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

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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

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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 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.

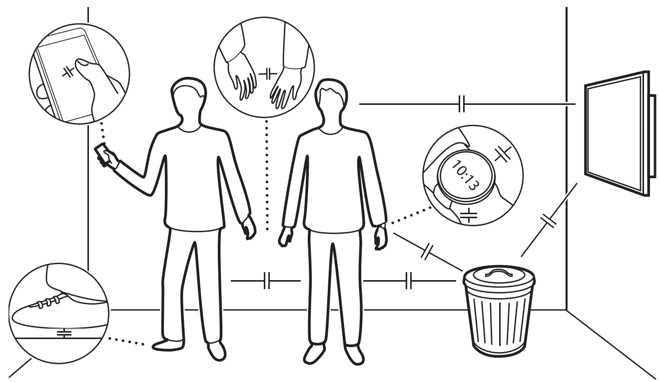

Figure 1. Capacitance (⊣⊢) naturally exists between people, their devices, and conductive objects in the environment. By measuring it, capacitive sensors can infer the position and proximity of users and other objects, supporting a range of different applications. However, this inherent capacitive coupling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

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*

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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 the *Theremin*, consisting of two capactively 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

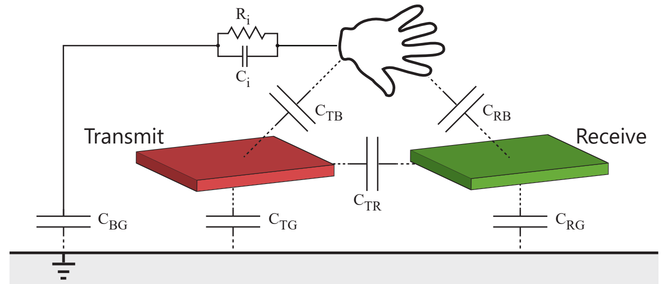

Figure 2. Lumped circuit model of capacitive sensing as introduced by Smith *et al.* [186]. Depending on the sensing mode, different capacitances are controlled or measured.

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 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].

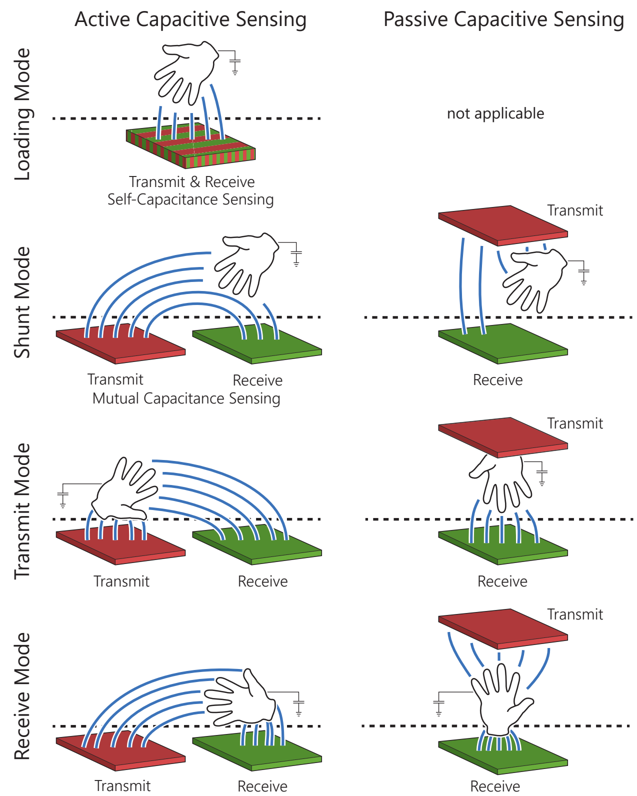

Figure 3. Capacitive sensing techniques can be divided into four operating modes: loading, shunt, transmit and receive. Except for loading mode, each mode may be implemented using active or passive sensing. The dashed line represents the boundary between the sensing system (bottom) and the environment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

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× touch, 29× <50 cm, 12× 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. Interestingly, 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.

Mode	Active Capacitive Sensing	Passive Capacitive Sensing
Loading mode	Augmenting clothes & fabric [8, 43, 76, 152, 158, 159, 185]	Not applicable
	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 (intrabdoy 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]

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.

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 DiamondTouch [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].

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] deliver 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 it 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 operate 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,

Copper - highly conductive, flexible	**Silver** - 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]+	**Carbon** - 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]	**ITO** - transparent electrodes [64, 119, 199]
→Ink [59, 57, 58]	**Anisotropic materials** - directing e-fields
→Paint [18]	→Anisotropic 'Zebra' tape [91]
→Metalization [208]	→Anisotropic 'Zebra' rubber [24]
Gold - non-corrosive, skin-friendly	**Other materials**
→Gold leaf [98]	→Water [41, 173] & Plants [153]
→Gold coating [11]	→Ionized gas [72]
Aluminum - 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
3D gesture controllers:	**Touch and proximity sensors:**
→MGC3130 [119]	→555 timer [19, 225, 64, 224]
Electric-field receiving amplifiers:	→AD7142 [92]
→MCP6041 [36]	→AD7147 [138, 73]
→OPA2322 [68]	→Arduino + CapTouch [201, 105, 175, 208]+
→OPA2350 [64]	→AT42QT1070 [118]
Electric-field sensors:	→CY8C2x [27, 59]
→Plessey PS25451 [67]	→Microcontroller [12, 29, 162]
Capacitance-to-digital converters:	→MPR121 [33, 43, 91, 139, 177]+
→AD7746 [96, 206]	→QT110x [92, 13, 175]
→AD7747 [76]	**Touch matrix sensors:**
Touch matrix sensors:	→MTCH6102 [103, 152]
→QT60248 [198, 199]	**Shield driver:**
→CY8CTMA463 [88, 229]	→THS4281 [64]
Development kits:	**Development kits:**
→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 considered. 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 innovately capacitive sensing or may in the future.

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