Hand as Sensor: Virtualizing Interactions with Everyday Object Affordances using Wrist-worn Hand Pose Sensing

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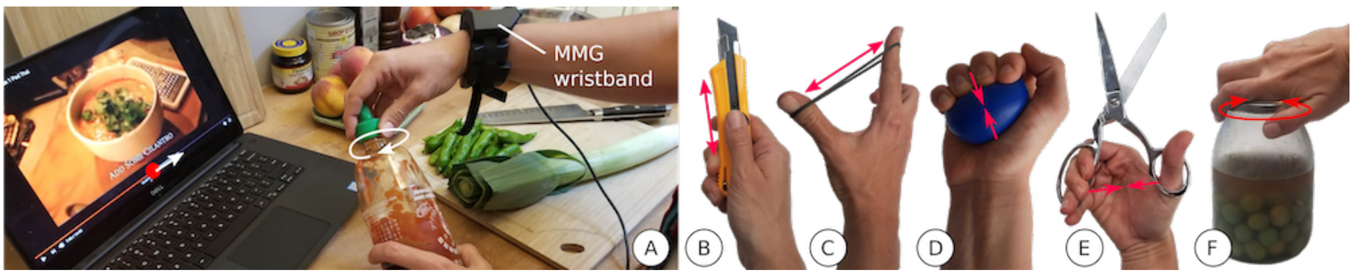

Figure 1: Ubiquitous Controls lets users leverage affordances of everyday objects as input components, for example twiddling a sauce bottle lid to control the seek position of a video while cooking (A). Our method utilizes a capacitive mechanomyography wristband to digitize single-handed prehensile interactions like sliding (B), stretching (C), squeezing (D), tripod pinching (E), and rocking (F).

ABSTRACT

We are a group of HCI researchers from a capacitive technology company, and we have been collaborating on hardware to enable sensing the posture and anatomy of hands for use in mixed reality. Through this process, we have been exploring the motion and activity of hands; after discovering that our sensor is sensitive not only to dynamic hand pose but also to tendon load (such as is caused by holding or pressing on an object), we began exploring the idea of using passive held or touched objects as support for gestural input. Specifically, we are interested less in the *passive haptics* of existing objects, and more in their *interactive affordances*.

This paper presents Ubiquitous Controls: a work-in-progress input technique measuring interactions between users' hands and objects' affordances powered by a wristband, which senses muscle pose and motion using capacitive-based mechanomyography (MMG). We use this technology to train machine learning models that map continuous object interactions—like "twisting a bottle cap" or "cutting with scissors"—to controls like dials or sliders.

Across 10 participants, our models discriminated between 6 object interactions and identified the correct range state with mean accuracies of 85.5–98.5 %. Furthermore, 8 users interactively controlled UI widgets using objects and valued their haptic feedback and enhanced state reproducibility over freehand gestures.

We also discuss some opportunities and discovered pitfalls of leveraging interactive affordances of everyday objects.

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CCS CONCEPTS

• **Human-centered computing → Interaction techniques**; **Ubiquitous and mobile computing systems and tools**; **Mixed / augmented reality**; **Interaction devices**.

KEYWORDS

affordances; mechanomyography; capacitive sensing; wristband

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1 INTRODUCTION

Weiser's vision of ubiquitous computing [34] has computers fade into the background of everyday life. The written word is a classic example of a ubiquitous technology; books, newspapers, signs, and many other objects are covered in text, offering information "at a glance" without disrupting our attention. However, implementing a high technology ubiquitous scenario is rife with challenges. Augmenting objects [16, 39] and surfaces [3, 35, 36] in our environment requires infrastructure and maintenance (e.g., [40]). Similarly, imbuing an everyday object with interactive potential often impacts its form, design, and relationship with a user. The wires, sensors, batteries, and PCBs that enable interaction place technology at the forefront of a user's attention. Although tablet computers and paper books can display the same literature, their user experiences are different [30] and reflect how well their underlying technologies have matured and faded into the periphery.

To approach the challenges of implementing ubiquitous interactions at scale, we propose decoupling technology from devices and focusing on ubiquitous sensing. Instead of instrumenting each water bottle or elastic band with touch or deformation sensors, we argue for understanding the dynamic interaction between a user's hand and a passive, everyday object. Sensing a hand's grasp and movement relative to an object means that a user can appropriate its mechanical affordances as input. This allows leveraging devices at hand for computational purposes—such as stretching a rubber band to zoom a map or twisting a bottle cap to adjust volume level.

To sense a user's manipulation of a broad set of objects, we use a capacitive mechanomyography (MMG) wristband (see Figure 1). This band senses small skin surface movements on the posterior forearm caused by muscle and tendon activity near the wrist. With machine learning, we can model these skin surface changes and map them to hand and arm movement, allowing us to determine when and how a user is grasping and manipulating an object. It also enables ad hoc ubiquitous input controls by shifting sensing to the wrist, instead of instrumenting individual objects with sensors.

2 RELATED WORK

We briefly discuss existing work in ubiquitous and tangible computing, as well as in wrist-worn sensing.

2.1 Interaction Paradigms

Ubiquitous computing [34] proposes a rich set of interaction paradigms suggesting we leveraging the affordances [10] of physical devices in UI design [31] and looking at everyday objects opportunistically as input devices [15]. Similar to Instant Controls (ICon) [6], Instant User Interfaces [7], and Ephemeral Interactions [33], our work appropriates a wide range of everyday objects for interaction, but we avoid the need to physically augment the objects or environment.

Pioneering work on graspable interfaces demonstrated repurposing and augmenting physical objects as tangible user interfaces (TUIs) [9, 17]. We build on these ideas and Ishii and Ullmer's vision removing the distinction between passive and interactive devices [20]; however, computation in every material is still a technical challenge in spite of proposed kits based on modular input/output [11] or reuse of existing objects [2]. Thus, for the time being, other solutions must be explored. BOXES proposes constructing physical interfaces with readily-accessible materials [19]. With the introduction of 3D printing, printing new devices can be just as easy. Savage, et al., propose printing passive shapes and augmenting them with capacitive sensors, cameras, or microphones [26, 28, 29], and Pineal uses embedded mobile devices to bring printed objects to life [23]. These are indeed a step in the right direction, but still require planning, materials, and time. Our vision calls for a user's hand to be a ubiquitous sensor for any object which is printed, assembled, or just picked up.

TUIs like URP [32] and Illuminating Clay [24] have explored projection on surfaces to make both virtual content and UIs more physical. Holman, et al.'s concept of organic user interfaces pushes projection augmentation further, making the UI conform to object shapes [18]. Using simple surfaces for interaction means designers can create proxy objects from low cost materials such as styrofoam or cardboard and transform them into UIs with a given shape, as in DisplayObjects [1], and these kinds of augmentations can be applied to multiple surfaces—at the cost of multiple cameras and projectors [35, 36]—or to bodies, including in mobile scenarios [13]. Annexing Reality [16] and Gripmarks [39] are closer to our approach. Annexing Reality re-targets proxy shapes in the environment for haptic feedback in VR, and Gripmarks focuses on graspable objects. While these approaches appropriate surfaces for interaction and focus on shape affordance, our approach leverages different objects' mechanical affordances to enable ubiquitous inputs.

2.2 Wrist-worn sensing for input

Smartwatches can monitor user activity using electromagnetic signals [22], EMG [8], or a mic and IMU [21]. This allows systems to display contextual information but offers limited dynamic control of interaction. Our work requires more minute activity monitoring to precisely map gestures and poses to virtual controls. Several wearable systems detect on-skin finger touches to interact with 2D UIs or perform simple gestures [14, 37, 38]. While we also target a wristband form factor, our approach leverages mechanomyography [12] to measure motions and hand activity.

3 PROTOTYPE IMPLEMENTATION

Our Ubiquitous Controls prototype system encompasses both hardware and software: we use a capacitive-based MMG wristband and train machine learning classification and regression. In the following section, we provide an interaction scenario and a system overview.

3.1 Using Ubiquitous Controls

A user following a cooking tutorial video has missed a step. They use a soy sauce bottle, which they happen to have at hand, as an input device, rather than washing their hands to interact directly with their computer (see Figure 2). They start by collecting samples of their hand twisting the cap to various extremes (i.e., far left, far right, centre): this data collection takes approximately 1 minute, is only required once per object, and can be done ahead of time. The samples of MMG and IMU data are sent to a classification optimizer, which compares several machine learning configurations to select two models. One separates "twiddling a bottle cap" from other recorded controls, like "squeezing a toy" or "sliding a hair dryer selector." The second regresses the position of the bottle cap interaction based on the three recorded states.

After model training and selection, the system awaits an interaction-triggering gesture by analyzing live IMU information. Once detected, MMG and IMU data are sent to the first classifier to classify the interaction. Data then goes to the interaction-specific model which regresses the range position. Finally, output is sent to the appropriate application: in this case, it adjusts the video playback location.

Figure 2: The Ubiquitous Controls system: a user wearing our custom wristband first generates offline training data by recording the middle and extremes of an interaction. A script extracts features, trains several models, and selects and saves the best one. In online use, we look for a "double flip" activation gesture, then send data to saved models. We classify interaction type, then regress range position and smooth output. Finally, data is sent to an application.

Figure 3: The object interactions tested in Study 1 with their heatmap signatures. Images from Study 2.

3.2 Hardware: Mechanomyography Wristband

Our MMG wristband sensor uses the basic theory of parallel plate capacitors: capacitance $\mathbb{C} \propto \mathbb{A}$ surface area of the conductor plates and $\mathbb{C} \propto \frac{1}{d}$ the distance between the plates. We measure skin surface change by treating the skin as a plate in this model. Movement at the skin surface causes a change in d (and thus $\mathbb{C}$). A high-frequency electrical signal "infused" on the skin by a soft pad covered in conductive fabric on the anterior wrist is received by a matrix of printed, flexible electrodes statically positioned above the posterior wrist. Anatomical motion beneath the skin surface modulates d, and generates a change in $\mathbb{C}$ localized to matrix sensors above that anatomy. Our prototype outputs a 2-dimensional "heatmap" of these spatial capacitive magnitude signals (see Figure 2, far left), along with IMU signals.

3.3 Software

We used a proprietary data collection software that prompts users to perform pre-defined states within the range of a gesture (see Figure 2, far left). Timestamped MMG-heatmap and IMU data is written to a csv file upon completion of a recording. For both the high-level interaction discrimination and the regression of the range-state we train ML models on the raw MMG-heatmap and IMU data alongside statistical features such as z-score and mean. We use a linear discriminant analysis (LDA) classifier to discriminate between interaction types and train linear regression models to interpolate values for continuous range interaction in live scenarios. Trained models are n-fold cross-validated, per user. In live mode, we detect a "double-flip" activation gesture [25] using the IMU gyro magnitude. Then, we determine what interaction a user is performing (e.g., palmar slide vs twiddle) using features from single heatmap/IMU frames (see Figure 3 for heatmap signatures of different interactions). Finally, we regress range position within the interaction, smooth using an empirically-tuned 1-Euro Filter [5] and send extracted interactions to an application.

4 EVALUATION

We performed two user studies. Study 1 was a data collection with 10 participants and an offline analysis to establish the feasibility and parameters of our approach. Study 2 assessed the usability of our system in a real-time scenario with 8 users who were tasked to interactively match prompts on a virtual slider, a knob widget, and a zoomable canvas using Ubiquitous Controls and freehand gestures. Participants were given complete freedom of choice for gestures and objects in Study 2 to apply to a more ubiquitous environment.

In Study 1, our classifiers robustly distinguished 6 targeted interaction types (see Figure 3), with a mean accuracy of 99.4 % per user. To evaluate range state prediction accuracy we compared the mean accuracies of 6 classification model structures for 3–5 state ranges (LDA, classification and regression trees (CART), logistic regression, naïve bayes classifiers, and linear support vector classification (SVC)). For all 6 interactions, the mean accuracies within 3-states were between 89.7–98.5 % using the model with the highest accuracy for each user/interaction combination.

In Study 2, most users could successfully control all widgets using both objects and freehand gestures. There were no significant differences between Ubiquitous Controls and freehand gestures in terms of input time, number of matched prompts, model fit, or interaction type discrimination accuracy. Three users preferred Ubiquitous Controls, three preferred freehand gestures, and two declared that it depends upon the situation.

Many users highlighted state reproducibility and haptic feedback, saying the "force made it easier to control" (P7) pinching with a rubber band versus freehand, or that feedback from a screw-top lid "lets you know where you are on the thing" (P4). Four of eight observed unique freehand gestures were "mimes" of object-supported gestures, whether they came before or after the object-supported condition in the study ordering. One user explained the "mime" version was easier, because they could put their hand in any position and not worry about where the object would go (P5), or because they had a motion in mind but didn't know an object with the right affordances (P3).

Many users explicitly mapped an object interaction or gesture to a widget's visual appearance or existing use in the wild. Users mentioned "if it's a video player, I'd like it to be linear" (P4), or

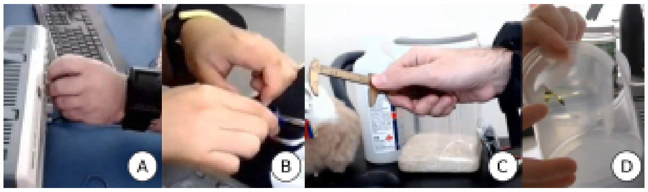

Figure 4: Users in Study 2 had various interesting strategies to interact. One used an unpowered oscilloscope (A). Another used both hands to precision-set a combination lock (B). Another precision input was a non-digital pair of brass calipers (C). One user's "squeeze" object, a thin plastic cup, broke through use as an input (D).

"I've turned the knob of a stereo, so I know that a bottlecap is more consistent with the experience [than a linear control]" (P3).

Our system's treatment of object-supported interactions did always not map well to users' understanding of how inputs work. For example, P1 used a twistable knob on an unpowered oscilloscope on their desk as an input: during training, they twisted it using mainly their wrist, while during testing they used mainly their fingers. In normal use of the oscilloscope, these methods would behave identically: however in our system they do not. We map an affordance to a range, and even a single object component may have multiple affordances (see Figure 4A).

On using objects as inputs, one user suggested they would carry a "collection of... favourite objects that were comfortable to use," or a multifunction input object (e.g., fidget cube) designed for this type of interaction (P6). Conversely, another mentioned that any object they have has to be "worthy of carrying with me," suggesting that an object only for input would not be worth the space in their bag or pockets (P2).

In the end, it seems both object-supported and freehand gestures have a role in pervasive interaction. If users are on the move, it might make more sense to leverage freehand gestures. We would like to explore this further in future work.

5 DISCUSSION

We envision that giving computational meaning to familiar, unaugmented objects will help interactive systems vanish into the fabric of reality. Ubiquitous Controls brings that reality one step closer, but it is not without a variety of yet-unanswered challenges and opportunities. Below, we summarize challenges encountered and opportunities discovered during our implementation of Ubiquitous Controls.

Discrete Events Continuous, range-based inputs are not the only type used in modern systems [4]: they must work in concert with discrete "events" like selecting a file or stopping an audio track. We consider events to be a special case of sequential, time-bounded range inputs, as users perform a sequence of continuous actions within a specific period of time. While we already use the "double flip" event to activate and deactivate range recognition, further work such as null set collection and dynamic time warping is needed to thoughtfully trigger general-purpose events.

Midas Touch As computation becomes distributed and everyday objects serve both analog and digital functions, we encounter the so-called "Midas Touch" problem, in which a computer must distinguish between a *functional interaction* and an *intentional input* with an object [7]. The ideal solution does not require a specific gesture to initiate recognition: this solution, however, is very dependent upon the available cues.

Dynamic and Configurable Mapping The distributed nature of input and output will also introduce challenges of *mapping*, in which paradigms for end user programming will need to be introduced to allow for tying a specific input to a specific output. All of our tested interactions included explicitly-coded mappings, in which the minimum value of a physical range is permanently connected to the minimum value of a digital range, and interactions are 1:1. More subtlety may be desirable: the abilities to map subranges, to dynamically map physical and digital inputs, or to choose a different gesture according to the situation (working out vs. lying in bed) each contribute to a personal mapping experience where the interface bends to meet the user's intentions.

Meaningful, pervasive mapping techniques coupled with Ubiquitous Controls may also allow more hygienic, personal interactions with public displays: one's own items can be leveraged in lieu of a public touchscreen.

Device Reuse An interesting corollary of re-purposing existing object affordances is reprogramming existing *input devices* for new use cases. After all, a disconnected game controller is akin to a high-quality fidget cube: both are primed with interesting physical mappings. A user could map the brightness of their living room lights to the roll of a mouse wheel, adjust which cooktop burner is active by thumbing a joystick, or just reuse a favourite PS/2 peripheral with a new machine without needing an adapter. For accessibility reasons, allowing a user to reuse an object or input device they are familiar with for new and arbitrary interactions is a boon.

Assemblage Relocating a component's sensing from the device to the user also enables a new way to prototype input devices: assemblage of existing affordances held together by clay or tape is easy to reconfigure and immediately test, similar to the concept of Makers' Marks [27].

6 CONCLUSION

We presented Ubiquitous Controls, a prototype system for capturing and classifying interactions with the mechanical affordances of everyday objects. We described the hardware and software components of this system, and its evaluation with users through a data collection and a study. We anticipate that measuring the dynamic interactions between hands and everyday objects will provide a powerful framework for ubiquitous computing, and hope that our work has opened fruitful opportunities and questions in this space.

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