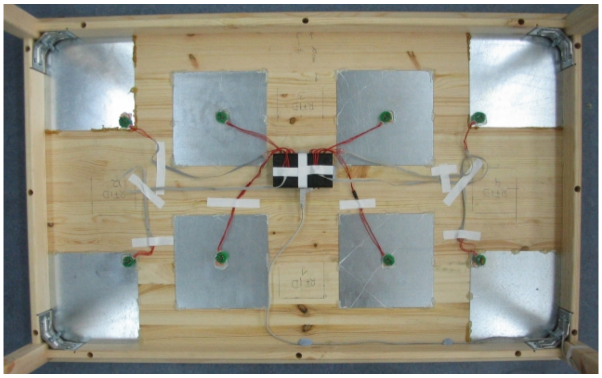

Figure 7. CapTable: 8 metal plates are mounted below the table to emit an electric field whose disturbance is measure by the sensor system.

With the arrangement of the plates, we can track several events and activities: The plates at the corners allow to 'see' passers-by and people advancing the table. This is even possible though the object is perpendicular to the plate surface. This can be exploited to trigger events like welcome messages or the displayal of a projection overlay. We are also able to determine how many people are currently situated at the table and the sitting configuration.

The plates in the middle can be used for various purposes. They can detect e.g. drinks and food and the changes of them, e.g. the fluid levels. This could be employed and used in a health and dietary scenario, as proposed by [4] and allow for a much more realistic scenario - people would be able to actually touch the table. In the proposed system based on load cells, any additional weight e.g. by arms, interferes with the weight-shift calculation algorithms.

Also, gestures performed of the capacitive sensors can be detected, e.g. 'rotate the display' by a circular gesture over the sensors.

Activity and Person Recognition In the current setup, we can reliably recognize, if persons are approaching the table or passing by it. The pattern always consists of a irritation of the two sensors on the side of the person. Depending on the sensor irritated first, the direction can be inferred. An approaching person just raises the sensor level of one or more sensors and when a certain threshold a person can reliably be detected. Determining the level of fluids is one common application of capacitive sensors. Interestingly enough, also empty containers, e.g. of glass or ceramic, can be tracked. As discussed before, as the sensors are blind, we have to know what is to be expected. This information can be taken from a database containing the capacitances of all objects that will be used on the table. Fig. 8.

5.1.2 CapKeyboard

An earlier version of our hardware has been attached to two small metal plates which are affixed to a computer keyboard (Fig. 9). Moving their hand above the plates the user can intuitively scroll in large documents, avoiding repetitive and stressing use of the mouse scroll wheel. Absolute positioning in a large document can be done but has shown less intuitive than relative positioning.

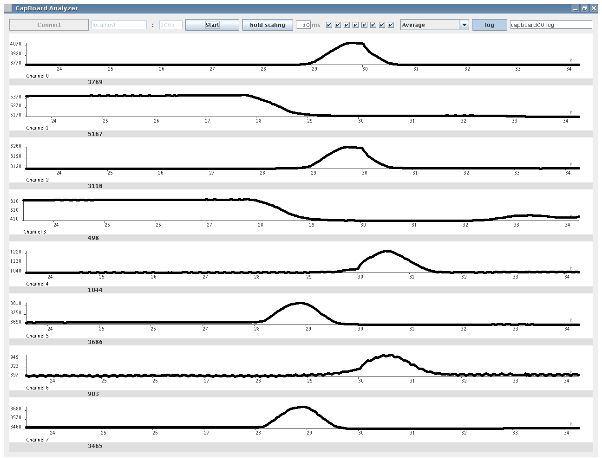

Figure 8. Even non-conductive objects can be tracked with CapSenseToolkit. The CapBoard Analyzer shows the effect of an empty glass bottle rolling over a table from the left to the right. The visualization shows the irritation of the sensors (y axis) over time (x axis). First sensors 1 and 3 (the leftmost) are triggered, the bottle then rolls over sensors 5 and 7, 0 and 2, 4 and 6, and finally drops off the table.

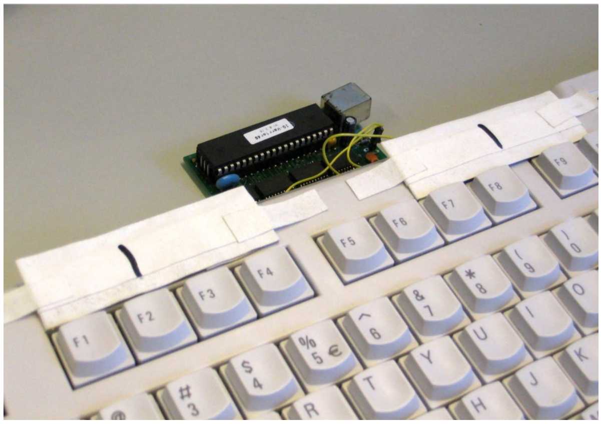

Figure 9. Augmenting a computer keyboard with two simple capacitive sensors can reduce keyboard-mouse-keyboard switches, and enables intuitive and precise scrolling

Another application we implemented (and use) is ’display switching’. Many computers have two displays attached to them. Switching between two windows on different displays either requires furious ’Alt-Tab’ing or repositioning the mouse. With CapKeyboard and ’focus follows mouse’ a simple wipe over the sensors moves the mouse pointer on either display, activating the window on it. Thus switching between keyboard and mouse can be reduced. This feature - while not really impressive - has shown it’s usefulness in everyday work.

5.1.3 CapShelf

The CapShelf is a regular kitchen shelf with three sensor plates connected to the CabBoard hardware. The kitchen shelf has one shelf plate in the middle of the shelf. On this plate one sensor plate is horizontally placed. At both sides, right and left of the middle plate, one vertical sensor plate is placed.

By this arrangement of sensor plates we can detect and track a human hand reaching for objects placed in the shelf, e.g. cleaning utilities. This allows to detect which thing has been taken or put back in the shelf, much like a RFID reader system would allow. Additionally, we can derive the position and duration of this activity to provide a richer set of data for this type of context.

5.1.4 Thracker

We previously built a prototype system that allows 2D gesture recognition based on capacitive sensing. The prototype is attached to a tablet PC with a 12.1" screen. Four sensor plates are arranged around the screen as shown in Fig. 10. They are connected to a predecessor of the CapBoard on the back of the tablet PC.

Basic input parameters supported by Thracker are absolute coordinates (like a touch screen) and relative movements (mouse-like) as well as simple gestures. Gestures can be single points moving over time or multiple points moving simultaneously (e.g. for bi-manual interaction). The capacitive sensing prototype uses input from 4 different sensors arranged around the screen.

Figure 10. The picture shows a prototype of a screen equipped with capacitive sensing technology. In this example the user navigates (scrolling/zooming) through an X-ray photograph by moving the hand and performing gestures in front of a screen.

Because Thracker measures the distance of the hand from each border, it offers additional degrees of freedom (DOFs) unique to this setup. We defined two modes which allow 3D interaction or 'Pick and Drop' interaction.

In 3D mode we can calculate the Z axis distance to the screen from the distances to two opposite plates and the distance between the plates themselves:

$$z = d_1 \arccos\left(\frac{w^2 + d_1^2 - d_2^2}{2wd_1}\right) \tag{1}$$

Whereas d_1 and d_2 are the distances between object and sensor plates and w is the distance between the two sensor plates.

This enables the user to interact in three dimensions with the screen. However, interpretation of Z axis data is not always clear. If the user wants to end an interaction session he or she will pull back th hand out of reach of the sensors. The sensors will interpret this first as a normal movement in Z axis before they can detect the user's intention of leaving the sensor area. If the Z axis data is used, e.g., for zoom control, this behavior will inadvertently change the displayed information. A workaround would be to introduce a small delay between gesture and display feedback. Gestures will only result in display changes if they stay within the sensor range long enough.

The Z axis data could also be used to simulate mouse clicks. This requires only two discrete positions. Movement farther away from the screen than three centimeters will be interpreted as pointer movement whereas movement within three centimeters of the screen will be interpreted as clicks.

The second mode which we called 'Pick and Drop' allows the user to intuitively interact with objects on the screen. The sensor plates of the Thracker device do not measure the distance to the center of the pointing hand but measure the distance to the nearest part of the hand. Thus Thracker can calculate the diameter of the pointing hand. A user can interact with the screen by spreading thumb and fingers.

This type of setup is interesting e.g. for medical scenarios where the doctor does not want to physically touch something as hygiene rules require that the doctor washes his hands every time he touches something before advancing to the next patient. Also for public installations this technology could replace expensive touch monitors with capacitive sensing. This significantly can reduce costs, especially when used in many places, e.g. ticket terminals.

6. Conclusion and Future Work

6.1 Conclusion

We introduced the CapSenseToolkit as out-of-the-box tool for prototyping human-computer interaction using capacitive sensing technology. We described the hard- and software components of the system and prototypically developed several applications using the CapSenseToolkit.

The hardware is easy to install and very cheap to build, even in low numbers. Everyday objects can easily be augmented with the sensing system introduced. The data that can be derived is useful for a wide range of applications, but still some advanced features are missing. This will be part of the future work as discussed below. The sample applications we built help the researcher to get an initial understanding of the data and can help to interpet the data for a full qualified context. The toolkit itself is a powerful prototyping tool for quickly developing context-aware applications.

6.2. Future Work

As we believe that there is an enormous potential for human-machine interaction and context-awareness using capacitive sensing, we will provide detailed guidelines and configuration information. This will allow researchers

as well as non-computer scientists to include capacitive sensing systems in their appliances. We will try to cover some of the most common arrangements of sensors e.g. for tables, shelfs and other furniture, giving information on how many plates in what position will be needed to reliably derive a certain activity or context. This will also comprise a visualization toolkit of which we already showed an early version in this papers.
We thereby hope to use the capacitive sensing as toolkit, much like e.g. the AR Toolkit for augmented reality applications. This we expect will have an impact on the easiness of using capacitive sensing in pervasive computing systems.

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