A Proposal for a Taxonomy to Survey the State-of-the-Art of Multi-Device Technologies

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Abstract

Keeping track and gaining an overview of multi-device technologies is an increasingly complex task and judging their quality is challenging. For example, it requires additional effort to gather often scattered information from various sources. This position paper proposes a taxonomy to survey state-of-the-art of multi-device technologies. It contributes nine dimensions that allow to categorize and compare technologies by their individual strengths and weaknesses. It further seeks to start an initiative that calls researchers and practitioners to contribute information on multi-device technologies to an open access catalog. This catalog ought to be the de facto standard and first source to consult when designing, implementing, and studying multi-device interactions.

Author Keywords

taxonomy; dimensions; multi-device; cross-device; multi-surface; cross-surface; enabling technology; open access catalog; comparison, discussion.

ACM Classification Keywords

H.5.2 [Information interfaces and presentation (e.g., HCI)]: Miscellaneous

Introduction & Motivation

Research and industry share the growing interest in multi-{device,surface}[1] and in particular in cross-{device,surface} interactions. For example, interests include (i) development of technologies enabling multi-device interactions (e.g., software APIs [27, 5, 13, 23], hardware technologies [17], and hybrids between software and hardware [19, 10]), (ii) design of interaction techniques for multi-device ecologies [4], and (iii) user studies showing benefits when using multiple devices sequentially or in parallel (e.g., active reading [3], sense-making [9, 20, 26], collaborative data analysis [7], collaborative shared workspaces [25], content curation of historical artefacts [1], and audience engagement in presentations [2]). At the same time, industry has started integrating multi-device functionality into the core of operating systems (e.g., Apple Handoff or Microsoft Continuum). New hardware appear at a steady rate that detects nearby devices and services (i.e. Estimote Beacons) together with software APIs to enable novel multi-device experiences (i.e. Google Nearby[2] or Mozilla FlyWeb[3]).

However, the knowledge on multi-device technologies is scattered and stored across different sources such as online databases, platforms, and repositories. For example, digital libraries such as the ACM Digital Library hold a vast amount of research papers, journals, or articles. Other sources are patent databases, online blogs, newsfeeds, and source code repositories such as Github or Bitbucket. Moreover, it is challenging to choose appropriate technology for a multi-device system design because of missing guidelines and metrics defining technology tradeoffs. In this position paper, we propose a taxonomy to survey state-of-the-art of multi-device technologies and evaluate their tradeoffs. We further call researchers and practitioners likewise to collect information on multi-device technologies and contribute this information to an open access catalog[4]. This catalog is supposed to become the de facto standard and first source to consult when designing, implementing, and studying multi-device experiences. It will help the HCI community to understand multi-device technology tradeoffs better and will open up possibilities for them to discuss these technologies alongside their benefits and shortcomings.

Goal and Expected Contributions

Despite existing studies on multi-device use [22, 12] and surveys on multi-device challenges [8] or device association techniques [6], literature is lacking appropriate tools to assess the quality of multi-device technologies. It is, therefore, challenging for designers to select appropriate technology when designing multi-device systems. For example, the design of a system might afford the use of a particular technology because of the requirement for spatial tracking of devices. However, benefits of technologies also often come at a cost such as additional instrumentation of an environment.

We want to support this decision making by providing a taxonomy for assessing multi-device technologies and report results in a publicly accessible catalog. This will inform researchers and practitioners about the state-of-the-art of multi-device technologies and allow them to understand technology tradeoffs. It will further overview and detail on multi-device application domains, interaction techniques designed for multi-device & cross-device use, multi-device

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[1]The terms *-device and *-surface are often used synonymously.

[2]Google Nearby Project Website – https://developers.google.com/nearby/ (last accessed: September, 29, 2016

[3]Mozilla FlyWeb Project Website – https://flyweb.github.io/ (last accessed: September 29, 2016

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[4]The open access catalog is inspired by the iLab Cookbook – http://grouplab.cpsc.ucalgary.ca/cookbook/ (last accessed: September 29, 2016).

user studies, and methods to systematically evaluate the past, present, and future technologies. Ideally, such an open access catalog will also guide future research by revealing remaining research challenges and research gaps.

In contrast to Grubert et al. [8], we narrow our focus to technology and only Weiserian devices [24]. This includes the three broad device types: *tabs* ("inch-scale"), *pads* ("foot-scale"), and *boards* ("yard-scale"). It also includes both traditional personal devices, but also shared devices such as wall-displays or interactive whiteboards. We opted for this focus because we believe that a too broad view on technology will impede the development of a taxonomy and eventually not allow for proper technology comparison. However, related technologies such as virtual reality (VR), augmented reality (AR), and mixed reality (MR) could potentially be added at a later stage when possible. It is important to notice that this position paper makes neither claim to feature a final set of taxonomy dimensions nor does it exhibit a complete summary of the state-of-the-art multi-device research. It is a starting point, which solicits the multi-device community to join forces and calls for their contribution.

In the remainder of this position paper, we present our initial set of taxonomy dimensions to survey multi-device technologies. Ideally, these dimensions offer a structured way to assess technologies and help to identify their commonalities, differences, and tradeoffs. Eventually, this structured analysis will reveal trends, challenges, and gaps in multi-device development, inform research questions and thrive future studies in this area.

Taxonomy and Dimensions
To categorize and rate enabling technologies, we created an initial set of nine dimensions for assessing different qualities: *device setup*, *environment instrumentation*, *tracking fidelity*, *tracking space & dimension*, *tracking quality*, *tracking versatility*, *tracking technology*, *hardware & material cost*, and *availability*. Each dimension is briefly described in the following sections (see Table 1 for an overview); dimensions are presented in no particular order. Also, we would like to take the opportunity to present and discuss the taxonomy and its nine dimensions at the cross-surface workshop. As a result of the workshop, a final taxonomy and its dimensions alongside example technologies will be submitted as an article to the special issue on "Interaction with Device Ecologies in the Wild".

Device Setup
An obvious aspect of multi-device technologies is device setup. An ideal technology works without prior configuration of the target hardware (*zero-conf*). It should run on commodity and off-the-shelf hardware [19]. For example, multi-device systems [5, 13, 23, 18] implemented on modern web standards operate in a browser and do not require the user to install additional software (*zero-install*).

Environment Instrumentation
To track spatial locations and orientation of devices, rooms or environments are often equipped with additional tracking hardware. For example, the Proximity Toolkit [15] requires a *fixed* instrumentation of an entire space with motion capture cameras such as Vicon or OptiTrack. Other systems like HuddleLamp [19] also require to instrument the environment. However, their setup is portable and therefore considered *semi-fixed*. Software frameworks like Weave [5] or Connichiwa [23] allow for development of *mobile* multi-device experiences.

Tracking Fidelity
The tracking fidelity of devices often resonates with aforementioned instrumentation of the environment. The Prox-

Dimension	Values
Device Setup	zero-conf, zero-install
Environment Instrumentation	fixed, semi-fixed, mobile
Tracking Fidelity	spatially-agnostic, synchronous gestures, spatially-aware
Tracking Space & Dimension	2D, 3D and small-scale, mid-scale, large-scale
Tracking Quality	accuracy, precision, reliability, and close, medium, far
Tracking Versatility	user identity, body, limbs, head, hand
Tracking Technology	computer vision, Bluetooth LE, infrared, (in-)audible sounds, radio signals, WLAN
Hardware & Material Cost	consumer hardware, special hardware, research prototype
Availability	open source, closed source, proprietary

Table 1: Taxonomy including nine dimensions to assess multi-device technologies.

imity Toolkit [15] and HuddleLamp [19] represent two examples of technologies that enable development of *spatially-aware* cross-device interactions. Connichiwa [23] implements *synchronous gestures* for display stitching and others like Webstrates [13] and XDBrowser [18] are yet *spatially-agnostic*. The survey paper by Chong et al. on spontaneous device associations [6] could inspire further values for this dimension.

Tracking Quality from HuddleLamp [19]

Precision is the standard deviation of the tracked position and orientation of a fixed tablet over time and thus measures noise and jittering (units: mm or degree).

Accuracy is the spatial accuracy of a tablet's position compared to a ground truth (unit: mm).

Reliability is the percentage of frames in which a present tablet was tracked (its tracking state is 'true') during measurement (unit: %).

Tracking Space & Dimension
Technologies that allows for spatial tracking can be further divided into tracking space and tracking dimension. While HuddleLamp [19] is restricted to a *small-scale* space approx. 100×60cm and only tracks devices in *2D* space, Tracko [11] (*mid-scale*) and the Proximity Toolkit [15] (*large-scale*) allow spatial tracking in *3D* space and to a much larger extent. Latter depends on the motion capture camera setup, which often spans an interaction space of several cubic meters.

Tracking Quality
User experience of multi-device and cross-device interaction heavily relies on the tracking quality. For example, HuddleLamp [19] introduces the three measures *accuracy*, *precision*, and *reliability* and uses them to assess the quality of their hybrid sensing, which exploits optical characteristics and computer vision to track mobile devices (see sidebar for definition of HuddleLamp's quality measures). Tracko [11], as another example, shows how to categorize tracking quality based on three discrete distances: *close* ($<$0.5m), *medium* (0.5m-1.0m), and *far* ($>$1.0m).

Tracking Versatility
In addition to device tracking, some technologies allow tracking of *users*, their *bodies* or *limbs*. HuddleLamp, for example, tracks users' *hands* for mid-air cross-device interactions [19]. The GroupTogether [16] system tracks users' *body* & *head* position and orientation to guide user interaction using F-formations theory.

Tracking Technology
Most tracking techniques exploit internal device sensors and/or external hardware to track devices. HuddleLamp uses an RGB-D camera and *computer vision* (CV) for its hybrid sensing tracking [19]. Sifteo cubes use *infrared light* (IR) to detect neighboring cubes [17], Connichiwa exploits

Bluetooth Low Energy (BT LE) signals to calculate distance to other devices [23], Tracko uses *in-audible sounds* and *microphones* for triangulation and location detection of devices [11], GroupTogether uses short-range communciation technology and *radio signal* trilateration [16], and ProxiMagic uses *WLAN* for proximity detection (proximity-adaptive HTTP responses) [14].

Hardware & Material Cost
For most controlled lab research, the cost for hardware & material necessary for multi-device interaction is not a primary concern. From our experience and working with public and academic libraries [21] and schools [20], the cost of technology, however, is often an important factor for "in-the-wild" deployments (e.g., to reduce operating costs or costs for replacement in case of vandalism). An ideal system exploits users' devices and encourages them to "bring-your-own-device" (BYOD). It, therefore, should work without or only a little instrumentation of the environment. Such concerns might resonate with "in-the-wild" deployments at other public spaces such as community centers and museums.

Availability
The use of multi-device technology is often limited by the availability of source code. The Tracko paper [11], for example, describes the tracking algorithms, but the source code is *propriety* and additional effort is needed to re-implement the tracking. Likewise, research projects keep source code offline (*closed source*). Recent projects, however, published code as *open source* such as Proximity Toolkit [15], Watch-Connect [10], Webstrates [13], and HuddleLamp [19].

Summary
We proposed a taxonomy to survey state-of-the-art of multi-device technologies and to assess their quality using the nine dimensions: *device setup*, *environment instrumenta-tion*, *tracking fidelity*, *tracking space & dimension*, *tracking quality*, *tracking versatility*, *tracking technology*, *hardware & material cost*, and *availability*. This taxonomy allows to categorize and compare multi-device technologies, help to identify their commonalities, differences, and tradeoffs. We further call researchers and practitioners to contribute information on multi-device technologies to an open access catalog. This catalog can become the first source to consult when designing, implementing, and studying multi-device interactions.

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