

# Finding Common Ground: A Survey of Capacitive Sensing in Human-Computer Interaction

Tobias Grosse-Puppendahl<sup>1</sup>, Christian Holz<sup>1</sup>, Gabe Cohn<sup>1</sup>, Raphael Wimmer<sup>2</sup>,  
Oskar Bechtold<sup>3</sup>, Steve Hodges<sup>1</sup>, Matthew S. Reynolds<sup>4</sup>, Joshua R. Smith<sup>4</sup>

<sup>1</sup>Microsoft Research, Cambridge, UK / Redmond, WA, USA; {tgp, cholz, gabe, shodges}@microsoft.com

<sup>2</sup>University of Regensburg, Regensburg, Germany; raphael.wimmer@ur.de

<sup>3</sup>Technische Universität Darmstadt, Darmstadt, Germany; oskar.bechtold@stud.tu-darmstadt.de

<sup>4</sup>University of Washington, Seattle, WA, USA; jrs@cs.washington.edu, matt.reynolds@ee.washington.edu

## ABSTRACT

For more than two decades, capacitive sensing has played a prominent role in human-computer interaction research. Capacitive sensing has become ubiquitous on mobile, wearable, and stationary devices—enabling fundamentally new interaction techniques on, above, and around them. The research community has also enabled human position estimation and whole-body gestural interaction in instrumented environments. However, the broad field of capacitive sensing research has become fragmented by different approaches and terminology used across the various domains. This paper strives to unify the field by advocating consistent terminology and proposing a new taxonomy to classify capacitive sensing approaches. Our extensive survey provides an analysis and review of past research and identifies challenges for future work. We aim to create a common understanding within the field of human-computer interaction, for researchers and practitioners alike, and to stimulate and facilitate future research in capacitive sensing.

## Author Keywords

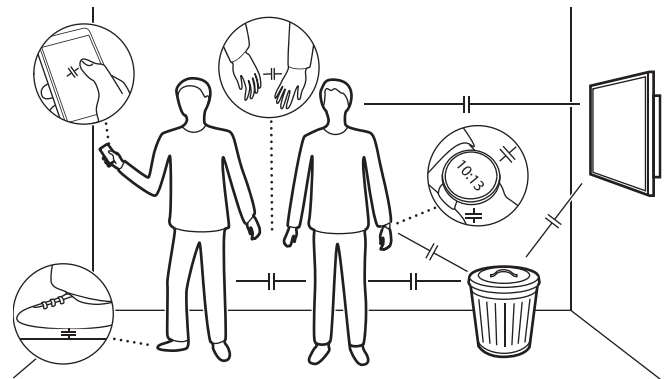
survey; capacitive sensing; electric field sensing

## ACM Classification Keywords

H.5.2. Information Interfaces and Presentation: User Interfaces - Graphical user interfaces; Input devices & strategies

## INTRODUCTION

Capacitive sensing has become so ubiquitous that it is hard to imagine the world without it. We are surrounded by capacitive sensors—from the touchscreens and touchpads on our phones, tablets, and laptops, to the capacitive “buttons” frequently used on consumer electronics devices and commercial equipment. In addition to widespread adoption in



**Figure 1.** Capacitance (+) naturally exists between people, their devices, and conductive objects in the environment. By measuring it, capacitive sensors can infer the position and proximity of users and other objects, supporting a range of different applications. However, this inherent capacitive coupling between objects also increases ambiguity of sensor readings and adds noise.

products, the use of capacitive sensing is common in human-computer interaction research, with examples ranging from grasp detection to the estimation of human positioning.

As shown in Figure 1, a plethora of natural capacitances exist between the people, devices and objects in the environment. It is important to realize that the capacitances shown in the figure are not capacitor components purchased from an electronics supplier. Instead, they represent the natural *capacitive coupling* between various objects. By measuring these ever-changing values it is possible to infer relative position, motion and more—supporting a multitude of interaction techniques and applications. The small size, low cost, and low power aspects of capacitive sensing make it an appealing technology for both products and research prototypes. Furthermore, its ability to support curved, flexible, and stretchable surfaces has enabled interaction designers to work with non-rigid objects and surfaces. The human-computer interaction community has developed numerous interaction modalities using capacitive sensing to operate devices from a distance, including gesture recognition and whole-body interaction.

With such a long history and so many different applications and instantiations of the technology, it is not surprising that the field has spawned research across many different domains, and with it a variety of different terminologies. For example, the terms *capacitive sensing* and *electric field sensing*

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from Permissions@acm.org.

CHI 2017, May 06 - 11, 2017, Denver, CO, USA

Copyright is held by the owner/author(s). Publication rights licensed to ACM.

ACM 978-1-4503-4655-9/17/05\$15.00

DOI: <http://dx.doi.org/10.1145/3025453.3025808>

refer to the same basic technique. In this paper, we will exclusively use the former. Similarly, various terms are used to describe the different types of capacitive sensing systems, such as self-capacitance and mutual-capacitance, both of which in conjunction with  $x/y$  grids are commonly referred to as projected-capacitive sensing. Other common terms include capacitive loading, shunt, and transmit modes; passive and active sensing; and static electric field sensing. This varied terminology can make it difficult to recognize the similarities and differences between established capacitive sensing systems, or to understand the contributions of new techniques.

In this paper we summarize and reflect on past work in the field with the aim of providing a resource for others working in the area of capacitive sensing. The contributions of this paper include: (1) a unified taxonomy to describe and classify capacitive sensing technologies, (2) a discussion of guidelines for reproducibility and challenges for future research, and (3) a thorough review and analysis of past work.

## BACKGROUND ON CAPACITIVE SENSING

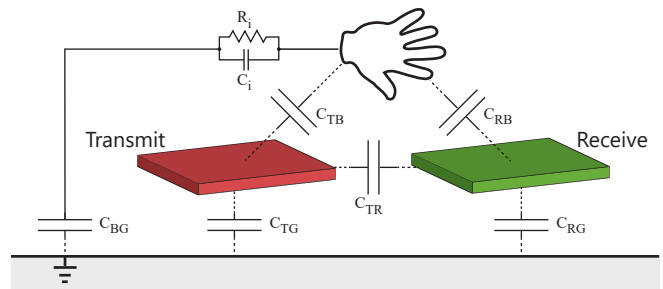
### History

While some animal species including electric fish and sharks have evolved organs capable of natural capacitive sensing [84], human exploitation only dates back about a century. In 1907, Cremer reported using a string electrometer—a sensitive current measuring device—to measure the physical motion of a beating frog heart [39]. The heart was placed between the plates of a capacitor, and as it moved with each beat a change in capacitance was observed. Later, in 1920, Léon Theremin demonstrated a gesture-controlled electronic musical instrument known as the *Theremin*, consisting of two capacitively tuned resonant circuits controlling pitch and volume [56]. While capacitive sensing grew to be an important tool for many engineering applications, such as sensing distance, acceleration, force, pressure, *etc.*, its use in HCI was limited at first. In 1973, engineers at CERN implemented a capacitive touch screen [11], and further work on touch surfaces grew rapidly in the 1980s and 1990s, including the introduction of the multi-touch capacitive tablet in 1985 [121]. In 1995, Zimmerman *et al.* [236] introduced new capacitive sensing approaches for HCI that went far beyond touch sensing on surfaces. With the widespread use of capacitive touch pads, displays, and other interactive devices on desktop, mobile, and wearable computers, the impact of capacitive sensing has exploded over the past 20 years.

### Physical Principles of Capacitive Sensing

Capacitive sensing can be used to estimate physical properties such as touch, proximity, or deformation by measuring the capacitance (*i.e.*, the ability to store charge in an electric field) between two or more conductors. These conductors, often called *electrodes*, are commonly solid metal parts, but they can also be made from other conductive materials including foils, transparent films (*e.g.*, indium tin oxide, ITO), plastics, rubbers, textiles, inks, and paints. In other cases, electrodes include the human body or objects in the environment.

Figure 2 depicts a *lumped circuit* model consisting of a transmit electrode, a receive electrode, part of a human body (to



**Figure 2. Lumped circuit model of capacitive sensing as introduced by Smith *et al.* [186]. Depending on the sensing mode, different capacitances are controlled or measured.**

be sensed), and a simplified view of the natural capacitances between them—each usually no more than several 100 pFs [64, 190]. Most capacitive sensing systems work by measuring changes in capacitive coupling between the human body and these transmit and receive electrodes. The role of *ground* is also important—it simply refers to a common potential to which all of the objects relevant to the system are electrically coupled. Without this common ground, capacitive sensing systems do not have a shared reference, which is critical to operation in many cases. Ground may refer to the electric potential of the floor, as depicted in Figure 1, or to the Earth itself. However, it is important to realize that in some cases, the ground potential is not the floor or the Earth, but simply a local common reference such as the human body itself, or the ground plane of a circuit board.

A capacitance exists whenever two electrodes are separated by some distance. When the conductors are at different electric potentials, an electric field exists between them. Capacitance  $C$  is the measure of the charge  $Q$  (*i.e.*, number of electrons) that a capacitor holds when a certain electric potential  $V$  is applied:  $C = Q/V$ . The SI unit of capacitance is the farad (F). Typical capacitances in HCI applications are on the order of picofarads (pF or  $10^{-12}$  F) and primarily depend on three properties: the size and shape of the electrodes [133], the distance between them, and the dielectric properties of any material which lies between them. Furthermore, when the electric potentials on the conductors are time-varying, a current known as the *displacement current* flows through the capacitor. We refer to related work for simple [225] and detailed [10] explanations of this general principle.

Capacitance is often measured by observing the displacement current that flows when the electrodes are driven by time-varying voltages with frequencies below 1 MHz [40]. However, some capacitive sensing approaches leverage higher frequencies, *e.g.*, by detuning an RFID antenna [108, 124], measuring phase differences of signals capacitively coupled to the human body [231], or measuring reflections caused by capacitive changes along a transmission line [81, 105, 222].

### Advantages and Limitations

Capacitive sensors can be used for a wide variety of applications because the electrodes—where the interaction occurs—can be physically decoupled from the location of the sensing circuitry. This enables extremely large (*e.g.*, room sized) or extremely small (*e.g.*, microscopic) electrodes which can be

fabricated from a variety of materials, including curved, flexible, and stretchable substrates. They can often be prototyped quickly using everyday materials, then subsequently mass-produced at low-cost. They typically have a minimal height profile and can be hidden under opaque, non-conductive materials, and can be arranged in large, high-resolution scanned arrays. Capacitive sensing is purely electrical, low power, and requires only cheap driving electronics with no moving parts or mechanical intermediaries [87]. A major advantage over other sensing modalities is the ability to sense a wide field of view at very close distances without a lens.

Although this “lens-less” property is a great advantage, it also serves as a limitation since capacitive sensors cannot “focus” their sensing on a specific area, which can reduce range [73, 190, 225] and introduce ambiguous readings [188, 66]. Additional limitations include electromagnetic noise [67, 38, 37] in the face of insufficient grounding, particularly on wearable devices [36]. Furthermore, touch interaction using capacitive sensing lacks inherent tactile feedback and can therefore result in inadvertent activation [87].

### A TAXONOMY FOR CAPACITIVE SENSING

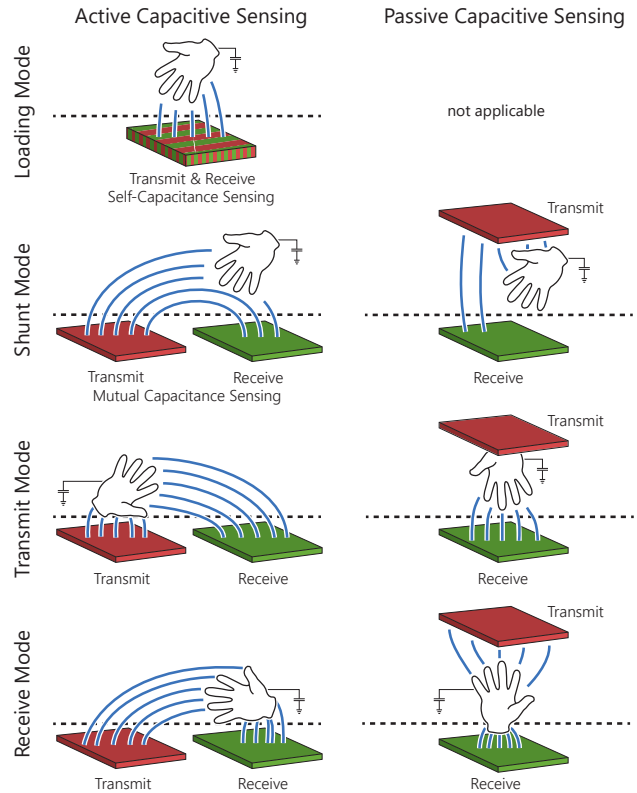
In the 1995 landmark paper, Zimmerman *et al.* proposed a taxonomy to describe types of capacitive sensing by introducing three *active* operating modes [236]. Over the following two decades, there has been a significant body of work in the field of capacitive sensing, including new methods of sensing that do not fit into the taxonomy originally outlined.

Having provided a background on capacitive sensing in the previous section, we now define consistent terminology and describe a new taxonomy which extends the classification proposed by Zimmerman *et al.* This new taxonomy defines a method for clearly grouping and classifying capacitive sensing approaches using two independent dimensions, as shown in Figure 3. Sensing techniques can be described as either *active* or *passive*. They can also be grouped into four different operating modes: *loading*, *shunt*, *transmit*, and *receive*.

#### Active vs. Passive Sensing

Zimmerman *et al.* conducted their initial research in the field of *active* capacitive sensing. In active capacitive sensing, a known signal is generated on the transmit electrode(s), capacitively coupled onto the body part, and then coupled into the receive electrode(s). The presence and movement of the body part can be sensed by measuring the strength of the signal coupled onto the receive electrode(s). Most of the past work in capacitive sensing has focused on active sensing, including capacitive touch buttons, touchpanels, and touchscreens.

In addition to active sensing, there is a growing body of work using *passive* capacitive sensing. While active sensing systems must *actively* generate an electric field, passive sensing systems rely on existing—external or ambient—electric fields which are *passively* sensed. The active vs. passive terminology is used analogously for other sensor types (*e.g.*, passive infrared sensors, which receive infrared energy radiated by warm objects). Passive capacitive sensing is sometimes referred to as ambient or opportunistic electric field sensing. Some examples of ambient electric field sources include



**Figure 3.** Capacitive sensing techniques can be divided into four operating modes: loading, shunt, transmit and receive. Except for loading mode, each mode may be implemented using active or passive sensing. The dashed line represents the boundary between the sensing system (bottom) and the environment (top).

power lines and appliances, and the low frequency electrostatic fields produced by the triboelectric effect when a user moves. Since the sensing system does not control the transmit signal, passive systems tend to be less precise and more susceptible to changes in their environment. Despite these limitations, passive capacitive sensing has shown promise in its ability to sense human activities with minimal power and infrastructure [36, 37, 38, 67, 156].

#### Operating Modes

The operating mode of a capacitive sensing system depends on the relative position between the human body and the transmit and receive electrodes, which in turn defines the relative magnitudes of the capacitances shown in Figure 2. This is independent of the system being either active or passive. In all cases an electric field is generated between the transmit electrode and ground, and a field is sensed between the receive electrode and ground. Although Figure 3 depicts only a single transmit and receive electrode, many capacitive sensing systems have multiple transmit and/or receive electrodes.

##### Loading Mode

Loading mode is the simplest and most common type of capacitive sensing. Here, the same electrode is used for both transmit and receive. The body capacitively loads the electrode and causes a displacement current to flow through the body to ground. As the body gets closer to the electrode, the

capacitive coupling ( $C_{TB}$ ) increases and so does the displacement current, which allows the system to sense the proximity of the body. Since the transmit and receive electrodes are the same, and are both part of the sensing system, there is no passive variant of loading mode. Due to its simplicity, loading mode is widely used for touch sensing, including capacitive buttons and touch panels. Commercial touch panels that use loading mode are often labeled as *self-capacitance* sensors. Electrodes are easy to shield [165, 213, 220], which makes for large detection ranges, *e.g.*, in 3D gesture recognition [63] or noise-resilient touchscreens [11].

#### Shunt Mode

In shunt mode, the transmit and receive electrodes are distinct, and thus there is some capacitive coupling between them ( $C_{TR}$ ). When the human body is in proximity to the electrodes, it will capacitively couple to both the transmit and receive electrodes with about the same order of magnitude as the coupling between the electrodes (*i.e.*,  $C_{TR} \approx C_{TB} \approx C_{RB}$ ). This will cause a displacement current to flow through the body to ground ( $i_{BG}$ ), and will thus reduce the displacement current flowing from the transmit to the receive electrode ( $i_{TR}$ ). By measuring the decrease in displacement current at the receive electrode, the body's proximity can be determined. In active capacitive sensing, shunt mode is often used for grid-based touch sensors [9] and interactive surfaces [161]. This is because all combinations of the grid electrodes can be exploited to yield high resolution sensing [73, 236]. As a result, shunt mode is often used for commercial touch panels, which are commonly labeled as *mutual-capacitance* sensors. In passive sensing, it is possible to detect when the human body shunts an electric field emitted by the infrastructure (*e.g.*, power lines and appliances). This enables indoor localization and gesture recognition [38, 156].

#### Transmit Mode

Transmit mode is similar to shunt mode, except that the body is very close to the transmitter. This proximity means that the coupling between the body and the transmitter is much greater than the coupling between the body and the receiver or between the transmitter and the receiver (*i.e.*,  $C_{TB} \gg C_{RB}$ ,  $C_{TB} \gg C_{TR}$ ). In this mode, the body essentially becomes an extension of the transmit electrode. When the body gets closer to the receive electrode, the displacement current into the receive electrode ( $i_{RB}$ ) increases. In active capacitive sensing, transmit mode allows for a human-mediated detection of an electric field, *e.g.*, to identify the floor tiles being occupied with remote sensors on the ceiling [207]. In passive capacitive sensing, transmit mode corresponds to the class of off-body sensors, *e.g.*, detecting a change in body potential when a person takes a step using remote sensors [4, 197].

#### Receive Mode

Receive mode is the inverse of transmit mode—the body is very closely coupled to the receive rather than the transmit electrode (*i.e.*,  $C_{RB} \gg C_{TB}$ ,  $C_{RB} \gg C_{TR}$ ). In this case, the body acts as an extension of the receive electrode and can pick up nearby electric fields, using the same operating principle as transmit mode. In active capacitive sensing, receive mode is mostly used when multiple transmit electrodes emit

different fields [40]. In passive sensing, on-body sensors use receive mode, to enable gesture recognition [37], touch sensing [38, 58], and object identification [117].

#### Transmit + Receive Mode (Intrabody Coupling)

A combination of transmit and receive mode occurs when the body has similar coupling to both the transmit and receive electrodes, yet the direct coupling between the electrodes is much less (*i.e.*,  $C_{TB} \approx C_{RB} \gg C_{TR}$ ). In this case, the human body acts as a conductor between both electrodes [49], and since this hybrid-mode is common, we refer to it as *intrabody coupling*. Past work used many terms to describe this hybrid-mode, including active intrabody communication, body channel communication [235, 7], passive bioelectrical measurements [157], and active bioimpedance sensing [97].

## RESEARCH CHALLENGES

Having provided a common context for work in the domain of capacitive sensing via the taxonomy in the previous section, we now describe a number of ongoing research challenges. We first discuss challenges that generally relate to methodology and then move on to specific topics.

### Towards Better Reproducibility

Throughout our literature review, we regularly observed that reconstructing a particular sensing approach would prove difficult due to missing details (*e.g.*, the number of sensors or the type of grounding). Only 68 of the surveyed papers report sensing range ( $27\times$  touch,  $29\times <50$  cm,  $12\times 100 - 300$  cm). The employed metrics vary widely. Of course, the necessary level of detail depends on the type of contribution—fewer details are needed for new applications of well-known capacitive sensing principles, but new approaches to capacitive sensing demand more detailed descriptions.

To enable reproducibility, we suggest that papers describing *applications* of capacitive sensing include: (1) whether active or passive sensing is used, (2) the operating mode, (3) the number of transmit and receive electrodes, as well as their material and shape, and (4) the hardware and software being used to conduct the measurement (*e.g.*, Arduino using CapLib). We suggest that *new approaches* in capacitive sensing additionally include: (5) how the sensor, the human body, and related objects in the environment are grounded, (6) a detailed description of hardware, including a schematic, (7) the sensor operating frequency, (8) the sample or scan rate, sample bit-depth, and any other relevant details that will enable others to understand the physical setup. If proximity is being measured, we suggest that the reported *range* corresponds to the state in which the detection accuracy for a human body part is expected to be greater than 95% (derived from [102]).

### Sensitivity to Grounding

As mentioned earlier, the grounding of the sensor(s) and user(s) is a critical aspect of capacitive sensor behavior. This is especially important in battery-powered applications, which often rely on a very weakly coupled ground reference, *e.g.*, to measure external electric fields [36, 37, 38, 68, 235]. When battery-powered devices are connected to grounded measurement equipment or long test leads, the performance

is artificially improved by the enhanced ground coupling, as a small grounded sensor tends to work better than a large ungrounded sensor [6]. Some wearable prototypes in the literature make use of external ground connections while prototyping, but would not work as standalone wearables.

To realize applications that suffer from insufficient grounding, two options exist. One is to enlarge the size of the ground plane [68, 235], but that can be a problem for some wearable applications. The other option is using a sensor with very high input impedance to detect small displacement currents [50, 79]. We refer the reader to additional literature on the various aspects of grounding [68, 100, 176, 202].

### Implications for Real-World Deployments

Today's widely available machine learning models have enabled researchers to make inferences on potentially high-dimensional capacitive sensor data relatively easily. However, much of this research—particularly N-fold cross-validation applied to data collected in relatively static laboratory settings—has treated these learning models as a black box. It is often hard to judge whether these classifiers would generalize effectively in a more realistic setting than in the specific experimental conditions reported. The concern is that these models are fragile, and therefore will likely break if any environmental changes occur [179]. Unfortunately, such changes are inherent in capacitive sensing through varying ground-coupling [119], changing user behavior over time [180], or environmental noise [38, 37, 225]. Although real-world deployments are very challenging, especially in terms of collecting ground-truth data, they are essential to demonstrate feasibility beyond a controlled lab setting.

As a complement to machine learning, we see a challenge of future research in models that are motivated by the underlying physics of capacitive sensing, the physical structure of the human body, and the sensing environment. For example, spatial models [66, 67, 168] help recognize the underdetermination of a problem [168], and produce inferences that are less dependent on users [198, 138] and environments. Using these models, a spatial representation of the surroundings can be obtained much like a 3D camera [53, 186]. This area of research is often called free space electric field tomography and was extensively researched in the 1990s [190, 186, 188]. Since then, little work has followed on developing spatial models that leverage electric field imaging [66]. A renewed effort around physically-motivated spatial models could enable capacitive sensing to truly 'see' the world, as such models provide an intermediary layer between raw sensor readings and machine learning by reconstructing human body parts in full 3D to provide an even richer context.

### Support for End-to-End Prototyping

Over the last several years, researchers have made capacitive sensing—particularly electrode design—more accessible by developing systems that support rapid prototyping and evaluation. A study by Unander *et al.* showed good performance using electrodes printed with both silver- and carbon-based ink [203]. New silver nanoparticle [105] and microparticle [170] ink technologies now allow electrode shapes and

configurations to be prototyped rapidly. We are also beginning to see the emergence of stretchable electrodes [217], which is ideal for wearable applications. Software systems, such as Midas [175] support the integration of electrode patterns with sensing electronics. Several works incorporate electrodes into 3D printed structures, enabling fast prototyping [20, 149, 177] and easy personalization [61].

While the integration of electrodes is much easier now than a few years ago, compact integrated end-to-end capacitive systems remain difficult to prototype. For example, CupidMZ [27] and NailO [103] required custom PCB circuitry to achieve wearable form factors. Other researchers have applied off-the-shelf electronic hardware for wearable systems (particularly Arduino [126, 208]), but this comes at the expense of form factor. In the future, we envision electronics prototyping tools (*e.g.*, CircuitStickers [91]) to support the integration of capacitive sensing electronics and electrodes into 2D and 3D printed structures. This would enable better miniaturization and robustness, and thus facilitate real-world deployments and longitudinal studies in realistic settings.

### Reducing Form Factor & Instrumentation

Due to the emergence of wearable interactive devices, such as augmented tattoos [98] and finger rings [215], the physical size of batteries is becoming a limiting factor for many capacitive systems [103]. To move beyond batteries as the determining factor for device size, researchers have been optimizing power consumption, for example by using low-power passive sensors for motion [36] and touch [45, 58]. However, for many applications, passive sensing does not offer sufficient fidelity in the sensor readings. Hence, the opportunity to combine active and passive sensing systems exists, in which the passive sensor runs in a low-power state and enables the higher-power active sensor only when it detects a signal of interest [36]. Gong *et al.* used a similar approach to implement power-efficient indoor localization [57]. Exploring sensible combinations of both sensing types can enhance battery life, enable harvested energy sources, extend perceptive capabilities, and allow for smaller form factors in the future.

Besides reducing the form factor of the electronics, it is often hard to achieve the same with electrodes. For example, in many capacitive indoor localization systems, a significant amount of instrumentation is needed underneath the floor [15, 194, 205]. Reusing parts of the environmental infrastructure for active sensing seems promising. For example, by injecting a signal into the power line of a house [148, 195], it can act as a transmit electrode for an indoor localization system. Other unused conductive structures include door knobs [173] or even floating water [41].

### Enabling Flexible and Stretchable Applications

The ability to use capacitive sensors on non-rigid substrates has enabled touch sensing in a number of new application domains, including wearables. Flexible and stretchable interfaces enable new types of interaction [60, 77] and support ubiquitous deployments, *e.g.*, in fabric and clothing [8, 30, 152, 185] or directly on the human body [98, 103, 217].

An inherent challenge arises when flexible interfaces are worn in close proximity to the body, as human motion causes substantial capacitance changes between the electrodes and the body [76, 152]. To prevent false activation, it becomes necessary to sense the deformation or motion of the electrode to compensate for artifacts in the signal. This can be achieved by using multiple types of capacitive sensing [58], biphasic electrode configurations [191], or other sensor types (*e.g.*, resistive pressure and bend sensors [58, 164]). While the use of electro-optic crystals is largely unexplored in HCI, their sensitivity to electric field changes appears promising, especially on or around the human body [50, 183].

Another significant challenge is the fabrication of conductive materials that are durable while still remaining flexible and stretchable. Recent advances in material science and chemical engineering have resulted in conductive polymers for the creation of flexible and stretchable electronics [128], conductive yarns [152], foils [137], liquid metals [44, 128, 125], and non-rigid micro and nano-structures [83, 193]. These new materials are well suited for interfacing with the organic and dynamic contours of the human body. As such techniques become more available, the HCI community should leverage them for creating novel applications in on-body capacitive sensing using flexible and stretchable electrodes.

### Unifying Approaches to Interpret Electric Fields

Within buildings, power lines and appliances emit an almost omnipresent ambient electric field [37, 38, 156]. Similarly, electric fields generated by mobile devices, such as smartphones [99] and household electronics [117] have been leveraged in passive capacitive sensing systems. An extension of this approach can be used to detect touches and gestures around uninstrumented appliances by leveraging unique properties of their operation, *e.g.*, through compact fluorescent lamps [72] or liquid crystal displays [28].

Electric fields are also produced due to human motion—the result of static charging, explained by the triboelectric effect [23], and by very low frequency changes in the capacitive coupling between the body and the environment during motion [36, 47, 67, 116, 197]. Furthermore, extremely weak electric fields are produced by the human body itself, including those generated by the human heart and other muscles. Although challenging to detect, heart activity has been sensed capacitively at distances of 40–100 cm [79, 157].

The electric field in our environment results from a superposition of fields produced by all the sources listed above and more. To date, most research has drawn from just one of these for specific applications [37, 38, 67, 117, 157, 156]. A challenge arises when analyzing multiple electric field sources with the same technical system. Ultimately, we envision miniaturized devices that detect indoor locations, user identities, user actions, and physiological signals — all at the same time. We also expect future wearables to distinguish between indoor and outdoor activities and to reliably count footsteps.

### Enriching Sensing with Communications

In the early 2000s, Rekimoto *et al.* introduced combining sensing *and* communications using touch-sensitive surfaces,

clothing, and wearable devices [159, 161]. More recent work has used wearables to communicate with touchscreens for token-based [214, 215] and biometric [97] authentication. However, the data rate of these approaches is limited by the slow update rates of commercial touchscreen controllers.

While through-body transmissions between surfaces and devices been demonstrated using other modalities [160, 219], enabling them using capacitive sensing requires rethinking mobile devices as a medium for both sensing touches and emitting signals for *two-way* communication. A recent project prototyped this by switching the touchscreen scanning on and off, achieving up to 50 bits per second [85]. If touchscreens were to be intentionally designed for the purpose of communication, much higher data rates could result.

On larger interactive surfaces, messages could be encoded and decoded locally in certain areas to exploit spatial correspondences in interaction design [161]. Applications range from transferring data from displays to smartwatches or using sensor-augmented tangible objects in proximity to touchscreens for gaming applications. Even when a screen is off, embedded electrodes can act as a hub for intrabody communications of data to other users [235] or touched devices [146].

## LITERATURE REVIEW

In this section, we describe the literature review which informed our taxonomy and discussion of outstanding research challenges. In the review we focus on novel research on capacitive sensing techniques and applications in human-computer interaction. Thus, we exclude technologies that measure the intrinsic properties of a material (*e.g.*, capacitive pressure sensors), as well as uses of commercial sensing systems, such as common touch screens.

In our experience, most HCI-related capacitive-sensing research is indexed by ACM and IEEE digital libraries. Therefore, we conducted an initial full-text search in these databases in June 2016. To avoid overlooking relevant publications, we searched for occurrences of *electric field* or *capacitive* together with search terms indicating human-computer interaction (activity, gesture, interaction, movement, touch). This search resulted in over 5,900 papers, which we loaded into a custom-developed paper management system. In the next stage, each paper was examined by at least one reviewer. Most papers were dismissed as off-topic as they did not fit the aforementioned criteria. By scanning the referenced literature of the papers matching our criteria, we added another 26 papers. The resulting 255 papers were then reviewed by at least two authors and tagged in various dimensions to allow us to identify trends among all papers.

Overall, our literature review comprises the 193 papers that we identified through our filtering process. Tagging all papers has allowed us to identify trends across this large body of work. Unsurprisingly, the majority of papers (125/193) present novel applications of capacitive sensing, while 100 papers include a hardware contribution. About one quarter of all papers present a quantitative study (54) or an algorithm contribution (45). About 32 papers include a model of the electrical properties, while 12 present simulation results. In-

terestingly, 22 papers present toolkits for capacitive sensing, but only 3 of them are open-source [64, 175, 225].

As we noted before, a multitude of terms has been applied to different types of capacitive sensing; however, the existing HCI literature shows significantly less variance. While many surveyed papers do not explicitly mention the sensing principle used, 75 papers use the generic term “capacitive sensing,” while 11 of them use the term “electric field sensing.” Besides these terms, a long but thin tail of alternative terms exist, such as “skin potential level,” “projected capacitance,” “electrostatic induction,” and “human body electric potential.”

Earlier in the paper, we presented a taxonomy for describing and classifying the different types of capacitive sensing. We have grouped much of the past literature using our taxonomy and distinguishing by application domain to present an overview of the research space, organized as in Table 1. As shown in the table and detailed throughout this section, capacitive sensing has been used to enable a wide variety of HCI applications using a variety of sensing techniques.

## Sensing Goal

### Touch Sensing

The most ubiquitous form of capacitive sensing is the touch-sensitive surface and the touchscreen [9], which emerged from early prototypes in the 1970s [11]. Through the 1980s, the HCI community made significant advancements by developing custom hardware to enable multi-touch screens [121]. Later projects, including SmartSkin [161] and Diamond-Touch [40] have highlighted the interaction potential of this emerging technology. More information on the large space of capacitive touch sensing can be found in surveys by Buxton [21], Barrett and Omote [9], and Schoening *et al.* [178]. Due to the broad availability of commercial touchscreen devices today, HCI research on fundamentally new touchscreen hardware is rare. Some exceptions exist, such as interactions based on a combination of capacitive sensing techniques in a novel device (*e.g.*, Pretouch [86] on a Fogale display) or new low-latency touch screens [122].

Touch sensing on surfaces other than displays has been investigated to create more expressive computing devices and peripherals, including mice [210], keyboards [13, 45], tablet PCs [88], pens [192], and tangibles [52, 68, 118]. Sensors distributed around the screen can help to avoid visual occlusion [139] or to enable interaction on near-eye displays [130].

As high-resolution touch input has become ubiquitous for desktop and mobile computing, lower resolution capacitive touch solutions have also been widely used in wearable technologies. Some wearable applications include touch surfaces on belts [43], finger rings [26, 218], devices worn near the ear [126], on fingernails [103], or even implanted underneath skin [96]. Following the emergence of flexible conductive materials, such as conductive paint and yarn, wearable interfaces have made hair extensions touch-sensitive [208] and enabled touch sensing on clothing [76, 92, 152]. Sensing touch input directly on the human body has recently been explored through augmenting skin with tattoos [98, 217].

Loading mode	
Augmenting clothes & fabric	[8, 43, 76, 152, 158, 159, 185]
Augmenting the human body	[75, 98, 103, 126, 208, 218, 232]
Gesture recognition	[1, 2, 16, 46, 64, 63, 120, 103, 126, 152, 185, 209, 224, 226]
Grip & grasp recognition	[25, 33, 32, 41, 86, 87, 138, 139, 162, 107, 112, 129, 168, 223]
Indoor localization & whole-body movements	[3, 15, 42, 69, 75, 112, 194, 220]
Prototyping user interfaces	[20, 91, 108, 120, 105, 140, 149, 175, 184, 177, 201, 203]
Ubiquitous touch interfaces	[12, 18, 16, 64, 127, 112, 126, 153, 173, 208, 226]
Shape sensing	[40, 95]
Shunt mode	
Augmenting clothes and fabric [92, 172, 159, 169]	Gesture recognition [37, 38, 136]
Augmenting the human body [30, 96, 217, 234]	Indoor localization [156, 37, 57, 38, 136]
Touch and gesture recognition [66, 93, 119, 120, 122, 189, 190, 187]	
Grip & grasp recognition [78, 131, 210, 229]	
Prototyping user interfaces [57, 58, 64, 142]	
Whole-body motions [54, 55, 162, 183, 194]	
Transmit mode	
Indoor localization [111, 205, 204]	Indoor localization [67, 136]
Whole-body movements [207]	Step detection [67, 116, 115, 155, 197, 233]
User distinction [150]	User identification [67]
	Input controller [45]
	Prototyping user interfaces [58]
Transmit + receive mode (intrabody coupling)	
Activity/physiological sensing [31, 216]	Identifying objects & users [85, 97, 117]
Intrabody communication (HCI) [68, 85, 97, 132, 146, 196, 235]	Step detection [163]
Indoor localization [57]	Whole-body movements [36, 109]
User identification and biometrics [95, 97, 215, 132, 214]	
Receive mode	
Touch and gesture recognition [40]	Gestures [36, 37, 109]
User distinction [40]	Identifying touched objects [117]
	Indoor localization [37, 38, 57]
	Whole-body movements [36]
Active Capacitive Sensing	
Passive Capacitive Sensing	

Not applicable

**Table 1. Past work on capacitive sensing grouped using our taxonomy. Most works apply active loading mode, whereas we found few papers that use active receive mode.**

Capacitive sensing has also been used to detect user interaction with the environment. Active sensing approaches instrument objects in the environment to sense user input, including plants [153] and household objects, such as door knobs [173]. Other work has passively sensed electric fields that are generated by the power lines and appliances in the environment, and monitored changes to observe touch events on instrumented objects [45, 58], walls [38], or appliances [117].

### User Grip & Grasp

Beyond sensing mere touch locations, capacitive sensors yield a rich enough signal to determine the shape of grasps on instrumented objects and devices [221]. Since capacitive sensors can adapt to arbitrary surfaces, researchers have sensing for grasp detection on mice for gesture input to desktop computers [87, 210] and interactive balls [78, 199].

In recent years, research has focused on mobile devices that detect the user’s grasp to support interaction [32, 33, 107, 198, 223]. To distinguish between commonly-used grasps, a relatively large number of sensors is often needed. Either high-resolution active shunt mode grids [88, 131, 192, 199, 210, 229] or a multitude of loading mode sensors [33, 107] de-

liver enough information to determine grasp. Some specific applications have used fewer sensors, for example to adapt the screen rotation depending on the user's grip [32], to start an application [118], or to sense a small number of different grasps through only a few sensors [223]. While the sensor data is often fed into a machine-learning classifier to estimate the grasp, specialized spatial sensors deliver the actual shape of grasps from estimated finger and hand proximities [86].

#### *Sensing Tangibles on the Touchscreen Surface*

Recognizing tangible objects on the surface of touchscreens has been shown to enrich the interactive experience by providing physicality [24]. These tangible interfaces are often realized by adding passive components to the bottom of the tangible. Fake touch points that spread across the bottom surface of the object allow the touchscreen to detect the object's position, orientation and identity much like a 2D barcode [24, 101, 113, 161]. However, this approach only works while a user is touching an object and thus a capacitance to ground is present through the body. Voelker *et al.* demonstrated a modified approach that bridges multiple touch points to enable ungrounded detection of tangibles [211, 212].

To communicate dynamic information between devices, touch events have been triggered on the screen using nearby voltage sources, *e.g.*, to perform biometric [97] or token-based [215] authentication. While the former sends a signal through the user's body, the latter is part of the class of direct capacitive communication. Similarly, Yu *et al.* uses active tags to encode information with high-voltage signals, which touchscreens receive when tags are placed on the surface [230]. Today's commercial styli are similar in their implementation, such as the Atmel maxStylus [5] or the Microsoft Surface Pen [135]—both use the capacitive sensor of the touch device for detecting and distinguishing touch from pen input. These devices are effectively grounded through the user when touched, and they transmit a signal through an electrode that couples to the screen.

#### *3D Gesture Sensing*

Capacitive sensing can be extended beyond surface interactions to enable proximity-based recognition of objects, which has been explored for 3D gesture interaction since the mid-1990s [236]. Early gesture recognition systems include the the compact Field Mice [187] and Lazy Fish [190] platforms, which evolved into the modular School-Of-Fish [188] platform. The latter detects gestures at distances up to 1 m [190]. This early work focused on gestural interactions for manipulating 3D objects [187], new forms of musical expression [144], and enabling tangible interactions [190].

More recent work has investigated generic proximity-sensing surfaces that sense 3D input to control computers [1, 2, 14, 16, 48, 66, 78, 120] and home automation systems [62]. More specialized deployments recognize proximity-based gestures in cars [17, 46] or on clothing [185]. Proximity-sensing surfaces deployed on or near displays [86, 119, 167, 168, 190] enable smartphones to show context-dependent menus before the touch contact [86], launch apps based on grasp [25], or detect 3D gestures above the surface [119]. Systems that op-

erate near displays are particularly challenging due to noise and nearby-conductive structures [224].

#### *Indoor Localization*

Active sensing approaches for indoor localization commonly involve embedding large loading mode electrodes underneath floor tiles to determine on which tile the user is standing [15, 57, 194]. Alternatively, the entire floor can act as a single transmit electrode using transmit mode. In such a constellation, the signal from several receive electrodes around the environment has been shown to determine the user's location [206, 207]. To reduce the required instrumentation, signals can be injecting directly into existing powerlines in place of dedicated transmit electrodes [19].

Similarly, some passive sensing systems leverage the ambient electric fields generated by the power lines and appliances to estimate the user's location [38, 57, 136, 156]. As these systems rely on ambient fields, they require prior training and are sensitive to changes in the environment. By detecting changes in the characteristic body electric potential during walking motions [47], passive capacitive sensors can detect indoor locations [67, 136], recognize gait patterns [36, 115, 116, 197, 233], or identify users [67].

#### *Posture & Whole-Body Tracking*

Capacitive systems that infer a user's pose often operate on the same principles as the indoor localization systems mentioned above. In an instrumented space, researchers have implemented body-pose tracking using active transmit mode [204, 207] and loading mode [220] sensing. Dance and athletics have been captured by transmitting signals among multiple sensor nodes [6]. Wearable systems usually offer a more specialized way of determining postures or motion. Using signal fingerprinting, ambient electric fields generated from the power lines have been used to passively recognize postures [38] and whole-body movements [37]. Passively perceiving changes in body electric potential through movement has been used to recognize steps [36, 67, 155, 163] and arm movements [36, 155]. By observing changes in body impedance, researchers have detected different poses [85].

#### *User Identification and Biometric Sensing*

Beyond detecting locations, it is often desirable to identify which user caused a touch. Systems have thus reused touch as a channel to transmit the identity of a wrist token to the touch device for authentication and personalization [132, 159].

Other systems *distinguish* simultaneous users without the need of a wearable token. Grosse-Puppendahl *et al.*'s ceiling sensors reconstruct users' electric potentials and distinguishes them from the characteristic changes while walking [67]. DiamondTouch configures the seats around the table as receive electrodes and determines the user that caused a touch through a receiver in each seat that observes the table's signal upon touch [40]. Similarly, measuring the user's impedance to ground upon touch has been shown to enable distinguishing two simultaneous users [80]. The same approach can determine if two wearable devices are on the same body through intrabody communication [149].



To *identify* and authenticate users from a touch using the user's fingerprint, a capacitive sensor requires an extremely high density sensor array [182]. Such capacitive fingerprint scanners are typically dedicated components using swipe and area sensors for authentication on and across [94] devices. Although in wide use, such scanners cannot currently be made from transparent materials for integration into a screen. To prototype interactions with touch devices that identify each user upon touch, Holz and Knaust demonstrated a wristband that measures biometric features and transmits them to the touchscreen using intrabody communication [97].

### Physiological Sensing

In addition to sensing biometrics for user identification and authentication on touchscreens, capacitive sensors have been used to create wearable devices that sense physiological signals during wear. Capacitive sensors have been embedded into clothing for detecting breathing [31], swallowing [30], and drinking [31]. Passive sensors can detect gait patterns including limping [36, 67, 115, 116]. Capacitive sensors have also been used to detect arm [232] and facial [158] muscle activity as an alternative to electromyography. These systems work by sensing changes in the proximity of the skin to a wearable during muscle flexion. Capacitive textile arrays have also been embedded into clothing to sense gestures and movement detection in patients with limited mobility [185] and other health-related applications [200].

### Instrumenting Everyday Objects

**Clothing.** The integration of capacitive touch sensors into clothing was first explored in 1998 [143]. Researchers have since used this approach to implement health applications [8, 30, 185] and ubiquitous touch interfaces [43, 76, 92, 143, 152]. Sensors have thereby been placed on pants [172, 185], belts [43, 196], shoes [145], gloves [104, 209], and jackets [152]. However, manufacturing techniques and long-term deployments (*i.e.*, surviving wash cycles) remain open research areas for such systems [152].

**Furniture.** Due to its simplicity and ease of shielding [69, 226], active loading mode is dominantly used for posture and touch recognition on furniture. Researchers have thereby augmented couches [69, 110], bath tubs [89], beds [42], chairs [112, 236], lamps [72], and tables [16, 90, 226] with capacitive sensing. Less conventional applications include fabric-based sensors inside bed sheets to enable low-power communication with wearable devices [68] or to recognize sleep postures [169].

**Rooms.** Room-size deployments of capacitive systems are often used for indoor localization, but have also been used for interactive art installations [18, 151] and gait recognition [115, 116]. To ease with the deployment of large form factors, electrodes can be printed on flexible rolls [57].

**Cars.** Detecting the presence of adult passengers to ensure the safe deployment of airbags is a common application of capacitive sensing [54, 55, 202]. Other applications have focused on user distinction [150] and gesture recognition using sensors in the steering wheel [46, 166] and armrests [17].

**Musical Instruments.** The thin profile of capacitive electrodes allows them to be unobtrusively integrated with existing musical instruments. Paradiso *et al.* first explored this with a cello bow and an augmented baton [144], and subsequent work has been applied to guitars [59, 70] and pianos [134].

### Sensor Design and Fabrication

Electrode design is a fundamental aspect of prototyping capacitive sensing applications. Besides traditional materials, such as copper or other metal plates, a growing variety of electrode designs have been made from conductive inks and paints as shown in Table 2. Through the use of inkjet printing, electrodes on both, flexible and cuttable substrates can be prototyped [57, 58, 105, 108, 141, 142]. As an alternative to inkjet printing, vinyl cutters can create customized adhesive electrodes [175] or cut a substrate for composite electrode materials, *e.g.*, conductive tattoos [98]. To build larger sensing systems, conductive paint can be used to apply electrodes on wall surfaces [18, 174]. To bridge the resulting gap between electrodes and electronics, CircuitStickers use pre-fabricated adhesive electronic components [91].

With the emergence of 3D printing, researchers have started to explore prototyping objects with integrated capacitive electrodes. For example, capacitive sensing can be enabled on printed objects by filling tubes inside the objects with conductive inks [174], interrupting the print process to integrate electronics [181] or combining conductive and non-conductive print materials [20, 123, 177]. Conductive yarns and fabrics open new possibilities for flexible electrode design, *e.g.*, the integration into clothing [8, 30, 92, 152, 185]. Conductive paint has also been applied to retrofit existing clothing with sensing capabilities [76, 200]. The durability of textile-based electrodes remains a challenge (*e.g.*, to support multiple washing cycles) [152].

### Sensing electronics

The choice of electronics depends primarily on the operating mode as shown in Table 3. Hardware for the shunt, transmit, and receive modes is similar and usually consists of an oscillator connected to the transmit electrode to generate an electric field, and an amplifier and analog-to-digital converter (ADC) connected to the receive electrode. In loading mode,

<b>Copper</b> - highly conductive, flexible	<b>Silver</b> - non-corrosive, flexible
→Wire [15, 45, 161, 169, 197]	→Ink [76, 87, 105, 108, 203]+
→Foil [32, 117, 146, 171, 78, 236]+	→Thread/Yarn [185]
→Vinyl [175]	→Plate [67]
→Plate [64, 66, 120, 226, 224]+	<b>Carbon</b> - enabling electrical conductivity
→PCB	→Ink [203]
→Rigid [16, 35, 40, 158, 229]+	→Carbon-filled PDMS (cPDMS) [217]
→Flex [25, 107, 138, 192, 210]+	→Filament [20, 123, 177]
→Tape [42, 64, 132, 162]	<b>ITO</b> - transparent electrodes [64, 119, 199]
→Ink [59, 57, 58]	<b>Anisotropic materials</b> - directing e-fields
→Paint [18]	→Anisotropic 'Zebra' tape [91]
→Metalization [208]	→Anisotropic 'Zebra' rubber [24]
<b>Gold</b> - non-corrosive, skin-friendly	<b>Other materials</b>
→Gold leaf [98]	→Water [41, 173] & Plants [153]
→Gold coating [11]	→Ionized gas [72]
<b>Aluminum</b> - flexible, high availability	→Metal objects [43, 68, 173, 207, 226]+
→Foil [70, 147, 196, 202]	→Electro-optic crystal [50, 183]
→Mylar [190]	→PEDOT:PSS [64, 142]

**Table 2. Materials used for capacitive electrodes: Copper and silver are the most prominent materials for realizing capacitive electrodes.**

Shunt / Transmit / Receive Mode	Loading Mode
<b>3D gesture controllers:</b>	<b>Touch and proximity sensors:</b>
→MGC3130 [119]	→555 timer [19, 225, 64, 224]
<b>Electric-field receiving amplifiers:</b>	→AD7142 [92]
→MCP6041 [36]	→AD7147 [138, 73]
→OPA2322 [68]	→Arduino + CapTouch [201, 105, 175, 208]+
→OPA2350 [64]	→AT42QT1070 [118]
<b>Electric-field sensors:</b>	→CY8C2x [27, 59]
→Plessey PS25451 [67]	→Microcontroller [12, 29, 162]
<b>Capacitance-to-digital converters:</b>	→MPR121 [33, 43, 91, 139, 177]+
→AD7746 [96, 206]	→QT110x [92, 13, 175]
→AD7747 [76]	<b>Touch matrix sensors:</b>
<b>Touch matrix sensors:</b>	→MTCH6102 [103, 152]
→QT60248 [198, 199]	<b>Shield driver:</b>
→CY8CTMA463 [88, 229]	→TMS4281 [64]
<b>Development kits:</b>	<b>Development kits:</b>
→Fogale display [86]	→SK7-ExtCS1 sensor pack [168, 167]
→RTL2832U SDR [85, 117]	→Fogale display [86]
	→Touché [80, 153, 173]

**Table 3. Electronics hardware used in capacitive sensing literature.**

MCU-based implementations (*e.g.*, Arduino CapLib) and 555 timers are commonly used. As shown in Table 3, specialized commercial hardware is also available specifically for capacitive sensing, with the MPR121 touch sensor being the most popular device. While most of the work mentioned above uses a single operating frequency, other recent work (*e.g.*, Touché [173]) has used a multiple frequency approach [154]. In some scenarios, the use of multiple frequencies can provide additional sensing information, though the effect on the signal is often similar across the frequencies being sensed [22, 100], and thus there is often little information gain.

## Signal Modeling and Processing

### Modeling & Physical Understanding

The first step to understanding a sensing problem is typically to develop a representative physical model. Researchers have traditionally used equivalent or lumped circuit models, such as the one shown in Figure 2 [190, 235, 236]. Particularly for loading mode, simple plate-capacitor models are dominantly used to model the distance between the body and the electrodes [30, 158, 168, 225]. In transmit mode, equivalent circuit models describe the coupling between the transmit and receive electrodes and the body [40, 67, 205]. Equivalent circuit models exist for shunt mode [55], which often use point charge estimations [66, 187] to model distance relationships. To compensate for physical inaccuracies, experimentally determined correction factors [66, 67, 187] or customized fit functions [156, 206] are applied.

When a field is measured passively, it is important to understand the electric field source. For example, a human body accumulates charge via the triboelectric effect [23], and thus varying electric fields are produced when the capacitive coupling between the user and environment changes, *e.g.*, through steps or other movements [36, 47, 67, 115, 116, 197].

Extensive research has been conducted in modeling the electric properties of the human body—most fundamentally gaining an understanding of the impedance of different types of tissues [49, 51]. Modeling such properties is important for intrabody communications [74, 228, 235], and for exploiting the transmit and receive modes. Equivalent circuit models can quickly become more complex when environmental effects, such as grounding [34] or wet skin [227] are consid-

ered. Several papers have shown that the human body reacts similarly to different frequencies [7, 22, 100], though Schenk *et al.* point out that it is hard to obtain such data with statistical significance [176]. There are no indications that the electric fields typically used in capacitive sensing systems have adverse effects on users’ health [71, 235].

### Classification & Continuous Object Tracking

Capacitive sensing inherently involves inferring information from signal data, either discrete (*e.g.*, for touch recognition) or continuous (*e.g.*, for estimating user positions). Thresholding is ubiquitously applied to realize discrete classifiers, *e.g.*, to passively sense user foot steps [163, 197], touches [12], or presence [42, 226]. If more than one state is being detected (*e.g.*, multiple postures on a couch), classifiers, such as support vector machines [78, 80, 107, 117] or decision trees [69, 109, 185, 208] are frequently used. In contrast to classification, models that determine continuous properties are often physically motivated. Such models can be based on pseudo-probability distributions that estimate the most probable system state, for example 3D hand positions [66, 167, 168, 187]. Researchers have used particle filters to enable real-time operation when multiple degrees-of-freedom are being calculated [66, 167, 168]. Le Goc *et al.* take a different approach by applying random decision forests directly to the highly non-linear sensing problem of measuring thumb positions in proximity to a touchscreen [119].

### Sensor Fusion

Inertial measurement units (IMU) are often paired with capacitive systems in order to reveal more contextual information [65, 88], or to provide an additional dimension for user input [114, 130, 209]. IMUs have also been used to correlate whole-body movements to capacitive sensing data [109, 194] and avoid accidental interactions [107]. Other work has combined acoustic sensors [16], cameras [48] and resistive sensors [112, 140, 145] with capacitive approaches.

## CONCLUSION

Capacitive sensing has been a key enabler for research in HCI for more than two decades. It provides a sensing modality that is cheap, easy to integrate, and enables rich interactions. For the same reasons, capacitive sensing has become an integral part of many wearable, mobile, and stationary devices. As such, we expect capacitive sensing to continue to have a prominent role in the coming decades.

In this paper, we have presented an analysis and review of the past literature as a reference for others working in this field. As we plan future research around novel sensing technologies and interaction techniques, we think it is important to understand the existing work, learn from its benefits and limitations, and build upon it. The taxonomy we have proposed describes and classifies the various types of capacitive sensing found in the literature. We hope it provides a useful baseline for the community and helps others set their work in the context of previous research. We also hope that our discussion of research challenges will inform and inspire others in the community to continue developing innovatively capacitive sensing or may in the future.

## REFERENCES

1. Fatemeh Aezinia, YiFan Wang, and Behraad Bahreyni. 2011. Touchless capacitive sensor for hand gesture detection. In *IEEE SENSORS Proceedings*. IEEE. DOI : <http://dx.doi.org/10.1109/icsens.2011.6127321>
2. Fatemeh Aezinia, Yifan Wang, and Behraad Bahreyni. 2012. Three dimensional touchless tracking of objects using integrated capacitive sensors. *IEEE Transactions on Consumer Electronics* 58, 3 (2012), 886–890. DOI : <http://dx.doi.org/10.1109/tce.2012.6311332>
3. Alireza Ramezani Akhmareh, Mihai Teodor Lazarescu, Osama Bin Tariq, and Luciano Lavagno. 2016. A Tagless Indoor Localization System Based on Capacitive Sensing Technology. *Sensors* 16(9) (2016).
4. Alan D. Aronoff. 1965. *Electrostatic Means for Intrusion Detection and Ranging*. Technical Report. National Technical Information System.
5. Atmel. 2016. mXTS220 maXStylus multiSense: One sensor to implement both a stylus and touch simultaneously. [http://www.atmel.com/products/touchsolutions/touchscreens/active\\_stylus.aspx](http://www.atmel.com/products/touchsolutions/touchscreens/active_stylus.aspx). (2016). Accessed 2016-09-18.
6. Ryan Aylward and Joseph A. Paradiso. 2007. A Compact, High-Speed, Wearable Sensor Network for Biomotion Capture and Interactive Media. In *2007 6th International Symposium on Information Processing in Sensor Networks*. IEEE. DOI : <http://dx.doi.org/10.1109/ipsn.2007.4379698>
7. Heribert Baldus, Steven Corroy, Alberto Fazzi, Karin Klabunde, and Tim Schenk. 2009. Human-centric connectivity enabled by body-coupled communications. *IEEE Commun. Mag.* 47, 6 (jun 2009), 172–178. DOI : <http://dx.doi.org/10.1109/mcom.2009.5116816>
8. Rebecca Baldwin, Stan Bobovych, Ryan Robucci, Chintan Patel, and Nilanjan Banerjee. 2015. Gait analysis for fall prediction using hierarchical textile-based capacitive sensor arrays. In *2015 Design, Automation Test in Europe Conference Exhibition (DATE)*. 1293–1298. DOI : <http://dx.doi.org/10.7873/DATE.2015.0943>
9. Gary Barrett and Ryomei Omote. 2010. Projected-capacitive touch technology. *Information Display* 26, 3 (2010), 16–21.
10. Larry K. Baxter. 1997. *Capacitive Sensors: Design and Applications*. IEEE Press.
11. Frank Beck and Bent Stumpe. 1973. *Two devices for operator interaction in the central control of the new CERN accelerator*. Technical Report. CERN.
12. Ray Bittner and Mike Sinclair. 2009. VersaPatch: A Low Cost 2.5D Capacitive Touch Sensor. In *Human-Computer Interaction. Novel Interaction Methods and Techniques*. Springer Science + Business Media, 407–416. DOI : [http://dx.doi.org/10.1007/978-3-642-02577-8\\_44](http://dx.doi.org/10.1007/978-3-642-02577-8_44)
13. Florian Block, Hans Gellersen, and Nicolas Villar. 2010. Touch-display keyboards: transforming keyboards into interactive surfaces. In *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10*. ACM. DOI : <http://dx.doi.org/10.1145/1753326.1753498>
14. Andreas Braun and Pascal Hamisu. 2011. Designing a multi-purpose capacitive proximity sensing input device. In *Proceedings of the 4th International Conference on Pervasive Technologies Related to Assistive Environments - PETRA '11*. ACM. DOI : <http://dx.doi.org/10.1145/2141622.2141641>
15. Andreas Braun, Henning Heggen, and Reiner Wichert. 2012. CapFloor – A Flexible Capacitive Indoor Localization System. In *Evaluating AAL Systems Through Competitive Benchmarking. Indoor Localization and Tracking*. Springer Science + Business Media, 26–35. DOI : [http://dx.doi.org/10.1007/978-3-642-33533-4\\_3](http://dx.doi.org/10.1007/978-3-642-33533-4_3)
16. Andreas Braun, Stefan Krepp, and Arjan Kuijper. 2015. Acoustic Tracking of Hand Activities on Surfaces. In *Proceedings of the 2Nd International Workshop on Sensor-based Activity Recognition and Interaction (WOAR '15)*. ACM, Article 9, 5 pages. DOI : <http://dx.doi.org/10.1145/2790044.2790052>
17. Andreas Braun, Stephan Neumann, Sönke Schmidt, Reiner Wichert, and Arjan Kuijper. 2014. Towards interactive car interiors. In *Proceedings of the 8th Nordic Conference on Human-Computer Interaction Fun, Fast, Foundational - NordiCHI '14*. ACM. DOI : <http://dx.doi.org/10.1145/2639189.2670191>
18. Leah Buechley, David Mellis, Hannah Perner-Wilson, Emily Lovell, and Bonifaz Kaufmann. 2010. Living wall: programmable wallpaper for interactive spaces. In *Proceedings of the international conference on Multimedia - MM '10*. ACM. DOI : <http://dx.doi.org/10.1145/1873951.1874226>
19. William Buller and Brian Wilson. 2006. Measuring the Capacitance of Electrical Wiring and Humans for Proximity Sensing with Existing Electrical Infrastructure. In *2006 IEEE International Conference on Electro/Information Technology*. IEEE. DOI : <http://dx.doi.org/10.1109/eit.2006.252172>
20. Jesse Burstyn, Nicholas Fellion, Paul Strohmeier, and Roel Vertegaal. 2015. *PrintPut: Resistive and Capacitive Input Widgets for Interactive 3D Prints*. Springer International Publishing, Cham, 332–339. DOI : [http://dx.doi.org/10.1007/978-3-319-22701-6\\_25](http://dx.doi.org/10.1007/978-3-319-22701-6_25)
21. Bill Buxton. 2016. Multi-Touch Systems that I Have Known and Loved. (2016). <http://www.billbuxton.com/multitouchOverview.html> [Online; accessed 21-September-2016].

22. Maria Amparo Callejon, David Naranjo-Hernandez, Javier Reina-Tosina, and Laura M Roa. 2013. A comprehensive study into intrabody communication measurements. *IEEE Transactions on Instrumentation and Measurement* 62, 9 (2013), 2446–2455. DOI : <http://dx.doi.org/10.1109/TIM.2013.2258766>
23. G.S.P. Castle. 1997. Contact charging between insulators. *Journal of Electrostatics* 40/41 (1997), 13–20.
24. Liwei Chan, Stefanie Müller, Anne Roudaut, and Patrick Baudisch. 2012. CapStones and ZebraWidgets: sensing stacks of building blocks, dials and sliders on capacitive touch screens. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*. ACM. DOI : <http://dx.doi.org/10.1145/2207676.2208371>
25. Wook Chang, Kee Kim, Hyunjeong Lee, Joon Cho, Byung Soh, Jung Shim, Gyunghye Yang, Sung jung Cho, and Joonah Park. 2006. Recognition of Grip-Patterns by Using Capacitive Touch Sensors. In *2006 IEEE International Symposium on Industrial Electronics*. IEEE. DOI : <http://dx.doi.org/10.1109/isie.2006.296083>
26. Ranajit Chatterjee and Fumtoshi Matsuno. 2006. Design of A Touch Sensor Based Single Finger Operated Wearable User-Interface Terminal. In *2006 SICE-ICASE International Joint Conference*. IEEE. DOI : <http://dx.doi.org/10.1109/sice.2006.314614>
27. Ranajit Chatterjee and Fumtoshi Matsuno. 2008. Capacitive touch sensor based user-interface : Generic design considerations and development of an wearable input device. In *SICE Annual Conference, 2008*. 2299–2303. DOI : <http://dx.doi.org/10.1109/SICE.2008.4655048>
28. Ke-Yu Chen, Gabe A. Cohn, Sidhant Gupta, and Shwetak N. Patel. 2013. uTouch: sensing touch gestures on unmodified LCDs. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*. ACM. DOI : <http://dx.doi.org/10.1145/2470654.2481356>
29. Bernard Cheng, Antonio Gomes, Paul Strohmeier, and Roel Vertegaal. 2014. Mood fern: exploring shape transformations in reactive environments. In *Proceedings of the 11th Conference on Advances in Computer Entertainment Technology - ACE '14*. ACM. DOI : <http://dx.doi.org/10.1145/2663806.2663818>
30. Jingyuan Cheng, Oliver Amft, and Paul Lukowicz. 2010. Active Capacitive Sensing: Exploring a New Wearable Sensing Modality for Activity Recognition. In *Lecture Notes in Computer Science*. Springer Science + Business Media, 319–336. DOI : [http://dx.doi.org/10.1007/978-3-642-12654-3\\_19](http://dx.doi.org/10.1007/978-3-642-12654-3_19)
31. Jingyuan Cheng and Paul Lukowicz. 2008. Towards wearable capacitive sensing of physiological parameters. In *2008 Second International Conference on Pervasive Computing Technologies for Healthcare*. IEEE. DOI : <http://dx.doi.org/10.1109/pcthealth.2008.4571087>
32. Lung-Pan Cheng, Meng Han Lee, Che-Yang Wu, Fang-I Hsiao, Yen-Ting Liu, Hsiang-Sheng Liang, Yi-Ching Chiu, Ming-Sui Lee, and Mike Y. Chen. 2013a. IrotateGrasp: automatic screen rotation based on grasp of mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*. ACM. DOI : <http://dx.doi.org/10.1145/2470654.2481424>
33. Lung-Pan Cheng, Hsiang-Sheng Liang, Che-Yang Wu, and Mike Y. Chen. 2013b. iGrasp: grasp-based adaptive keyboard for mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*. ACM. DOI : <http://dx.doi.org/10.1145/2470654.2481422>
34. Namjun Cho, Jerald Yoo, Seong-Jun Song, Jeabin Lee, Seonghyun Jeon, and Hoi-Jun Yoo. 2007. The human body characteristics as a signal transmission medium for intrabody communication. *IEEE transactions on microwave theory and techniques* 55, 5 (2007), 1080–1086. DOI : <http://dx.doi.org/10.1109/TMTT.2007.895640>
35. Tanay Choudhary, Saurabh Kulkarni, and Pradyumna Reddy. 2015. A Braille-based mobile communication and translation glove for deaf-blind people. In *2015 International Conference on Pervasive Computing (ICPC)*. IEEE. DOI : <http://dx.doi.org/10.1109/pervasive.2015.7087033>
36. Gabe Cohn, Sidhant Gupta, Tien-Jui Lee, Dan Morris, Joshua R. Smith, Matthew S. Reynolds, Desney S. Tan, and Shwetak N. Patel. 2012. An ultra-low-power human body motion sensor using static electric field sensing. In *Proceedings of the 2012 ACM Conference on Ubiquitous Computing - UbiComp '12*. ACM. DOI : <http://dx.doi.org/10.1145/2370216.2370233>
37. Gabe Cohn, Daniel Morris, Shwetak Patel, and Desney Tan. 2012. Humantenna: using the body as an antenna for real-time whole-body interaction. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*. ACM. DOI : <http://dx.doi.org/10.1145/2207676.2208330>
38. Gabe Cohn, Daniel Morris, Shwetak N. Patel, and Desney S. Tan. 2011. Your noise is my command: sensing gestures using the body as an antenna. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*. ACM. DOI : <http://dx.doi.org/10.1145/1978942.1979058>
39. Max Cremer. 1907. Ueber die Registrierung mechanischer Vorgänge auf elektrischem Wege, speziell mit Hilfe des Saitengalvanometers und Saitenelectrometers. *Münchner Medizinische Wochenschrift* 54 (August 1907), 1629–1630.

40. Paul Dietz and Darren Leigh. 2001. DiamondTouch: a multi-user touch technology. In *Proceedings of the 14th annual ACM symposium on User interface software and technology - UIST '01*. ACM. DOI : <http://dx.doi.org/10.1145/502348.502389>
41. Paul Dietz, Jonathan Westhues, John Barnwell, Jefferson Y. Han, and William Yerazunis. 2006. Submerging technologies. In *ACM SIGGRAPH 2006 Emerging technologies on - SIGGRAPH '06*. ACM. DOI : <http://dx.doi.org/10.1145/1179133.1179164>
42. Maxim Djakow, Andreas Braun, and Alexander Marinc. 2014. *MoviBed - Sleep Analysis Using Capacitive Sensors*. Springer International Publishing, Cham, 171–181. DOI : [http://dx.doi.org/10.1007/978-3-319-07509-9\\_17](http://dx.doi.org/10.1007/978-3-319-07509-9_17)
43. David Dobbstein, Philipp Hock, and Enrico Rukzio. 2015. Belt: An Unobtrusive Touch Input Device for Head-worn Displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*. ACM. DOI : <http://dx.doi.org/10.1145/2702123.2702450>
44. Collin B. Eaker and Michael D. Dickey. 2015. Liquid metals as ultra-stretchable, soft, and shape reconfigurable conductors. In *SPIE Defense+ Security*. International Society for Optics and Photonics, 946708–946708.
45. H. M. Elfekey and H. A. Bastawrous. 2013. Design and implementation of a new thin cost effective AC hum based touch sensing keyboard. In *2013 IEEE International Conference on Consumer Electronics (ICCE)*. IEEE. DOI : <http://dx.doi.org/10.1109/icce.2013.6487036>
46. Christoph Endres, Tim Schwartz, and Christian A. Müller. 2011. Geremin": 2D microgestures for drivers based on electric field sensing. In *Proceedings of the 15th international conference on Intelligent user interfaces - IUI '11*. ACM. DOI : <http://dx.doi.org/10.1145/1943403.1943457>
47. T. Ficker. 2006. Electrification of human body by walking. *Journal of Electrostatics* 64 (2006), 10–16.
48. Sean Follmer, Micah Johnson, Edward Adelson, and Hiroshi Ishii. 2011. deForm: an interactive malleable surface for capturing 2.5D arbitrary objects, tools and touch. In *Proceedings of the 24th annual ACM symposium on User interface software and technology - UIST '11*. ACM. DOI : <http://dx.doi.org/10.1145/2047196.2047265>
49. Kenneth R Foster and Henry C Lukaski. 1996. Whole-body impedance—what does it measure? *The American journal of clinical nutrition* 64, 3 (1996), 388S–396S.
50. Masaaki Fukumoto and Mitsuru Shinagawa. 2005. CarpetLAN: A Novel Indoor Wireless(-like) Networking and Positioning System. In *Lecture Notes in Computer Science*. Springer Science + Business Media, 1–18. DOI : [http://dx.doi.org/10.1007/11551201\\_1](http://dx.doi.org/10.1007/11551201_1)
51. S. Gabriel, R.W. Lau, and C. Gabriel. 1996. The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz. *Physics in Medicine and Biology* 41, 11 (1996), 2251–2269.
52. Steven Gelineck, Dan Overholt, Morten Büchert, and Jesper Andersen. 2013. Towards an Interface for Music Mixing based on Smart Tangibles and Multitouch. In *New Interfaces for Musical Expression*. Association for Computing Machinery.
53. E.R. Generazio. 2015. Electric Potential and Electric Field Imaging with Applications. *Materials Evaluation* 73, 11 (Nov. 2015).
54. Bobby George, Hubert Zangl, and Thomas Bretterkieber. 2009. Seat Occupancy Detection Based on Capacitive Sensing. *IEEE Trans. Instrum. Meas.* 58, 5 (may 2009), 1487–1494. DOI : <http://dx.doi.org/10.1109/tim.2009.2009411>
55. Bobby George, Hubert Zangl, Thomas Bretterkieber, and Georg Brasseur. 2010. A Combined Inductive & Capacitive Proximity Sensor for Seat Occupancy Detection. *IEEE Trans. Instrum. Meas.* 59, 5 (may 2010), 1463–1470. DOI : <http://dx.doi.org/10.1109/tim.2010.2040910>
56. Albert Glinsky. 2000. *Theremin: Ether Music and Espionage*. University of Illinois Press. <http://books.google.de/books?id=6DH1QJcMpBQC>
57. Nan-Wei Gong, Steve Hodges, and Joseph A. Paradiso. 2011. Leveraging conductive inkjet technology to build a scalable and versatile surface for ubiquitous sensing. In *Proceedings of the 13th international conference on Ubiquitous computing - UbiComp '11*. ACM. DOI : <http://dx.doi.org/10.1145/2030112.2030120>
58. Nan-Wei Gong, Jürgen Steimle, Simon Olberding, Steve Hodges, Nicholas Edward Gillian, Yoshihiro Kawahara, and Joseph A. Paradiso. 2014. PrintSense: a versatile sensing technique to support multimodal flexible surface interaction. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*. ACM. DOI : <http://dx.doi.org/10.1145/2556288.2557173>
59. Nan-Wei Gong, Nan Zhao, and Joseph A. Paradiso. 2011. A Customizable Sensate Surface for Music Control. In *Proceedings NIME'11 (NIME'11)*.
60. Daniel Gotsch, Xujing Zhang, Jesse Burstyn, and Roel Vertegaal. 2016. HoloFlex: A Flexible Holographic Smartphone with Bend Input. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. ACM, 3675–3678. DOI : <http://dx.doi.org/10.1145/2851581.2890258>

61. Daniel Groeger, Elena Chong Loo, and Jürgen Steimle. 2016. HotFlex: Post-print Customization of 3D Prints Using Embedded State Change. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 420–432. DOI : <http://dx.doi.org/10.1145/2858036.2858191>
62. Tobias Grosse-Puppendahl, Sebastian Beck, and Daniel Wilbers. 2014a. Rainbowfish: visual feedback on gesture-recognizing surfaces. In *Proceedings of the extended abstracts of the 32nd annual ACM conference on Human factors in computing systems - CHI EA '14*. ACM. DOI : <http://dx.doi.org/10.1145/2559206.2574787>
63. Tobias Grosse-Puppendahl, Sebastian Beck, Daniel Wilbers, Steeven Zeiß, Julian von Wilmsdorff, and Arjan Kuijper. 2014b. Ambient Gesture-Recognizing Surfaces with Visual Feedback. In *Distributed, Ambient, and Pervasive Interactions*. Springer Science + Business Media, 97–108. DOI : [http://dx.doi.org/10.1007/978-3-319-07788-8\\_10](http://dx.doi.org/10.1007/978-3-319-07788-8_10)
64. Tobias Grosse-Puppendahl, Yannick Berghoefler, Andreas Braun, Raphael Wimmer, and Arjan Kuijper. 2013. OpenCapSense: A rapid prototyping toolkit for pervasive interaction using capacitive sensing. In *2013 IEEE International Conference on Pervasive Computing and Communications (PerCom)*. IEEE. DOI : <http://dx.doi.org/10.1109/percom.2013.6526726>
65. Tobias Grosse-Puppendahl, Eugen Berlin, and Marko Borazio. 2012. Enhancing Accelerometer-Based Activity Recognition with Capacitive Proximity Sensing. In *Ambient Intelligence*. Lecture Notes in Computer Science, Vol. 7683. Springer Berlin Heidelberg, 17–32. DOI : [http://dx.doi.org/10.1007/978-3-642-34898-3\\_2](http://dx.doi.org/10.1007/978-3-642-34898-3_2)
66. Tobias Grosse-Puppendahl, Andreas Braun, Felix Kamieth, and Arjan Kuijper. 2013. Swiss-cheese extended: an object recognition method for ubiquitous interfaces based on capacitive proximity sensing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*. ACM. DOI : <http://dx.doi.org/10.1145/2470654.2466186>
67. Tobias Grosse-Puppendahl, Xavier Dellangnl, Christian Hatzfeld, Biying Fu, Mario Kupnik, Arjan Kuijper, Matthias R. Hastall, James Scott, and Marco Gruteser. 2016. Platypus: Indoor Localization and Identification Through Sensing of Electric Potential Changes in Human Bodies. In *Proceedings of the 14th Annual International Conference on Mobile Systems, Applications, and Services (MobiSys '16)*. ACM, 17–30. DOI : <http://dx.doi.org/10.1145/2906388.2906402>
68. Tobias Grosse-Puppendahl, Sebastian Herber, Raphael Wimmer, Frank Englert, Sebastian Beck, Julian von Wilmsdorff, Reiner Wichert, and Arjan Kuijper. 2014. Capacitive near-field communication for ubiquitous interaction and perception. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing - UbiComp '14 Adjunct*. ACM. DOI : <http://dx.doi.org/10.1145/2632048.2632053>
69. Tobias Grosse-Puppendahl, Alexander Marinc, and Andreas Braun. 2011. Classification of User Postures with Capacitive Proximity Sensors in AAL-Environments. In *Lecture Notes in Computer Science*. Springer Science + Business Media, 314–323. DOI : [http://dx.doi.org/10.1007/978-3-642-25167-2\\_43](http://dx.doi.org/10.1007/978-3-642-25167-2_43)
70. Enric Guaus, Tan Hakan Ozaslan, Eric Palacios, and Josep Lluís Arcos. 2010. A Left Hand Gesture Caption System for Guitar Based on Capacitive Sensors. In *International Conference on New Interfaces for Musical Expression (NIME)*. 238–243.
71. ICNIRP Guideline. 1998. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). *Health Phys* 74, 4 (1998), 494–522.
72. Sidhant Gupta, Ke-Yu Chen, Matthew S. Reynolds, and Shwetak N. Patel. 2011. LightWave: using compact fluorescent lights as sensors. In *Proceedings of the 13th international conference on Ubiquitous computing - UbiComp '11*. ACM. DOI : <http://dx.doi.org/10.1145/2030112.2030122>
73. Iman Habib, Niklas Berggren, Erik Rehn, Gustav Josefsson, Andreas Kunz, and Morten Fjeld. 2009. DGTS: Integrated Typing and Pointing. In *Human-Computer Interaction – INTERACT 2009*. Springer Science + Business Media, 232–235. DOI : [http://dx.doi.org/10.1007/978-3-642-03658-3\\_30](http://dx.doi.org/10.1007/978-3-642-03658-3_30)
74. Keisuke Hachisuka, Yusuke Terauchi, Yoshinori Kishi, Ken Sasaki, Terunao Hirota, Hiroshi Hosaka, Katsuyuki Fujii, Masaharu Takahashi, and Koichi Ito. 2006. Simplified circuit modeling and fabrication of intrabody communication devices. *Sensors and Actuators A: Physical* 130-131 (aug 2006), 322–330. DOI : <http://dx.doi.org/10.1016/j.sna.2006.04.044>
75. Marian Haescher, Denys J. C. Matthies, Gerald Bieber, and Bodo Urban. 2015. CapWalk: A Capacitive Recognition of Walking-based Activities As a Wearable Assistive Technology. In *Proceedings of the 8th ACM International Conference on Pervasive Technologies Related to Assistive Environments (PETRA '15)*. ACM, Article 35, 8 pages. DOI : <http://dx.doi.org/10.1145/2769493.2769500>
76. Marius Hagan and Horia-Nicolai Teodorescu. 2013. Intelligent clothes with a network of painted sensors. In *2013 E-Health and Bioengineering Conference (EHB)*. IEEE. DOI : <http://dx.doi.org/10.1109/ehb.2013.6707390>

77. Jaehyun Han, Jiseong Gu, and Geehyuk Lee. 2014. Trampoline: A Double-sided Elastic Touch Device for Creating Reliefs. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, 383–388. DOI : <http://dx.doi.org/10.1145/2642918.2647381>
78. Seungju Han and Joonah Park. 2013. Grip-Ball: A spherical multi-touch interface for interacting with virtual worlds. In *2013 IEEE International Conference on Consumer Electronics (ICCE)*. IEEE. DOI : <http://dx.doi.org/10.1109/icce.2013.6487035>
79. C. J. Harland, T. D. Clark, and R. J. Prance. 2002. Electric potential probes - new directions in the remote sensing of the human body. *Measurement Science and Technology* 13, 2 (2002), 163. <http://stacks.iop.org/0957-0233/13/i=2/a=304>
80. Chris Harrison, Munehiko Sato, and Ivan Poupyrev. 2012. Capacitive fingerprinting: exploring user differentiation by sensing electrical properties of the human body. In *Proceedings of the 25th annual ACM symposium on User interface software and technology - UIST '12*. ACM. DOI : <http://dx.doi.org/10.1145/2380116.2380183>
81. Takahiro Hashizume, Takuya Sasatani, Koya Narumi, Yoshiaki Narusue, Yoshihiro Kawahara, and Tohru Asami. 2016. Passive and Contactless Epidermal Pressure Sensor Printed with Silver Nano-particle Ink. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp '16)*. ACM, 190–195. DOI : <http://dx.doi.org/10.1145/2971648.2971705>
82. Yuki Hayashida, Ryo Sugiyama, Yusuke Ido, Akito Suzuki, Yasuaki Takizawa, Mitsuru Shinagawa, Yuichi Kado, and Nozomi Haga. 2014. Capacitance Model of Embedded Transceiver for Intra-body Communication. In *Proceedings of the 9th International Conference on Body Area Networks*. Institute for Computer Sciences, Social Informatics and Telecommunications Engineering (ICST). DOI : <http://dx.doi.org/10.4108/icst.bodynets.2014.258238>
83. Junwen He, Ralph G Nuzzo, and John A Rogers. 2015. Inorganic materials and assembly techniques for flexible and stretchable electronics. *Proc. IEEE* 103, 4 (2015), 619–632. DOI : <http://dx.doi.org/10.1109/JPROC.2015.2396991>
84. W. Heiligenberg. 1977. *Principles of electrolocation and jamming avoidance in electric fish: a neuroethological approach*. Springer-Verlag. <http://books.google.de/books?id=cKpqAAAAMAAJ>
85. Mehrdad Hesar, Vikram Iyer, and Shyamnath Gollakota. 2016. Enabling On-body Transmissions with Commodity Devices. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp '16)*. ACM, 1100–1111. DOI : <http://dx.doi.org/10.1145/2971648.2971682>
86. Ken Hinckley, William Buxton, Seongkook Heo, Michel Pahud, Christian Holz, Hrvoje Benko, Abigail Sellen, Richard Banks, Kenton O'Hara, and Gavin Smyth. 2016. Pre-Touch Sensing for Mobile Interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*. ACM. DOI : <http://dx.doi.org/10.1145/2858036.2858095>
87. Ken Hinckley and Mike Sinclair. 1999. Touch-sensing input devices. In *Proceedings of the SIGCHI conference on Human factors in computing systems the CHI is the limit - CHI '99*. ACM. DOI : <http://dx.doi.org/10.1145/302979.303045>
88. Ken Hinckley, Andrew Wilson, Michel Pahud, Hrvoje Benko, Pourang Irani, François Guimbretière, Marcel Gavriliu, Xiang 'Anthony' Chen, Fabrice Matulic, and William Buxton. 2014. Sensing techniques for tablet+stylus interaction. In *Proceedings of the 27th annual ACM symposium on User interface software and technology - UIST '14*. ACM. DOI : <http://dx.doi.org/10.1145/2642918.2647379>
89. Shigeyuki Hirai, Yoshinobu Sakakibara, and Hironori Hayashi. 2013. Enabling Interactive Bathroom Entertainment Using Embedded Touch Sensors in the Bathtub. In *Lecture Notes in Computer Science*. Springer Science + Business Media, 544–547. DOI : [http://dx.doi.org/10.1007/978-3-319-03161-3\\_49](http://dx.doi.org/10.1007/978-3-319-03161-3_49)
90. Nguyen Huy Hoang Huy, Gihan Hettiarachchi, Youngki Lee, and Rajesh Krishna Balan. 2016. Small Scale Deployment of Seat Occupancy Detectors. In *Proceedings of the 3rd International on Workshop on Physical Analytics (WPA '16)*. ACM, 25–30. DOI : <http://dx.doi.org/10.1145/2935651.2935660>
91. Steve Hodges, Nicolas Villar, Nicholas Chen, Tushar Chugh, Jie Qi, Diana Nowacka, and Yoshihiro Kawahara. 2014. Circuit stickers: peel-and-stick construction of interactive electronic prototypes. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*. ACM. DOI : <http://dx.doi.org/10.1145/2556288.2557150>
92. Paul Holleis, Albrecht Schmidt, Susanna Paasovaara, Arto Puikkonen, and Jonna Häkkinä. 2008. Evaluating capacitive touch input on clothes. In *Proceedings of the 10th international conference on Human computer interaction with mobile devices and services - MobileHCI '08*. ACM. DOI : <http://dx.doi.org/10.1145/1409240.1409250>
93. Christian Holz and Patrick Baudisch. 2010. The Generalized Perceived Input Point Model and How to Double Touch Accuracy by Extracting Fingerprints. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, 581–590. DOI : <http://dx.doi.org/10.1145/1753326.1753413>

94. Christian Holz and Frank R. Bentley. 2016. On-Demand Biometrics: Fast Cross-Device Authentication. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 3761–3766. DOI : <http://dx.doi.org/10.1145/2858036.2858139>
95. Christian Holz, Senaka Buthpitiya, and Marius Knaust. 2015. Bodyprint: Biometric User Identification on Mobile Devices Using the Capacitive Touchscreen to Scan Body Parts. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 3011–3014. DOI : <http://dx.doi.org/10.1145/2702123.2702518>
96. Christian Holz, Tovi Grossman, George Fitzmaurice, and Anne Agur. 2012. Implanted User Interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, 503–512. DOI : <http://dx.doi.org/10.1145/2207676.2207745>
97. Christian Holz and Marius Knaust. 2015. Biometric Touch Sensing: Seamlessly Augmenting Each Touch with Continuous Authentication. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 303–312. DOI : <http://dx.doi.org/10.1145/2807442.2807458>
98. Cindy Hsin-Liu Kao, Christian Holz, Asta Roseway, Andres Calvo, and Chris Schmandt. 2016. DuoSkin: Rapidly Prototyping On-Skin User Interfaces Using Skin-Friendly Materials. In *Proceedings of the International Symposium on Wearable Computers 2016 (ISWC'16) (ISWC'16)*. ACM. DOI : <http://dx.doi.org/10.1145/2971763.2971777>
99. Manh Huynh, Phuc Nguyen, Marco Gruteser, and Tam Vu. 2015. POSTER: Mobile Device Identification by Leveraging Built-in Capacitive Signature. In *Proceedings of the 22Nd ACM SIGSAC Conference on Computer and Communications Security (CCS '15)*. ACM, 1635–1637. DOI : <http://dx.doi.org/10.1145/2810103.2810118>
100. J. H. Hwang, T. W. Kang, and S. W. Kang. 2011. Measurement results of human body's signal loss with multiple subjects for human body communication. In *2011 IEEE International Symposium on Antennas and Propagation (APSURSI)*. IEEE. DOI : <http://dx.doi.org/10.1109/aps.2011.5996624>
101. Kohei Ikeda and Koji Tsukada. 2015. CapacitiveMarker: novel interaction method using visual marker integrated with conductive pattern. In *Proceedings of the 6th Augmented Human International Conference on - AH '15*. ACM. DOI : <http://dx.doi.org/10.1145/2735711.2735783>
102. ISO 10012-1:1992-01 1992. ISO/TC 176/SC 3. Quality assurance requirements for measuring equipment - Part 1: Metrological confirmation system for measuring equipment (ISO 10012-1:1992-01, *withdrawn*). (1992).
103. Hsin-Liu (Cindy) Kao, Artem Dementyev, Joseph A. Paradiso, and Chris Schmandt. 2015. NailO: Fingernails as an Input Surface. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*. ACM. DOI : <http://dx.doi.org/10.1145/2702123.2702572>
104. N. Karlsson, B. Karlsson, and P. Wide. A glove equipped with finger flexion sensors as a command generator used in a fuzzy control system. In *IMTC/98 Conference Proceedings. IEEE Instrumentation and Measurement Technology Conference (Cat. No.98CH36222)*. IEEE. DOI : <http://dx.doi.org/10.1109/imtc.1998.679825>
105. Yoshihiro Kawahara, Steve Hodges, Benjamin S. Cook, Cheng Zhang, and Gregory D. Abowd. 2013. Instant inkjet circuits: lab-based inkjet printing to support rapid prototyping of UbiComp devices. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing - UbiComp '13*. ACM. DOI : <http://dx.doi.org/10.1145/2493432.2493486>
106. Behailu Kibret, MirHojjat Seyedi, Daniel T. H. Lai, and Micheal Faulkner. 2014. Investigation of Galvanic-Coupled Intrabody Communication Using the Human Body Circuit Model. *IEEE Journal of Biomedical and Health Informatics* 18, 4 (jul 2014), 1196–1206. DOI : <http://dx.doi.org/10.1109/jbhi.2014.2301165>
107. Kee-Eung Kim, Wook Chang, Sung-Jung Cho, Junghyun Shim, Hyunjeong Lee, Joonah Park, Youngbeom Lee, and Sangryong Kim. 2006. Hand Grip Pattern Recognition for Mobile User Interfaces. In *Proceedings of the 18th Conference on Innovative Applications of Artificial Intelligence - Volume 2 (IAAI'06)*. AAAI Press, 1789–1794. <http://dl.acm.org/citation.cfm?id=1597122.1597138>
108. Sangkil Kim, Yoshihiro Kawahara, Apostolos Georgiadis, Ana Collado, and Manos M. Tentzeris. 2013. Low-cost inkjet-printed fully passive RFID tags using metamaterial-inspired antennas for capacitive sensing applications. In *2013 IEEE MTT-S International Microwave Symposium Digest (MTT)*. IEEE. DOI : <http://dx.doi.org/10.1109/mwsym.2013.6697644>
109. Yuhwan Kim, Seungchul Lee, Inseok Hwang, Hyunho Ro, Youngki Lee, Miri Moon, and Juneha Song. 2014. High5: promoting interpersonal hand-to-hand touch for vibrant workplace with electrodermal sensor watches. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing - UbiComp '14 Adjunct*. ACM. DOI : <http://dx.doi.org/10.1145/2632048.2632072>



110. Sauli Kivikunnas, Esko Strommer, Marko Korkalainen, Tapio Heikkila, and Mikko Haverinen. 2010. Sensing sofa and its ubiquitous use. In *2010 International Conference on Information and Communication Technology Convergence (ICTC)*. IEEE. DOI : <http://dx.doi.org/10.1109/ictc.2010.5674767>
111. Tero Kivimaki, Timo Vuorela, Miika Valtonen, and Jukka Vanhala. 2013. Reliability of the TileTrack capacitive user tracking system in smart home environment. In *ICT 2013*. IEEE. DOI : <http://dx.doi.org/10.1109/ictel.2013.6632162>
112. Heather Knight, Jae-Kyu Lee, and Hongshen Ma. 2008. Chair Alarm for patient fall prevention based on Gesture Recognition and Interactivity. In *2008 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE. DOI : <http://dx.doi.org/10.1109/iembs.2008.4650012>
113. Sven Kratz, Tilo Westermann, Michael Rohs, and Georg Essl. 2011. CapWidgets: Tangible Widgets Versus Multi-touch Controls on Mobile Devices. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems (CHI EA '11)*. ACM, 1351–1356. DOI : <http://dx.doi.org/10.1145/1979742.1979773>
114. Paul G. Kry and D. K. Pai. 2006. Grasp recognition and manipulation with the tango. In *International Symposium on Experimental Robotics*, Vol. 10. Springer.
115. K. Kurita. 2010. New Approach to Touch Sensing Technique Based on Measurement of Current Generated by Electrostatic Induction. In *iSAIRAS*.
116. K. Kurita, R. Takizawa, and H. Kumon. 2009. Detection of human walking motion based on measurement system of current generated by electrostatic induction. In *ICCAS-SICE, 2009*. 5485–5488.
117. Gierad Laput, Chouchang Yang, Robert Xiao, Alanson Sample, and Chris Harrison. 2015. EM-Sense: Touch Recognition of Uninstrumented, Electrical and Electromechanical Objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, 157–166. DOI : <http://dx.doi.org/10.1145/2807442.2807481>
118. Mathieu Le Goc, Pierre Dragicevic, Samuel Huron, Jeremy Boy, and Jean-Daniel Fekete. 2015. SmartTokens: Embedding Motion and Grip Sensing in Small Tangible Objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, 357–362. DOI : <http://dx.doi.org/10.1145/2807442.2807488>
119. Mathieu Le Goc, Stuart Taylor, Shahram Izadi, and Cem Keskin. 2014. A low-cost transparent electric field sensor for 3d interaction on mobile devices. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*. ACM. DOI : <http://dx.doi.org/10.1145/2556288.2557331>
120. Chia-Hsun Lee and Ted Selker. 2004. iSphere: A Proximity-based 3D Input Device. In *ACM SIGGRAPH 2004 Posters (SIGGRAPH '04)*. ACM, 72–. DOI : <http://dx.doi.org/10.1145/1186415.1186499>
121. S. K. Lee, W. Buxton, and K. C. Smith. 1985. A Multi-touch Three Dimensional Touch-sensitive Tablet. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '85)*. ACM, 21–25. DOI : <http://dx.doi.org/10.1145/317456.317461>
122. Darren Leigh, Clifton Forlines, Ricardo Jota, Steven Sanders, and Daniel Wigdor. 2014. High Rate, Low-latency Multi-touch Sensing with Simultaneous Orthogonal Multiplexing. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, 355–364. DOI : <http://dx.doi.org/10.1145/2642918.2647353>
123. Simon J. Leigh, Robert J. Bradley, Christopher P. Pursell, Duncan R. Billson, and David A. Hutchins. 2012. A Simple, Low-Cost Conductive Composite Material for 3D Printing of Electronic Sensors. *PLoS ONE* 7, 11 (11 2012), 1–6. DOI : <http://dx.doi.org/10.1371/journal.pone.0049365>
124. Hanchuan Li, Eric Brockmeyer, Elizabeth J. Carter, Josh Fromm, Scott E. Hudson, Shwetak N. Patel, and Alanson Sample. 2016. PaperID: A Technique for Drawing Functional Battery-Free Wireless Interfaces on Paper. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, 5885–5896. DOI : <http://dx.doi.org/10.1145/2858036.2858249>
125. Yiliang Lin, Christopher Cooper, Meng Wang, Jacob J Adams, Jan Genzer, and Michael D Dickey. 2015. Handwritten, soft circuit boards and antennas using liquid metal nanoparticles. *Small* 11, 48 (2015), 6397–6403. DOI : <http://dx.doi.org/10.1002/smll.201502692>
126. Roman Lissermann, Jochen Huber, Aristotelis Hadjakos, Suranga Nanayakkara, and Max Mühlhäuser. 2014. EarPut: augmenting ear-worn devices for ear-based interaction. In *Proceedings of the 26th Australian Computer-Human Interaction Conference on Designing Futures the Future of Design - OzCHI '14*. ACM. DOI : <http://dx.doi.org/10.1145/2686612.2686655>
127. Wei Liu, Bing Qiang Ng, Terrence Lim, Liu Bin, Boon Hee Soong, Adnan Nasir, and Merrill Chia. 2012. A novel RFID and capacitive sensing based smart bookshelf. In *2012 18th IEEE International Conference on Networks (ICON)*. IEEE. DOI : <http://dx.doi.org/10.1109/icon.2012.6506540>

128. Tong Lu, Lauren Finkenauer, James Wissman, and Carmel Majidi. 2014. Rapid Prototyping for Soft-Matter Electronics. *Advanced Functional Materials* 24, 22 (2014), 3351–3356. DOI : <http://dx.doi.org/10.1002/adfm.201303732>
129. Chenchi Luo, Milind A. Borkar, Arthur J. Redfern, and James H. McClellan. 2012. Compressive Sensing for Sparse Touch Detection on Capacitive Touch Screens. *IEEE Journal on Emerging and Selected Topics in Circuits and Systems* 2, 3 (sep 2012), 639–648. DOI : <http://dx.doi.org/10.1109/jetcas.2012.2217033>
130. Kent Lyons, Seung Wook Kim, Shigeyuki Seko, David Nguyen, Audrey Desjardins, Mélodie Vidal, David Dobbelstein, and Jeremy Rubin. 2014. Loupe: a handheld near-eye display. In *Proceedings of the 27th annual ACM symposium on User interface software and technology - UIST '14*. ACM. DOI : <http://dx.doi.org/10.1145/2642918.2647361>
131. Jani Mäntyjärvi, Kjell Nybergh, Johan Himberg, and Kari Hjelt. 2004. *Touch Detection System for Mobile Terminals*. Springer Berlin Heidelberg, Berlin, Heidelberg, 331–336. DOI : [http://dx.doi.org/10.1007/978-3-540-28637-0\\_32](http://dx.doi.org/10.1007/978-3-540-28637-0_32)
132. N. Matsushita, S. Tajima, Y. Ayatsuka, and J. Rekimoto. 2000. Wearable key: device for personalizing nearby environment. In *Wearable Computers, The Fourth International Symposium on*. 119–126. DOI : <http://dx.doi.org/10.1109/ISWC.2000.888473>
133. Brian Mayton, Louis LeGrand, and Joshua R Smith. 2010. An electric field pretouch system for grasping and co-manipulation. In *Robotics and Automation (ICRA), 2010 IEEE International Conference on*. IEEE, 831–838. DOI : <http://dx.doi.org/10.1109/ROBOT.2010.5509658>
134. Andrew P. McPherson, Adrian Gierakowski, and Adam M. Stark. 2013. The space between the notes: adding expressive pitch control to the piano keyboard. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*. ACM. DOI : <http://dx.doi.org/10.1145/2470654.2481302>
135. Microsoft. 2016. Surface Pen and Touch Digitizer. <https://www.microsoft.com/surface/en-us/support/hardware-and-drivers/surface-pen-pro-4>. (2016). Accessed 2016-09-18.
136. Adiyani Mujibiya and Jun Rekimoto. 2013, revised 2015. Mirage: exploring interaction modalities using off-body static electric field sensing. In *Proceedings of the 26th annual ACM symposium on User interface software and technology - UIST '13*. ACM. DOI : <http://dx.doi.org/10.1145/2501988.2502031>
137. Anh Nguyen, Raghda Alqurashi, Zohreh Raghebi, Farnoush Banaei-kashani, Ann C. Halbower, Thang Dinh, and Tam Vu. 2016. In-ear Biosignal Recording System: A Wearable For Automatic Whole-night Sleep Staging. In *Proceedings of the 2016 Workshop on Wearable Systems and Applications (WearSys '16)*. ACM, 19–24. DOI : <http://dx.doi.org/10.1145/2935643.2935649>
138. Mohammad Faizuddin Mohd Noor, Andrew Ramsay, Stephen Hughes, Simon Rogers, John Williamson, and Roderick Murray-Smith. 2014. 28 frames later: predicting screen touches from back-of-device grip changes. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*. ACM. DOI : <http://dx.doi.org/10.1145/2556288.2557148>
139. Ian Oakley and Doyoung Lee. 2014. Interaction on the edge: offset sensing for small devices. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*. ACM. DOI : <http://dx.doi.org/10.1145/2556288.2557138>
140. Simon Olberding, Nan-Wei Gong, John Tiab, Joseph A. Paradiso, and Jürgen Steimle. 2013. A cuttable multi-touch sensor. In *Proceedings of the 26th annual ACM symposium on User interface software and technology - UIST '13*. ACM. DOI : <http://dx.doi.org/10.1145/2501988.2502048>
141. Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt, and Jürgen Steimle. 2015. Foldio: Digital Fabrication of Interactive and Shape-Changing Objects With Foldable Printed Electronics. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, 223–232. DOI : <http://dx.doi.org/10.1145/2807442.2807494>
142. Simon Olberding, Michael Wessely, and Jürgen Steimle. 2014. PrintScreen: fabricating highly customizable thin-film touch-displays. In *Proceedings of the 27th annual ACM symposium on User interface software and technology - UIST '14*. ACM. DOI : <http://dx.doi.org/10.1145/2642918.2647413>
143. Maggie Orth, Rehmi Post, and Emily Cooper. 1998. Fabric Computing Interfaces. In *CHI 98 Conference Summary on Human Factors in Computing Systems (CHI '98)*. ACM, 331–332. DOI : <http://dx.doi.org/10.1145/286498.286800>
144. Joseph A. Paradiso and Neil Gershenfeld. 1997. Musical Applications of Electric Field Sensing. *Computer Music Journal* 21 (1997), 69–89.
145. Joseph A. Paradiso, Stacy J. Morris, Ari Y. Benbasat, and Erik Asmussen. 2004. Interactive therapy with instrumented footwear. In *Extended abstracts of the 2004 conference on Human factors and computing systems - CHI '04*. ACM. DOI : <http://dx.doi.org/10.1145/985921.986059>

146. Duck Gun Park, Jin Kyung Kim, Jin Bong Sung, Jung Hwan Hwang, Chang Hee Hyung, and Sung Weon Kang. 2006. TAP: Touch-and-play. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '06)*. ACM, 677–680. DOI : <http://dx.doi.org/10.1145/1124772.1124873>
147. Kurt Partridge, Bradley Dahlquist, Alireza Veisesh, Annie Cain, Ann Foreman, Joseph Goldberg, and Gaetano Borriello. 2001. Empirical measurements of intrabody communication performance under varied physical configurations. In *Proceedings of the 14th annual ACM symposium on User interface software and technology - UIST '01*. ACM. DOI : <http://dx.doi.org/10.1145/502348.502381>
148. Shwetak N. Patel, Khai N. Truong, and Gregory D. Abowd. 2006. *PowerLine Positioning: A Practical Sub-Room-Level Indoor Location System for Domestic Use*. Springer Berlin Heidelberg, Berlin, Heidelberg, 441–458. DOI : [http://dx.doi.org/10.1007/11853565\\_26](http://dx.doi.org/10.1007/11853565_26)
149. Huaishu Peng, Jennifer Mankoff, Scott E. Hudson, and James McCann. 2015. A Layered Fabric 3D Printer for Soft Interactive Objects. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, 1789–1798. DOI : <http://dx.doi.org/10.1145/2702123.2702327>
150. Carl A. Pickering. 2008. *Human Vehicle Interaction Based On Electric Field Sensing*. Springer Berlin Heidelberg, Berlin, Heidelberg, 141–154. DOI : [http://dx.doi.org/10.1007/978-3-540-77980-3\\_11](http://dx.doi.org/10.1007/978-3-540-77980-3_11)
151. Ingrid Maria Pohl. 2013. Folded sensitive surface. In *Proceedings of the 9th ACM Conference on Creativity & Cognition - C&C '13*. ACM. DOI : <http://dx.doi.org/10.1145/2466627.2481212>
152. Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E. Robinson. 2016. Project Jacquard: Interactive Digital Textiles at Scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, 4216–4227. DOI : <http://dx.doi.org/10.1145/2858036.2858176>
153. Ivan Poupyrev, Philipp Schoessler, Jonas Loh, and Munehiko Sato. 2012. Botanicus Interacticus: Interactive Plants Technology. In *ACM SIGGRAPH 2012 Emerging Technologies (SIGGRAPH '12)*. ACM, Article 4, 1 pages. DOI : <http://dx.doi.org/10.1145/2343456.2343460>
154. Ivan Poupyrev, Zhiquan Yeo, Joshua D. Griffin, and Scott Hudson. 2010. Sensing Human Activities with Resonant Tuning. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems (CHI EA '10)*. ACM, 4135–4140. DOI : <http://dx.doi.org/10.1145/1753846.1754115>
155. A. Pouryazdan, R. J. Prance, H. Prance, and D. Roggen. 2016. Wearable Electric Potential Sensing: A New Modality Sensing Hair Touch and Restless Leg Movement. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct (UbiComp '16)*. ACM, 846–850. DOI : <http://dx.doi.org/10.1145/2968219.2968286>
156. H. Prance, P. Watson, R. J. Prance, and S. T. Beardsmore-Rust. 2012. Position and movement sensing at metre standoff distances using ambient electric field. *Measurement Science and Technology* 23, 11 (2012), 115101. <http://stacks.iop.org/0957-0233/23/i=11/a=115101>
157. R. J. Prance, S. T. Beardsmore-Rust, P. Watson, C. J. Harland, and H. Prance. 2008. Remote detection of human electrophysiological signals using electric potential sensors. *Applied Physics Letters* 93, 3 (2008).
158. Ville Rantanen, Hanna Venesvirta, Oleg Spakov, Jarmo Verho, Akos Vetek, Veikko Surakka, and Jukka Leikkala. 2013. Capacitive Measurement of Facial Activity Intensity. *IEEE Sensors J.* 13, 11 (nov 2013), 4329–4338. DOI : <http://dx.doi.org/10.1109/jsen.2013.2269864>
159. Jun Rekimoto. GestureWrist and GesturePad: unobtrusive wearable interaction devices. In *Proceedings Fifth International Symposium on Wearable Computers*. IEEE. DOI : <http://dx.doi.org/10.1109/iswc.2001.962092>
160. Jun Rekimoto. 1997. Pick-and-drop: A Direct Manipulation Technique for Multiple Computer Environments. In *Proceedings of the 10th Annual ACM Symposium on User Interface Software and Technology (UIST '97)*. ACM, 31–39. DOI : <http://dx.doi.org/10.1145/263407.263505>
161. Jun Rekimoto. 2002. SmartSkin: an infrastructure for freehand manipulation on interactive surfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems Changing our world, changing ourselves - CHI '02*. ACM. DOI : <http://dx.doi.org/10.1145/503376.503397>
162. Jun Rekimoto, Takaaki Ishizawa, Carsten Schwesig, and Haruo Oba. 2003. PreSense: interaction techniques for finger sensing input devices. In *Proceedings of the 16th annual ACM symposium on User interface software and technology - UIST '03*. ACM. DOI : <http://dx.doi.org/10.1145/964696.964719>
163. Jun Rekimoto and Hua Wang. 2004. Sensing GamePad: electrostatic potential sensing for enhancing entertainment oriented interactions. In *Extended abstracts of the 2004 conference on Human factors and computing systems - CHI '04*. ACM. DOI : <http://dx.doi.org/10.1145/985921.986089>

164. Christian Rendl, David Kim, Sean Fanello, Patrick Parzer, Christoph Rhemann, Jonathan Taylor, Martin Zirkel, Gregor Scheipl, Thomas Rothländer, Michael Haller, and Shahram Izadi. 2014. FlexSense: A Transparent Self-sensing Deformable Surface. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, 129–138. DOI : <http://dx.doi.org/10.1145/2642918.2647405>
165. Ferran Reverter, Xiujun Li, and Gerard C M Meijer. 2006. Stability and accuracy of active shielding for grounded capacitive sensors. *Measurement Science and Technology* 17, 11 (2006), 2884. <http://stacks.iop.org/0957-0233/17/i=11/a=004>
166. Wintersberger Riener. 2011. 3D Theremin: A Novel Approach for Convenient Point and Click-Interactions in Vehicles. In *3rd International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI'11)*. Adjunct proceedings.
167. Simon Rogers, John Williamson, Craig Stewart, and Roderick Murray-Smith. 2010. FingerCloud: uncertainty and autonomy handover incapacitive sensing. In *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10*. ACM. DOI : <http://dx.doi.org/10.1145/1753326.1753412>
168. Simon Rogers, John Williamson, Craig Stewart, and Roderick Murray-Smith. 2011. AnglePose: robust, precise capacitive touch tracking via 3d orientation estimation. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*. ACM. DOI : <http://dx.doi.org/10.1145/1978942.1979318>
169. Silvia Rus, Tobias Grosse-Puppendahl, and Arjan Kuijper. 2014. *Recognition of Bed Postures Using Mutual Capacitance Sensing*. Springer International Publishing, Cham, 51–66. DOI : [http://dx.doi.org/10.1007/978-3-319-14112-1\\_5](http://dx.doi.org/10.1007/978-3-319-14112-1_5)
170. Analisa Russo, Bok Yeop Ahn, Jacob J. Adams, Eric B. Duoss, Jennifer T. Bernhard, and Jennifer A. Lewis. 2011. Pen-on-Paper Flexible Electronics. *Advanced Materials* 23, 1 (2011), 3426–3430. DOI : <http://dx.doi.org/10.1002/adma.201101328>
171. A. P. Sample, D. J. Yeager, and J. R. Smith. 2009. A capacitive touch interface for passive RFID tags. In *2009 IEEE International Conference on RFID*. IEEE. DOI : <http://dx.doi.org/10.1109/rfid.2009.4911212>
172. T. Scott Saponas, Chris Harrison, and Hrvoje Benko. 2011. PocketTouch: through-fabric capacitive touch input. In *Proceedings of the 24th annual ACM symposium on User interface software and technology - UIST '11*. ACM. DOI : <http://dx.doi.org/10.1145/2047196.2047235>
173. Munehiko Sato, Ivan Poupyrev, and Chris Harrison. 2012. Touché: enhancing touch interaction on humans, screens, liquids, and everyday objects. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*. ACM. DOI : <http://dx.doi.org/10.1145/2207676.2207743>
174. Valkyrie Savage, Ryan Schmidt, Tovi Grossman, George Fitzmaurice, and Björn Hartmann. 2014. A Series of Tubes: Adding Interactivity to 3D Prints Using Internal Pipes. In *Proceedings of the 27th annual ACM symposium on User interface software and technology - UIST '14*. ACM. DOI : <http://dx.doi.org/10.1145/2642918.2647374>
175. Valkyrie Savage, Xiaohan Zhang, and Björn Hartmann. 2012. Midas: fabricating custom capacitive touch sensors to prototype interactive objects. In *Proceedings of the 25th annual ACM symposium on User interface software and technology - UIST '12*. ACM. DOI : <http://dx.doi.org/10.1145/2380116.2380189>
176. Tim C. W. Schenk, Nafiseh Seyed Mazloum, Luc Tan, and Peter Rutten. 2008. Experimental characterization of the body-coupled communications channel. In *2008 IEEE International Symposium on Wireless Communication Systems*. IEEE. DOI : <http://dx.doi.org/10.1109/iswcs.2008.4726053>
177. Martin Schmitz, Mohammadreza Khalilbeigi, Matthias Balwierz, Roman Lissermann, Max Mühlhäuser, and Jürgen Steimle. 2015. Capricate: A Fabrication Pipeline to Design and 3D Print Capacitive Touch Sensors for Interactive Objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, 253–258. DOI : <http://dx.doi.org/10.1145/2807442.2807503>
178. Johannes Schöning, Peter Brandl, Florian Daiber, Florian Echter, Otmar Hilliges, Jonathan Hook, Markus Löchtefeld, Nima Motamedi, Laurence Muller, Patrick Olivier, Tim Roth, and Ulrich von Zadow. 2008. *Multi-Touch Surfaces: A Technical Guide*. techreport. <http://drehscheibe.in.tum.de/forschung/pub/reports/2008/TUM-I0833.pdf.gz>
179. D. Sculley, Gary Holt, Daniel Golovin, Eugene Davydov, Todd Phillips, Dietmar Ebner, Vinay Chaudhary, and Michael Young. 2014. Machine Learning: The High Interest Credit Card of Technical Debt. In *SE4ML: Software Engineering for Machine Learning (NIPS 2014 Workshop)*.
180. X. Shang, R.N.J. Veldhuis, A.M. Bazen, and W.P.T. Ganzevoort. 2005. Algorithm design for grip-pattern verification in smart gun. In *Proceedings of ProRISC 2005, 16th Annual Workshop on Circuits, Systems and Signal Processing*. STW Technology Foundation, Utrecht, The Netherlands, 674–678. <http://doc.utwente.nl/53692/>

181. C. Shemelya, F. Cedillos, E. Aguilera, E. Maestas, J. Ramos, D. Espalin, D. Muse, R. Wicker, and E. MacDonald. 2013. 3D printed capacitive sensors. In *SENSORS, 2013 IEEE*. 1–4. DOI : <http://dx.doi.org/10.1109/ICSENS.2013.6688247>
182. S. Shigematsu, H. Morimura, Y. Tanabe, T. Adachi, and K. Machida. 1999. A single-chip fingerprint sensor and identifier. *IEEE Journal of Solid-State Circuits* 34, 12 (Dec 1999), 1852–1859. DOI : <http://dx.doi.org/10.1109/4.808910>
183. M. Shinagawa, M. Fukumoto, K. Ochiai, and H. Kyuragi. 2004. A Near-Field-Sensing Transceiver for Intrabody Communication Based on the Electrooptic Effect. *IEEE Trans. Instrum. Meas.* 53, 6 (dec 2004), 1533–1538. DOI : <http://dx.doi.org/10.1109/tim.2004.834064>
184. Michael Shorter, Jon Rogers, and John McGhee. 2014. Enhancing Everyday Paper Interactions with Paper Circuits. In *Proceedings of the 2014 Conference on Designing Interactive Systems (DIS '14)*. ACM, 39–42. DOI : <http://dx.doi.org/10.1145/2598510.2598584>
185. Gurashish Singh, Alexander Nelson, Ryan Robucci, Chintan Patel, and Nilanjan Banerjee. 2015. Inviz: Low-power personalized gesture recognition using wearable textile capacitive sensor arrays. In *2015 IEEE International Conference on Pervasive Computing and Communications (PerCom)*. IEEE. DOI : <http://dx.doi.org/10.1109/percom.2015.7146529>
186. J. R. Smith. 1995. *Toward Electric Field Tomography*. Master's thesis. MIT.
187. J. R. Smith. 1996. Field mice: Extracting hand geometry from electric field measurements. *IBM Syst. J.* 35, 3.4 (1996), 587–608. DOI : <http://dx.doi.org/10.1147/sj.353.0587>
188. J. R. Smith. 1999. *Electric Field Imaging*. Ph.D. Dissertation. MIT.
189. J. R. Smith, C. Salthouse, and N. Gershenfeld. 1999. Code-division multiplexing of a sensor channel: a software implementation. *IEEE J. Select. Areas Commun.* 17, 4 (apr 1999), 725–731. DOI : <http://dx.doi.org/10.1109/49.761048>
190. J. R. Smith, T. White, C. Dodge, J. Paradiso, N. Gershenfeld, and D. Allport. 1998. Electric field sensing for graphical interfaces. *IEEE Comput. Grap. Appl.* 18, 3 (1998), 54–60. DOI : <http://dx.doi.org/10.1109/38.674972>
191. James R Solberg, Kevin M Lynch, and Malcolm A MacIver. 2008. Active electrolocation for underwater target localization. *The International Journal of Robotics Research* 27, 5 (2008), 529–548.
192. Hyunyoung Song, Hrvoje Benko, Francois Guimbretiere, Shahram Izadi, Xiang Cao, and Ken Hinckley. 2011. Grips and Gestures on a Multi-touch Pen. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, 1323–1332. DOI : <http://dx.doi.org/10.1145/1978942.1979138>
193. Lingnan Song, Amanda C Myers, Jacob J Adams, and Yong Zhu. 2014. Stretchable and reversibly deformable radio frequency antennas based on silver nanowires. *ACS applied materials & interfaces* 6, 6 (2014), 4248–4253. DOI : <http://dx.doi.org/10.1021/am405972e>
194. M. Sousa, A. Techmer, A. Steinhage, C. Lauterbach, and P. Lukowicz. 2013. Human tracking and identification using a sensitive floor and wearable accelerometers. In *2013 IEEE International Conference on Pervasive Computing and Communications (PerCom)*. IEEE. DOI : <http://dx.doi.org/10.1109/percom.2013.6526728>
195. Erich P. Stuntebeck, Shwetak N. Patel, Thomas Robertson, Matthew S. Reynolds, and Gregory D. Abowd. 2008. Wideband Powerline Positioning for Indoor Localization. In *Proceedings of the 10th International Conference on Ubiquitous Computing (UbiComp '08)*. ACM, 94–103. DOI : <http://dx.doi.org/10.1145/1409635.1409649>
196. Masato Takahashi, Charith Lasantha Fernando, Yuto Kumon, Shuhey Takeda, Hideaki Nii, Takuji Tokiwa, Maki Sugimoto, and Masahiko Inami. 2011. Earthlings Attack!: a ball game using human body communication. In *Proceedings of the 2nd Augmented Human International Conference on - AH '11*. ACM. DOI : <http://dx.doi.org/10.1145/1959826.1959843>
197. Kiyooki Takiguchi, Takayuki Wada, and Shigeki Toyama. 2007. Human Body Detection that Uses Electric Field by Walking. *Journal of Advanced Mechanical Design, Systems, and Manufacturing* 1, 3 (2007), 294–305. DOI : <http://dx.doi.org/10.1299/jamdsm.1.294>
198. Brandon T. Taylor and V Michael Bove. 2008. The bar of soap: a grasp recognition system implemented in a multi-functional handheld device. In *Proceeding of the twenty-sixth annual CHI conference extended abstracts on Human factors in computing systems - CHI '08*. ACM. DOI : <http://dx.doi.org/10.1145/1358628.1358874>
199. Brandon T. Taylor and V. Michael Bove. 2009. Graspables: grasp-recognition as a user interface. In *Proceedings of the 27th international conference on Human factors in computing systems - CHI 09*. ACM. DOI : <http://dx.doi.org/10.1145/1518701.1518842>
200. H. N. Teodorescu. 2013. Textile-, conductive paint-based wearable devices for physical activity monitoring. In *E-Health and Bioengineering Conference (EHB), 2013*. 1–4. DOI : <http://dx.doi.org/10.1109/EHB.2013.6707241>

201. Takahiro Tsujii, Naoya Koizumi, and Takeshi Naemura. 2014. Inkantatory paper: dynamically color-changing prints with multiple functional inks. In *Proceedings of the adjunct publication of the 27th annual ACM symposium on User interface software and technology - UIST'14 Adjunct*. ACM. DOI : <http://dx.doi.org/10.1145/2658779.2659103>
202. David Tumpold and Armin Satz. 2009. Contactless seat occupation detection system based on electric field sensing. In *2009 35th Annual Conference of IEEE Industrial Electronics*. IEEE. DOI : <http://dx.doi.org/10.1109/iecon.2009.5414836>
203. Tomas Unander, Hans-Erik Nilsson, and Bengt Oelmann. 2007. Printed touch sensor for interactive packaging and display. In *Polytronic 2007 - 6th International Conference on Polymers and Adhesives in Microelectronics and Photonics*. IEEE. DOI : <http://dx.doi.org/10.1109/polytr.2007.4339128>
204. Miika Valtonen, Lasse Kaila, Jaakko Mäentausta, and Jukka Vanhala. 2011. Unobtrusive Human Height and Posture Recognition with a Capacitive Sensor. *J. Ambient Intell. Smart Environ.* 3, 4 (Dec. 2011), 305–332. DOI : <http://dx.doi.org/10.3233/AIS-2011-0120>
205. Miika Valtonen, Jaakko Maentausta, and Jukka Vanhala. 2009. TileTrack: Capacitive human tracking using floor tiles. In *2009 IEEE International Conference on Pervasive Computing and Communications*. IEEE. DOI : <http://dx.doi.org/10.1109/percom.2009.4912749>
206. Miika Valtonen, Henrik Raula, and Jukka Vanhala. 2010. Human body tracking with electric field ranging. In *Proceedings of the 14th International Academic MindTrek Conference on Envisioning Future Media Environments - MindTrek '10*. ACM. DOI : <http://dx.doi.org/10.1145/1930488.1930527>
207. Miika Valtonen and Jukka Vanhala. 2009. Human tracking using electric fields. In *2009 IEEE International Conference on Pervasive Computing and Communications*. IEEE. DOI : <http://dx.doi.org/10.1109/percom.2009.4912795>
208. Katia Vega, Marcio Cunha, and Hugo Fuks. 2015. Hairware: The Conscious Use of Unconscious Auto-contact Behaviors. In *Proceedings of the 20th International Conference on Intelligent User Interfaces - IUI '15*. ACM. DOI : <http://dx.doi.org/10.1145/2678025.2701404>
209. Ansh Verma, Gabriel Culbertson, and Karthik Ramani. 2014. Chiron: interpreting signals from capacitive patterns and inertial sensors for intuitive shape modeling. In *Proceedings of the extended abstracts of the 32nd annual ACM conference on Human factors in computing systems - CHI EA '14*. ACM. DOI : <http://dx.doi.org/10.1145/2559206.2581161>
210. Nicolas Villar, Xiang Cao, Billy Chen, Shahram Izadi, Dan Rosenfeld, Hrvoje Benko, John Helmes, Jonathan Westhues, Steve Hodges, Eyal Ofek, and Alex Butler. 2009. Mouse 2.0: multi-touch meets the mouse. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology - UIST '09*. ACM. DOI : <http://dx.doi.org/10.1145/1622176.1622184>
211. Simon Voelker, Christian Cherek, Jan Thar, Thorsten Karrer, Christian Thoresen, Kjell Ivar Øvergård, and Jan Borchers. 2015. PERCs: Persistently Trackable Tangibles on Capacitive Multi-Touch Displays. In *UIST '15: Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology (UIST '15)*. ACM, New York, NY, USA, 351–356. DOI : <http://dx.doi.org/10.1145/2807442.2807466>
212. Simon Voelker, Kosuke Nakajima, Christian Thoresen, Yuichi Itoh, Kjell Ivar Øvergård, and Jan Borchers. 2013. PUCs: detecting transparent, passive untouched capacitive widgets on unmodified multi-touch displays. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces - ITS '13*. ACM. DOI : <http://dx.doi.org/10.1145/2512349.2512791>
213. J.M. Vranish and R.L. McConnell. 1992. Driven shielding capacitive proximity sensor. (Nov. 24 1992). US Patent 5,166,679.
214. Tam Vu, Akash Baid, Simon Gao, Marco Gruteser, Richard Howard, Janne Lindqvist, Predrag Spasojevic, and Jeffrey Walling. 2012. Distinguishing users with capacitive touch communication. In *Proceedings of the 18th annual international conference on Mobile computing and networking - Mobicom '12*. ACM. DOI : <http://dx.doi.org/10.1145/2348543.2348569>
215. Tam Vu and Marco Gruteser. 2013. Personal Touch-Identification Tokens. *IEEE Pervasive Comput.* 12, 2 (apr 2013), 10–13. DOI : <http://dx.doi.org/10.1109/mprv.2013.33>
216. Y. Wang, C. Yu, L. Du, J. Huang, and Y. Shi. 2014. BodyRC: Exploring Interaction Modalities Using Human Body as Lossy Signal Transmission Medium. In *Ubiquitous Intelligence and Computing (UTC-ATC-ScalCom)*. 260–267. DOI : <http://dx.doi.org/10.1109/UIC-ATC-ScalCom.2014.73>
217. Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. 2015. iSkin: Flexible, Stretchable and Visually Customizable On-Body Touch Sensors for Mobile Computing. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*. ACM. DOI : <http://dx.doi.org/10.1145/2702123.2702391>

218. Mathias Wilhelm, Daniel Krakowczyk, Frank Trollmann, and Sahin Albayrak. 2015. eRing: multiple finger gesture recognition with one ring using an electric field. In *Proceedings of the 2nd international Workshop on Sensor-based Activity Recognition and Interaction - WOAR '15*. ACM. DOI : <http://dx.doi.org/10.1145/2790044.2790047>
219. Andrew D. Wilson and Hrvoje Benko. 2010. Combining Multiple Depth Cameras and Projectors for Interactions on, Above and Between Surfaces. In *Proceedings of the 23rd Annual ACM Symposium on User Interface Software and Technology (UIST '10)*. ACM, 273–282. DOI : <http://dx.doi.org/10.1145/1866029.1866073>
220. Raphael Wimmer. 2011. *Capacitive Sensors for Whole Body Interaction*. Springer London, London, 121–133. DOI : [http://dx.doi.org/10.1007/978-0-85729-433-3\\_10](http://dx.doi.org/10.1007/978-0-85729-433-3_10)
221. Raphael Wimmer. 2015. *Grasp-sensitive surfaces: utilizing grasp information for human-computer interaction*. Ph.D. Dissertation. University of Munich. <https://edoc.ub.uni-muenchen.de/18095/>
222. Raphael Wimmer and Patrick Baudisch. 2011. Modular and Deformable Touch-sensitive Surfaces Based on Time Domain Reflectometry. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology (UIST '11)*. ACM, 517–526. DOI : <http://dx.doi.org/10.1145/2047196.2047264>
223. Raphael Wimmer and Sebastian Boring. 2009. HandSense: discriminating different ways of grasping and holding a tangible user interface. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction - TEI '09*. ACM. DOI : <http://dx.doi.org/10.1145/1517664.1517736>
224. Raphael Wimmer, Paul Holleis, Matthias Kranz, and Albrecht Schmidt. 2006. Thracker - Using Capacitive Sensing for Gesture Recognition. In *26th IEEE International Conference on Distributed Computing Systems Workshops (ICDCSW'06)*. IEEE. DOI : <http://dx.doi.org/10.1109/icdcs.2006.109>
225. Raphael Wimmer, Matthias Kranz, Sebastian Boring, and Albrecht Schmidt. 2007a. A Capacitive Sensing Toolkit for Pervasive Activity Detection and Recognition. In *Fifth Annual IEEE International Conference on Pervasive Computing and Communications (PerCom'07)*. IEEE. DOI : <http://dx.doi.org/10.1109/percom.2007.1>
226. Raphael Wimmer, Matthias Kranz, Sebastian Boring, and Albrecht Schmidt. 2007b. CapTable and CapShelf - Unobtrusive Activity Recognition Using Networked Capacitive Sensors. In *2007 Fourth International Conference on Networked Sensing Systems*. IEEE. DOI : <http://dx.doi.org/10.1109/inss.2007.4297395>
227. Yu Xie, Yinlin Li, Zhonghua Huang, and Zhanzhong Cui. 2009. Preliminary study of rain effect on channel gain of body area communication. In *2009 Joint Conferences on Pervasive Computing (JCPC)*. IEEE. DOI : <http://dx.doi.org/10.1109/jcpc.2009.5420102>
228. Ruoyu Xu, Wai Chiu Ng, Hongjie Zhu, Hengying Shan, and Jie Yuan. 2012. Equation Environment Coupling and Interference on the Electric-Field Intrabody Communication Channel. *IEEE Transactions on Biomedical Engineering* 59, 7 (jul 2012), 2051–2059. DOI : <http://dx.doi.org/10.1109/tbme.2012.2197212>
229. Dongwook Yoon, Ken Hinckley, Hrvoje Benko, François Guimbretière, Pourang Irani, Michel Pahun, and Marcel Gavrilu. 2015. Sensing Tablet Grasp + Micro-mobility for Active Reading. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology - UIST '15*. ACM. DOI : <http://dx.doi.org/10.1145/2807442.2807510>
230. Neng-Hao Yu, Li-Wei Chan, Lung-Pan Cheng, Mike Y. Chen, and Yi-Ping Hung. 2010. Enabling tangible interaction on capacitive touch panels. In *Adjunct proceedings of the 23rd annual ACM symposium on User interface software and technology - UIST '10*. ACM. DOI : <http://dx.doi.org/10.1145/1866218.1866269>
231. Yang Zhang, Junhan Zhou, Gierad Laput, and Chris Harrison. 2016. SkinTrack: Using the Body As an Electrical Waveguide for Continuous Finger Tracking on the Skin. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, 1491–1503. DOI : <http://dx.doi.org/10.1145/2858036.2858082>
232. Enhao Zheng, Baojun Chen, Qining Wang, Kunlin Wei, and Long Wang. 2012. A wearable capacitive sensing system with phase-dependent classifier for locomotion mode recognition. In *2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechanics (BioRob)*. IEEE. DOI : <http://dx.doi.org/10.1109/biorob.2012.6290721>
233. W. Zheng and Z. Cui. 2011. Determination of velocity and direction of human body motion based on electrostatic measurement. In *Consumer Electronics, Communications and Networks (CECNet), 2011 International Conference on*. 4035–4039. DOI : <http://dx.doi.org/10.1109/CECNET.2011.5769004>
234. Junhan Zhou, Yang Zhang, Gierad Laput, and Chris Harrison. 2016. AuraSense: Enabling Expressive Around-Smartwatch Interactions with Electric Field Sensing. In *Proceedings of the 29th Annual ACM Symposium on User Interface Software & Technology (UIST '16)*. ACM. DOI : <http://dx.doi.org/10.1145/2984511.2984568>

235. Thomas G. Zimmerman. 1996. Personal Area Networks: Near-field intrabody communication. *IBM Syst. J.* 35, 3.4 (1996), 609–617. DOI: <http://dx.doi.org/10.1147/sj.353.0609>
236. Thomas G. Zimmerman, Joshua R. Smith, Joseph A. Paradiso, David Allport, and Neil Gershenfeld. 1995.

Applying Electric Field Sensing to Human-computer Interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '95)*. ACM Press/Addison-Wesley Publishing Co., 280–287. DOI: <http://dx.doi.org/10.1145/223904.223940>