Toward New Ecologies of Cyberphysical Representational Forms, Scales, and Interaction Modalities

Alexandre G. de Siqueira
Clemson, SC, United States
gomesde@clemson.edu

ABSTRACT

Research on tangible user interfaces commonly focuses on tangible interfaces acting alone or in comparison with multi-touch or graphical interfaces. In contrast, hybrid approaches can be seen as the norm for established "mainstream" interaction paradigms. In my work, I propose interfaces that support complementary interaction modalities, representational forms and scales, toward hybrid systems which are more legible and actionable than any strategy considered separately. I describe systems involving dial-like tangibles, which are passive and active, and systems combining interaction modalities such as tangible and multi-touch, and tangible and VR interaction. I briefly describe some of the planned and performed evaluations, and draw lessons from an already completed study involving a computationally-mediated scientific poster platform with content developed by undergraduate students.

CCS Concepts

•**Human-centered computing** → **Haptic devices;** *Mixed / augmented reality; Virtual reality;* •**Hardware** → **Haptic devices;**

Author Keywords

Hybrid Interaction; tangible user interfaces; tangible interaction; multi-touch interaction; Virtual Reality Interaction; cyberphysical interfaces;

INTRODUCTION

Screen-based graphics and text still remain the primary means for representing digital information. Screens, both big and small, in our desks, pockets, head-mounted, or embedded in the environment that surrounds us, usually in combination with general-purpose input devices, are still the predominant paradigm in human-computer interaction.

While successful, one recognized limitation of graphical user interfaces (GUI) in general, and the "WIMP" (windows-icon-menu-pointer) in particular is the "input" and "output" asymmetry. About this issue, Ullmer [13] asserts:

TEI '19, May 17–20, 2019, Tempe, AZ, USA
ACM 978-1-4503-6196-5/19/03…$15.00
DOI: https://doi.org/10.1145/3294109.3302960

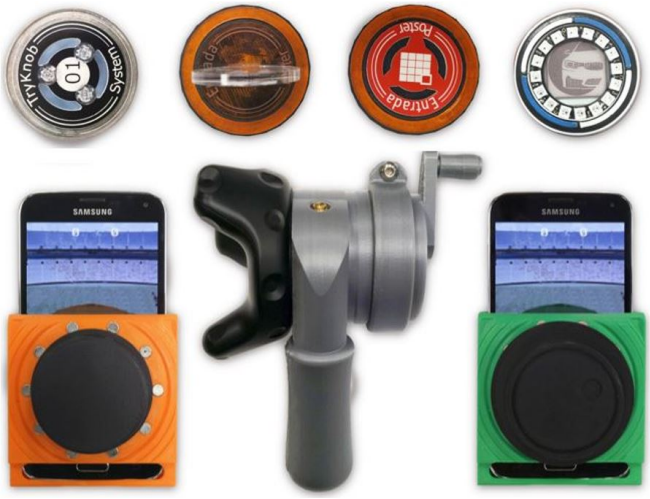

Figure 1. Tangibles created toward hybrid forms, interaction, and mediation modalities *(top row) Capacitive sensed dials were part of poster sessions at several venues in a system combining tangibles and multi-touch interaction. (top right) Active challenge coin combines LED and electronic paper mediation to provide legibility and user feedback. (bottom) VintagePong controllers and VRFishing Rod were part of a conference workshop and a demo session, toward interfaces which combine tangibles and Virtual Reality simulations.*

> *"While often employing millions of pixels of graphical output, WIMP interfaces generally rely upon a single locus of pointer-driven input, in a style largely devoid of physical and kinesthetic affordances, or other handles for engaging with a world of multiple users, each with two hands and a lifetime of physical skills ."*

The last decades have seen a number of research efforts, and commercially available systems, exploring ways to overcome these limitations, and better link the physical and digital worlds. These efforts have inspired several research areas, such as virtual and augmented reality, ubiquitous computing, wearable computing, research on tangible user interfaces (TUI), and driven the popularization of diverse interaction paradigms such as gestural interaction, and voice activated systems.

While tangible interfaces offer interaction beyond the trio screen-mouse-keyboard, within the tangible interaction field, research often focuses on tangible interfaces acting by themselves, or tangible interfaces in comparison with "competing" interaction techniques (e.g. graphical and multi-touch

interfaces [17, 1]). In contrast, when considering established "mainstream" interaction paradigms, hybrid approaches can be seen as more the norm than the exception.

Reflecting upon the Xerox Star system, its creators warned not to be dogmatic about the direct manipulation on Desktop metaphors [6]. Contemporary operating systems and desktop computer applications tend to combine both graphical user interfaces and textual/command-line interfaces. Operating systems, in particular smart-phone platforms, typically blend multi-touch with more "traditional" applications (e.g., web browsers), or even voice commands [2]. Voice activated devices, such as Amazon Echo [10], often come in a number of sizes, and do not rely solely on audio input/output, instead they combine a primary voice-activated interaction with buttons for input, and sound and (LED) illumination for output.

These combinations of forms, fabrication approaches, materials, scales, input and output modalities may be key to circumventing issues and limitations of interfaces embodying single-approach prospects. In my research, I investigate ecologies of systems combining a number of cyberphysical representational forms, scales, and interaction modalities. I anticipate that hybrids of multiple complimentary scales, forms, and mediation modalities – including passive and dynamic, physical and virtual, or combinations thereof – can be more legible and actionable than any of them considered alone. Figure 1 shows some artifacts created for interfaces that combine hybrid forms, mediation and interaction modalities.

Design Heuristics and Approach

The systems I research engage multiple computationally-mediated forms, scales, and interaction modalities, including touching something, moving something, rotating something, and beyond. Typical challenges of computationally-mediated systems relate to how one can tell what, how, and when to *do* something, especially at a first exposure to a system. One common term associated with these challenges is Donald Norman's "affordance" [5]: perceived properties (that may not actually exist), which may provide suggestions or clues as to how, or when to use such properties. As illustrated by Donald Norman's work, even a single affordance may pose a design challenge (e.g. exploring the rotational affordance of a door knob is a typical example [5]). These become even more complex as a number of forms, scale and modalities are combined.

Partly in response to such design challenges, I co-authored with Ullmer and others the LAVA heuristics [12]. The LAVA heuristics – **L**egible, **A**ctionable, **V**eritable, and **A**spirational – provide a conceptual tool for regarding different aspects of representational forms, scales and modalities within interaction design. Here, I will focus on the first two concepts:

- **legible:** *are artifacts expressed in physical and visual representational forms that allow users and systems to "read" them?* For *human legibility*, functions may be labeled with words or icons. However, form, choice of materials, spatial distribution, etc. may overcome this need, possibly leading to more elegant designs. In either case, human and system legibility is important [12]. If a user cannot distinguish (e.g.) a functional from a non-functional element (e.g., a button, RFID/NFC sensing zone, etc.), it is difficult for her to engage. *System legibility* relates to the sensing and communication strategies employed by the system to perceive its elements. These may be active (e.g. Bluetooth communication), or passive (e.g. constellations of conductive touch points on a multi-touch screen), and may be legible only by the systems, or by both humans and systems. A tracking label that communicates information to a system (e.g. via a computer vision) and, at the same time, is legible by humans is an example of an artifact which is legible by both humans and systems.

- **actionable:** *do the physical artifacts provide paths to access and/or manipulate aspects of their cyberphysical associations?* Interaction with physical objects should be reflected both in the physical and virtual spaces, and users should be able to perceive such actions as expressed by one or more forms of feedback.

In my work, I analyze and discuss the design and interaction of computationally-mediated systems consisting of a number of scales, forms and mediation modalities in light of the LAVA heuristics. In particular, how these hybrid systems can be more legible and actionable than when those mediation modalities are considered separately.

THESIS STATEMENT

My dissertation works to support the following thesis:

> *Computationally-mediated systems consisting of hybrids of complimentary cyberphysical representational forms, scales, and mediation modalities can be more legible and actionable than non-hybrid ones.*

The systems proposed by my dissertation often offer functionality *with* and *without* tangibles, and *with* and *without* virtual/"soft" interactors, including combinations of both. I regard (e.g.) "pure-multitouch" and "pure-tangible" variants, big or small, with active and passive artifacts, as well as hybrids thereof, all as "first class citzens". In this sense, the proposed systems are often not strictly a "tangible interface" system alone, but rather (inspired by [8, 9, 7]) what I and others have begun to consider as *cyberphysical interfaces* – systems designed to integrate support for multiple physical and virtual interaction.

RESEARCH APPROACH AND EVALUATION

Mark Weiser, when discussing ubiquitous computing for the twenty-first century [14] envisioned devices of three scales: tabs, pads and boards. Inch-scale devices, which he envisioned as active Post-it notes; foot-scale devices, like a sheet of paper, a book, or magazine, and yard-scale devices, equivalent to blackboards. Each with particular roles, and affordances. In this work, I explore inch-scale devices such as passive and active dials, and active challenge coins (Fig. 2); foot scale devices such as computationally mediated books, clocks, and table-sized tangible work-spaces, as well as room-sized interfaces which may combine all of the above into a single system.

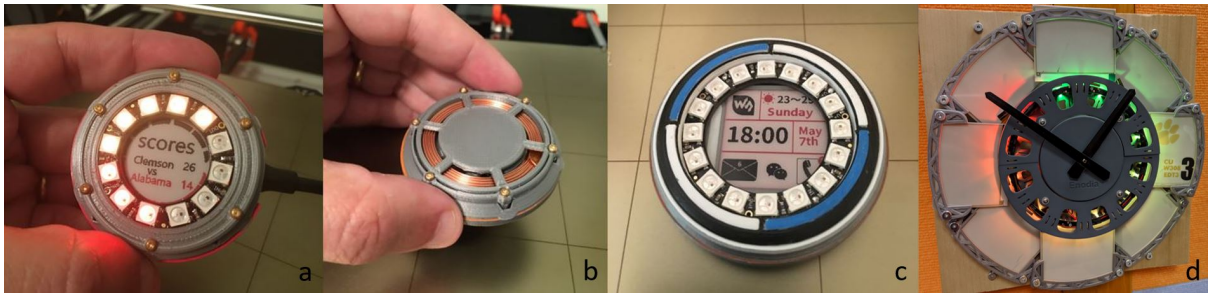

Figure 2. Active Challenge Coins and Clock mediating information through combinations of electronic paper and LED rings. *a) 12-LED tethered challenge coin. b) Active challenge coin equipped with wireless-charging. c) 16-LED active challenge coin equipped with wireless data communication via wifi showing iconic and textual information. d) Detail of a Challenge Clock.*

In my preliminary work, I investigate the class of tangibles that involves passive and active cylinders, wheels, dials, pucks, and knobs. I explore combining diverse shapes, materials, fabrication approaches (e.g. 3D printing and laser cutting), and sensing strategies toward dials which are reproducible, and interact with multiple systems. I am currently evaluating active challenge coins (evaluation planned to be completed by February 2019), which provide legibility to users both with e-ink displays and and LED rings (Fig. 2a). Toward characterizing how their unique combination of electronic-paper and LEDs can lead to more legible artifacts, I plan to measure an index of conspicuity, considering a single active challenge coin. As defined by Wertheim [15, 16], conspicuity is the extent to which an object, when viewed peripherally, is visually masked by its embedding surroundings. I will also measure glance legibility of an interface composed of groups of active challenge coins. Glance legibility measures the time a user takes looking at an interface before being able to answer a question about said interface. I expect that combinations of LED and electronic-paper mediation will provide higher levels conspicuity and glance legibility when compared to tokens employing any of the mediation strategies separately.

In another study, (mostly qualitative – completed) I have explored combining diverse interaction modalities, such as tangible and multi-touch interaction into a single experience, with neither being considered intrinsically superior to the other [4]. Here, a computationally-mediated scientific poster platform was created, combining both tangible and multi-touch interaction. Six undergraduate students participated in a number of workshops offered by us, created several posters with their own content, and presented as part of a summer undergraduate research program. Some of the observed results were that in general, poster creators tended to use buttons and gui interactors while developing the posters. "Hard" tangibles were mainly used for testing purposes during short periods of time, independently of the activity performed (e.g. selecting content or zooming an image). When presenting the posters in a public setting, most poster creators tended to use all three modes of interaction (hard, soft tangibles and multi-touch interaction,) with choice depending on the activity being performed. The apparent contrasting behavior toward tangibles we observed between poster creators while developing posters in the lab, and while presenting the posters seems to be in agreement with observations by others. Tangibles tend to be chosen more often when multiple users are collaborating, and not as often when working individually [3, 11]. This supports our hybrid interaction approach, optimizing the system for single and multiple-user modalities, instead of favoring one or the other.

Following that work, I have explored other combinations of interaction modalities, such as tangible and virtual reality (VR), including immersive, non-immersive VR simulations, and combinations of both. Evaluation of this work will be done by analyzing qualitative and quantitative (task performance) of pure tangible interaction, pure VR, and utilization of tangibles while immersed in the VR environment to accomplish a number of tasks. This final evaluation step is planned to be completed by July 2019.

Lastly, a number of artifacts have been completed (e.g. a number of passive and active tokens, active challenge coins, active challenge clocks, and active challenge books). Currently, beyond the envisionments, which have already been realized, a table-sized interface is being prototyped, in the context of a larger room-sized "inteface", also under development. However, given the current state of development, evaluations of systems at these (larger) scales are beyond the scope of my dissertation, and I plan to pursue them as future work.

THESIS CONTRIBUTION

In supporting the thesis statement, this research makes a number of specific contributions.

1. *Identification and characterization of hybrid representational forms, scales, and modalities as an approach toward more legible and actionable cyberphysical systems.*

   The thesis is broadly concerned with the design and characterization of systems embodying hybrids of "cyberphysical representational forms, scales, and modalities." This approach is supported both by systems designed toward the thesis, as well as other previous work. However, the identification, expression, and characterization of these hybrids as promoting more legible and actionable cyberphysical systems is original to the work of this thesis.

2. *Realization and demonstration of a number of prototyped cyberphysical systems, which embody multiple complimentary representational forms, scales, and mediation modalities.*

   The thesis develops the use of cyberphysical systems, which embody a number of representational forms, scales and mediation modalities. I argue and empirically demonstrate

that such systems may be more legible and actionable than non-hybrid ones.

3. *Entrada Poster Platform* The Entrada Poster Platform proposes a platform for scientific poster presentation combining tangible and multi-touch interaction, with large (approx. 55-inch) displays, and small-scale (tablet sized) variants, with and without physical interactors. This work is followed by a number of others, such as combining tangibles and virtual reality.
4. *Experimental comparison of tangible tokens combining electronic paper and LED mediation modalities, toward more legible artifacts.* Conspicuity legibility and glance legibility will be evaluated with a single active challenge coin, and a group of active challenge coins, informing the design of more legible interfaces with token-like elements.
5. *Experimental comparison of hybrids of tangible and VR interaction.* Hybrids of tangible and VR interaction systems will be experimentally compared with pure tangible and pure VR interfaces. These user studies will seek to empirically establish quantitative and qualitative benefits of hybrid cyberphysical systems embodying combinations of those interaction modalities.

STATEMENT OF MOTIVATION

The Graduate Student Consortium represents an opportunity to share current and planned directions of my research, as well as, receive valuable insights toward evolving and enhancing the work. Beyond the scope of one's thesis, this event also gives graduate students the opportunity to have one-to-one discussions with senior researchers and investigators in the field, which is invaluable for the current and future prospects as graduate students assume faculty, or post-doc positions. With this opportunity, I look forward to receive feedback from fellow students, and senior investigators, and hopefully contribute with my own constructive feedback toward the work of other graduate students. I find that in many occasions, by looking critically at the work of others, I can identify strengths and weaknesses of my own work. In particular, I hope that this experience can help me identify intersections and future collaboration opportunities that I hope can last for years beyond this much appreciated event.

ACKNOWLEDGEMENTS

This research was partially supported by NSF MRI CNS-1828611, and the Coordination for the Improvement of Higher Education Personnel (CAPES). I thank Dr. Brygg Ullmer who provided insight and opportunities that supported this research. I thank the undergraduate students Wajdi Halabi, and Carson Wood, and graduate students Moloud Nasiri, and Jing Lyu for their work and dedication supporting the development of the prototypes discussed in this paper.

REFERENCES

[1] Alissa N Antle and Sijie Wang. 2013. Comparing motor-cognitive strategies for spatial problem solving with tangible and multi-touch interfaces. In *Proc. of TEI'13*. ACM, 65–72.

[2] Jacob Aron. 2011. How innovative is Apple's new voice assistant, Siri? (2011).

[3] Jonathan Cohen, Meg Withgott, and Philippe Piernot. 1999. Logjam: a tangible multi-person interface for video logging. In *Proc. of the SIGCHI conference on Human Factors in Computing Systems*. ACM, 128–135.

[4] Alexandre G de Siqueira, Brygg Ullmer, Mark Delarosa, Chris Branton, and Miriam K Konkel. 2018. Hard and Soft Tangibles: Mixing Multi-touch and Tangible Interaction in Scientific Poster Scenarios. In *Proc. of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 476–486.

[5] Norman Donald. 1988. The design of everyday things. *Doubled Currency* (1988).

[6] J. Johnson, T.L. Roberts, W. Verplank, D.C. Smith, C.H. Irby, M. Beard, and K. Mackey. 1989. The Xerox Star: a retrospective. *Computer* 22, 9 (Sep. 1989), 11 –26. DOI: http://dx.doi.org/10.1109/2.35211

[7] P Venkata Krishna. 2014. *Challenges, Opportunities, and Dimensions of Cyber-Physical Systems*. IGI Global.

[8] E. Lee. 2008. Cyber Physical Systems: Design Challenges. In *Proc. of ISORC'08*. 363–369.

[9] Jay Lee, Behrad Bagheri, and Hung-An Kao. 2015. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manufacturing Letters* 3 (2015), 18–23.

[10] Amanda Purington, Jessie G Taft, Shruti Sannon, Natalya N Bazarova, and Samuel Hardman Taylor. 2017. Alexa is my new BFF: social roles, user satisfaction, and personification of the amazon echo. In *Proc. of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 2853–2859.

[11] Bertrand Schneider, Patrick Jermann, Guillaume Zufferey, and Pierre Dillenbourg. 2011. Benefits of a tangible interface for collaborative learning and interaction. *IEEE Transactions on Learning Technologies* 4, 3 (2011), 222–232.

[12] Brygg Ullmer, Alexandre Siqueira, Chris Branton, and Miriam K Konkel. 2016. Weaving peripheral interaction within habitable architectures. In *Peripheral Interaction*. Springer, 253–272.

[13] Brygg Anders Ullmer and Hiroshi Ishii. 2002. *Tangible interfaces for manipulating aggregates of digital information*. Ph.D. Dissertation. Citeseer.

[14] Mark Weiser. 1995. The computer for the 21st century: specialized elements of hardware and software, connected by wires, radio waves and infrared, will be so ubiquitous that no one will notice their presence. In *Readings in Human–Computer Interaction*. Elsevier, 933–940.

[15] AH Wertheim. 1989. A quantitative conspicuity index: theoretical foundation and experimental validation of a measurement procedure. *Report C-20 (in Dutch). TNO Human Factors Research Institute, Soesterberg, The Netherlands* (1989).

[16] Alexander H Wertheim. 2010. Visual conspicuity: a new simple standard, its reliability, validity and applicability. *Ergonomics* 53, 3 (2010), 421–442.

[17] Lesley Xie, Alissa N Antle, and Nima Motamedi. 2008. Are tangibles more fun?: comparing children's enjoyment and engagement using physical, graphical and tangible user interfaces. In *Proc. of TEI'08*. ACM, 191–198.