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

Tobias Grosse-Puppendahl, Christian Holz, Gabe Cohn, Raphael Wimmer, Oskar Bechtold, Steve Hodges, Matthew S. Reynolds, Joshua R. Smith
Frank Beck and Bent Stumpe: Two devices for operator interaction in the central control of the new CERN accelerator
captive sensor  capacitive sensing    mutual capacitance sensing    Capacitively coupled body communication capacitive touch sensor capacitive touch sensing Electric Potential Sensing PowerLine positioning Loading mode electric field sensing Capacitive Proximity Sensing Electrostatic Induction Electric Field Imaging n/a Measurement of Electric Field bioimpedance Passive Sensing of Changes in Body Electric Potential capacitive multi-touch sensing electro-magnetic sensing Ambient electric field sensing TouchNet Intrabody Communication Intrabody communications Mutual-Capacitance sensing AC hum detection combined inductive-conductive proximity sensing carrier-frequency method near field imaging Body-coupled communications capacitive coupling capacitance proximity sensing body area communication touch-identification tokens Self-Capacitance capacitive sensor arrays capacitance measuring compressive sensing on capacitive touch screens active capacitive sensing capacitive positioning capacitance sensor intra-body communication human body communication capacitive finger sensing 2.5D capacitive touch sensor capacitive sensor array capacitive multitouch sensor electric field ranging projected capacitance capacitive touch panel Electrostatic Potential sensing capacitive touch communication time-multiplexed loading mode capacitive sensing Swept Frequency Capacitive Sensing Capacitive widgets indirect capacitive sensing using electromagnetic interference single capacitive touch sensor capacitive touch-sensing EM sensing capacitive coupling low-frequency signals electromagnetic noise sensing electromagnetic interference capacitance interactions capacitive charging time passive measurement of static electric field of the environment capacitive and resistive touch sensing static electric field sensing capacitive position measurements signal potential level Swept Frequency Capacitive Sensing Capacitive Near-Field Communication
electric field sensing
Proposed Taxonomy

Shunt Mode
- Active: Transmit Mutual Capacitance Sensing
- Passive: Receive

Transmit Mode
- Active: Transmit
- Passive: Receive

Receive Mode
- Active: Transmit
- Passive: Receive

Loading Mode
- Active: Transmit & Receive Self-Capacitance Sensing
- Passive: Not applicable
Proposed Taxonomy

Shunt Mode
- Transmit
- Receive Mutual Capacitance Sensing

Transmit Mode
- Transmit
- Receive

Receive Mode
- Transmit
- Receive

Loading Mode
- Transmit & Receive Self-Capacitance Sensing

Active
- Transmit
- Receive

Passive
- Transmit
- Receive

Not applicable
Proposed Taxonomy

Active
- **Shunt Mode**
  - Transmit Mutual Capacitance Sensing
  - Receive
- **Transmit Mode**
  - Transmit
  - Receive
- **Receive Mode**
  - Transmit
  - Receive
- **Loading Mode**
  - Transmit & Receive Self-Capacitance Sensing

Passive
- **Shunt Mode**
  - Transmit
  - Receive
- **Transmit Mode**
  - Transmit
  - Receive
- **Receive Mode**
  - Transmit
  - Receive
- **Loading Mode**
  - Not applicable
22 papers present toolkits for capacitive sensing, of them are open-source [64, 175, 225].

As mentioned before, a multitude of terms has been applied to different types of capacitive sensing; however, the existing nomenclature shows significantly less variance. While many papers do not explicitly mention the sensing principle, most papers use the generic term “capacitive sensing,” whereas some use the term “electric field sensing.” Besides, a long but thin tail of alternative terms exist, such as “contact potential level,” “projected capacitance,” “electric induction,” and “human body electric potential.”

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

<table>
<thead>
<tr>
<th>Loading mode</th>
<th>Gesture recognition</th>
<th>Shunt mode</th>
<th>Indoor localization &amp; whole-body movements</th>
<th>Prototyping user interfaces</th>
<th>Ubiquitous touch interfaces</th>
<th>Shape sensing</th>
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</thead>
<tbody>
<tr>
<td>Indoor localization &amp; whole-body movements</td>
<td>[3, 15, 42, 69, 75, 112, 124, 220]</td>
<td>Prototyping user interfaces</td>
<td>[20, 91, 108, 120, 125, 140, 149, 150, 184, 177, 201, 203]</td>
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<tr>
<td>Ubiquitous touch interfaces</td>
<td>[12, 18, 19, 62, 127, 112, 129, 135, 173, 208, 226]</td>
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<tr>
<th>Transmit mode</th>
<th>Transmit + receive mode (intrabody coupling)</th>
<th>Receive mode</th>
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</thead>
<tbody>
<tr>
<td>Indoor localization</td>
<td>[111, 205, 204]</td>
<td>Touch and gesture recognition</td>
</tr>
<tr>
<td>Whole-body movements</td>
<td>[207]</td>
<td>User distinction</td>
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<tr>
<td>User distinction</td>
<td>[150]</td>
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**Goal**

The ubiquitous form of capacitive sensing is the touchscreen interface and the touchscreen [9], which emerged in prototypes in the 1970s [11]. Through the 1980s, the academic community made significant advancements by developing new interfaces and hardware to enable multi-touch screens [121]. Subsequent developments, including SmartSkin [161] and DiamondSkin, have highlighted the interaction potential of this technology. More information on the large space of touch sensing can be found in surveys by Buxton et al. [86] and Dey et al. [117].
1. Crawling > 5900 Papers indexed by IEEE and ACM
2. Review of each paper: Does it match our criteria?
3. Tagging of 193 relevant papers by > 2 authors

2. Review of each paper: Does it match our criteria?
# Papers

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Contains

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Start date
- Year
- Month
End date
- Year
- Month

**BibTeX**
- Any

**Items per page**
10

**Operations**
- Choose an operation

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<th>Keywords</th>
<th>Pdfuri</th>
<th>Trash</th>
<th>Status</th>
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<th>assigned</th>
<th>Final Paper Voting</th>
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<tr>
<td>Single User Multouch on the</td>
<td>Berard, Francois; Laurinlia, Yann</td>
<td>Thursday, January 1, 2005</td>
<td>DiamondTouch, expectation maximization.</td>
<td>Pdfuri</td>
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<td>* Trash phase finished</td>
<td>admin</td>
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</tbody>
</table>
Type of Contribution (193 Papers)

- Novel Applications of Capacitive Sensing: 120
- Hardware Contribution: 100
- Quantitative Study: 40
- Algorithm: 40
- Model of Electrical Properties: 20
- Toolkits for Capacitive Sensing: 20
- Simulation Results: 10

Read our paper: aka.ms/capsense
A New Taxonomy

Research Challenges
A Taxonomy for Capacitive Sensing

Shunt Mode

Active Capacitive Sensing

Transmit Mutual Capacitance Sensing

Receive

A Taxonomy for Capacitive Sensing


Jun Rekimoto: SmartSkin: An Infrastructure for Freehand Manipulation on Interactive Surfaces. CHI ’02.


Jun Rekimoto: SmartSkin: An Infrastructure for Freehand Manipulation on Interactive Surfaces. CHI ’02.


A Taxonomy for Capacitive Sensing

Shunt Mode

Transmit Mutual Capacitance Sensing

Transmit Mode

Receive

Receive Mode

Transmit

Receive
A Taxonomy for Capacitive Sensing

A Taxonomy for Capacitive Sensing

- **Shunt Mode**
- **Transmit Mode**
- **Receive Mode**
- **Loading Mode**

*Active*
- Transmit Mutual Capacitance Sensing
- Transmit
- Transmit
- Transmit & Receive Self-Capacitance Sensing
A Taxonomy for Capacitive Sensing


A Taxonomy for Capacitive Sensing

- **Shunt Mode**: Transmit Mutual Capacitance Sensing, Receive
- **Transmit Mode**: Transmit, Receive
- **Receive Mode**: Transmit, Receive
- **Loading Mode**: Transmit & Receive Self-Capacitance Sensing
A Taxonomy for Capacitive Sensing

A Taxonomy for Capacitive Sensing

Active

Shunt Mode
- Transmit Mutual Capacitance Sensing
- Receive

Transmit Mode
- Transmit
- Receive

Receive Mode
- Transmit
- Receive

Loading Mode
- Transmit & Receive Self-Capacitance Sensing
- Receive

Passive

- Transmit
- Receive
- Receive
A Taxonomy for Capacitive Sensing

Rekimoto et al.: Sensing GamePad: electrostatic potential sensing for enhancing entertainment oriented interactions. CHI ’04
A Taxonomy for Capacitive Sensing
A Taxonomy for Capacitive Sensing

A Taxonomy for Capacitive Sensing

Shunt Mode
- Transmit Mutual Capacitance Sensing
- Receive

 Transmit Mode
- Transmit
- Receive

Receive Mode
- Transmit
- Receive

Loading Mode
- Transmit & Receive Self-Capacitance Sensing

Active

Passive
- Receive

Read our paper: aka.ms/capsense
A New Taxonomy

Research Challenges
Research Challenge #1: Sensitivity to Grounding
Research Challenge #1: Sensitivity to Grounding

How can we bring these powerful interactions to devices that only have floating references for practical applications?
Research Challenge #1: Sensitivity to Grounding

Masaaki Fukumoto and Mitsuru Shinagawa.
CarpetLAN: A Novel Indoor Wireless(-like) Networking and Positioning System. Ubicomp ’05

Electro-optic crystals:

Ultra-high input impedance sensors:

Research Challenge #2: Support for End-to-End Prototyping

**Cutting**

Valkyrie Savage et al.: Midas: fabricating custom capacitive touch sensors to prototype interactive objects. UIST ’12.

**Ink-based Printing**

Nan-Wei Gong et al.: PrintSense: a versatile sensing technique to support multimodal flexible surface interaction. CHI ’14.

**3D Printing**

Martin Schmitz et al.: Capricate: A Fabrication Pipeline to Design and 3D Print Capacitive Touch Sensors for Interactive Objects. UIST ’15
Research Challenge #2: Support for End-to-End Prototyping

We are making great advances with prototyping electrodes.... But real end-to-end systems are still hard to prototype.

Valkyrie Savage et al.: Midas: fabricating custom capacitive touch sensors to prototype interactive objects. UIST '12.

Nan-Wei Gong et al.: PrintSense: a versatile sensing technique to support multimodal flexible surface interaction. CHI ’14.

Martin Schmitz et al.: Capricate: A Fabrication Pipeline to Design and 3D Print Capacitive Touch Sensors for Interactive Objects. UIST ’15
Research Challenge #2: Support for End-to-End Prototyping

Research Challenge #2: Support for End-to-End Prototyping

Super small and thin prototyping electronics for capacitive sensing are needed.

Research Challenge #2: Support for End-to-End Prototyping

1. Reduce the size of prototyping electronics


2. Reduce the size of the battery by using hybrid active / passive capacitive sensing

Nan-Wei Gong, Steve Hodges, and Joseph A. Paradiso. Leveraging conductive inkjet technology to build a scalable and versatile surface for ubiquitous sensing. UbiComp ’11.
Research Challenge #3: Enabling Flexible and Stretchable Applications


Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. iSkin: Flexible, Stretchable and Visually Customizable On-Body Touch Sensors for Mobile Computing.
Research Challenge #3: Enabling Flexible and Stretchable Applications

How can we make touch and gesture recognition robust?


Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. iSkin: Flexible, Stretchable and Visually Customizable On-Body Touch Sensors for Mobile Computing.
Research Challenge #4: Enriching Sensing with Communications

**Passive Tags**


**Active Tags**

Research Challenge #4: Enriching Sensing with Communications

Passive Tags


Higher spatial and temporal resolution touch-screens would make a difference.

Active Tags

Research Challenge #4: Enriching Sensing with Communications

Receive


Transmit


(a) Authenticating door locks  (b) Secret keys for wearables
Research Challenge #4: Enriching Sensing with Communications

Commercially available touchscreens impose limits on communication mechanisms

(a) Authenticating door locks
(b) Secret keys for wearables


Research Challenges: Touch Screen Research @ CHI

Jun Rekimoto. SmartSkin: an infrastructure for freehand manipulation on interactive surfaces. CHI ’02.

Darren Leigh, Clifton Forlines, Ricardo Jota, Steven Sanders, and Daniel Wigdor. High Rate, Low-latency Multi-touch Sensing with Simultaneous Orthogonal Multiplexing. UIST ‘14
Reviving touch screen research can enable great new tangible and wearable experiences.

Jun Rekimoto. SmartSkin: an infrastructure for freehand manipulation on interactive surfaces. CHI ’02.

Darren Leigh, Clifton Forlines, Ricardo Jota, Steven Sanders, and Daniel Wigdor. High Rate, Low-latency Multi-touch Sensing with Simultaneous Orthogonal Multiplexing. UIST ‘14
Conclusion

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<td>Receive</td>
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<td>Not applicable</td>
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Read our paper: aka.ms/capsense
Capacitance is Everywhere!
Research Challenges

- Towards Better Reproducibility
- Sensitivity to Grounding
- Implications for Real-World Deployments
- Support for End-to-End Prototyping
- Reducing Form Factor & Instrumentation
- Enabling Flexible and Stretchable Applications
- Unifying Approaches to Interpret Electric Fields
- Enriching Sensing with Communications