Made of Tiny Robots

An Investigation of the Ecology of Responsive Environments

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Abstract

ABSTRACT GOES HERE

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Chapter 1

Introduction

What follows is an investigation into the ways the burgeoning **ubiquity of computation**[1] will reshape the way we relate to our physical environment. Putting computers and screens and sensors and networking and even motors in artifacts whose utility was previously primarily conferred by their physical form will give the artifacts in our environment internal states and behaviors; our physical environment will become responsive. In the extreme case of artifacts composed of **self-reconfiguring materials** the form of an artifact will become just another aspect of its behavior. This change from form-governed artifacts (where an artifacts's utility is conferred by its form) to behavior-governed artifacts (where an artifacts's utility is conferred by its behavior) is the hallmark of a *responsive environment*[2]. Thus in a responsive environment our role shifts from being the sole actors who make use of the tools we surround ourselves with to being (perhaps leading) members of a social network of robotic[3] artifacts.

We suggest that taking an ecological perspective is important to understanding the shift to responsive environments for two reasons:

1. these networked robotic artifacts will serve as cybernetic extensions of our capabilities, and the level of the interface will be ecological; and
2. the complexity of producing these artifacts combined with their intimate connection with and knowledge of our personal lives will change the dynamics of their production, distribution and use.

[1] Terms rendered in bold on first use are defined in the Glossary.

[2] Terms coined here are emphasized on first use.

[3] We will be considering robots in the broadest possible sense of any machine capable of sensing input and responding with various behaviors.

To be clear, when we speak of ecology we do not intend it in the sense of the natural environment. We will be investigating *artifact ecologies*, the systems we apply and roles we adopt in the creation and use of physical artifacts, and the network of relations thus engendered.

In the rest of the introduction we will further elaborate on the evolution of artifact ecologies, how we will interface with responsive environments composed of robotic artifacts, and the roles we will adopt in creating and customizing these new robotic artifacts. We will then lay out the project at hand, which is briefly the development of an ontology of responsive environments and the consideration of possible ecologies of their production and use.

1.1 The Evolution of Artifact Ecologies

To understand the manner in which we are embedded in ecologies of the creation, distribution and use of artifacts we need a theory of how we relate to individual artifacts. Gibson (1979) suggests that we are able to appreciate the value of physical artifacts through our (innate) recognition of the uses **afforded** by their form. We recognize without effort that a chair affords the possibility of sitting and a door in a wall affords the possibility of entering a building.

We propose that the history of artifact ecologies consists of two broad eras, and we are now on the cusp of a third era.

As our (primate) ancestors developed the faculties to recognize that, for example, flint could be **knapped** to produce a blade, which could then be used to skin animals to create clothing, we entered the first era of the *wild environment*. These sorts of artifact ecologies are characterized by a distinction between a local collection of useful artifacts with clear affordances, generally carried on one's person, and a vast external environment that does not particularly respond to the human scale and within which affordances can be perceived only with significant knowledge and effort. Artifacts are generally crafted by the bearer for personal use from raw materials harvested from the wild surroundings. The chief social aspect of these artifact ecologies was the verbal transfer of the relevant methods to close acquaintances.

The next era was ushered in by the development of urban settlements. In these *leveraged environments* our artifact ecology has expanded to the horizon; we are now surrounded by manufactured artifacts designed to present a variety of helpful affordances. These artifacts give us leverage over our local conditions, for example doors allow us to easily restrict access to a space. Artifacts are no longer simply controlled by their bearer and encode complex social dynamics; roads and sidewalks are shared by citizens, stores provide artifacts in exchange for money, doors open for those who bear their keys. In order to produce these new artifacts in sufficient quantity to literally pave over the natural environment significant social changes are required; artifacts are designed by one set of specialists, produced by another, and distributed by yet another. As desirable artifacts are mass-manufactured through a complex bureacracy they are frequently unevenly distributed. The artifact ecologies of this era frequently engender social unrest due to inequities in the control of public artifacts and the distribution of private artifacts.

Many people already carry small computational devices with them and routinely interact with these newly familar robitic interfaces. As this computational ubiquity spreads we are already transitioning into a third era of artifact ecologies: responsive environments. These ecologies will be characterized by the promotion of our artifacts from passive tools to networked social peers. The intimacy of these relationships will place much more power over our behaviors and emotions in the hands of those who dictate the behavior of these artifacts. At the same time these artifacts have the potential to allow mass customization to the desires of those bearing a given artifact.

1.2 Where Do We Plug In?

Science fiction stories have led many people to ask: (when) will we have computer chips in our heads?[4] The answer for most of us is probably never, as we do not actually need to cut into our brains to become **cyborgs**; we are fully capable of interfacing with computers through language, through **GUI interfaces** and through **tangible interfaces**. By embedding ourselves in artifact ecologies populated with robotic devices with these sorts of interfaces, we in effect incorporate these other computational systems into our own thought processes. The best current example of this kind of cybernetic interface is **googling**; once one learns basic techniques for interacting with internet search engines and acquires a persistent network interface (such as a **smart phone**[5]) one becomes a sort of information-retrieval cyborg. The googlebot is so easily incorporated into our minds because our minds are already just a collection of specialized computational units that in concert to

[4] I am indebted to William Gibson for this formulation. (cite?)

[5] While this term is currently well known we expect that in the near future it will seem as antiquated as “personal digital assistant”.

form a "society of mind" (Minsky, 1985). As the philosopher of mind Daniel Dennett is fond of saying, "Yes we have a soul; but it's made of lots of tiny robots" (2003, p. 1). Although these tiny robots have historically happened to all be in our brains, with the advent of responsive environments we will be incorporating more and more robotic devices into our local cybernetic artifact ecologies.

As we are getting so familiar with this sort of robotic device we propose to give them a name: *robunculi*[6]. This name is a play on **homunculus**, an anthropomorphization of the human soul visualized as a little man sitting in our head issuing instructions, or sometimes as two little men on our shoulders whispering arguments into our ears. (TODO: figure) With the advent of robunculi we now have the googlebot whispering to us through our smartphones.

While some robunculi may be as apparently[7] discorporate as the googlebot, we suggest that others will play prominent roles in our physical surroundings. While our leveraged environment has familiarized us with the affordances of a wide variety of specific forms (i.e. cups and bowls, hammers and nails, shoelaces and zippers) as the physical artifacts in our environment gain internal states and behaviors we will need new models for recognizing and exploiting the affordances presented by robunculi. As models we propose to adopt **manipulatives**, tangible interfaces, **modular robots** and **self-reconfiguring materials**, as we will discuss further as we develop an ontology of responsive environments in the following section.

(TODO: expand, maybe whole introductory section on these models?)

1.3 Our Project

The work presented here is motivated by the following thesis: *our current artifact ecologies will not survive the transition from leveraged to responsive environments.*

(TODO: expand)

The question at hand then is: how we can live amongst robots in a way that empowers us to take control of the sorts of environments that ubiquitous computation will soon allow? To address this question we first need

[6]Applying the Latin plural diminutive '-unculi' to 'robot' gives 'robunculi', literally 'little robots'.

[7]The googlebot actually has a physical stature in line with its apparent omniscience; it fills several enormous buildings spread around the world and consumes enormous amounts of energy from both the grid and dedicated power plants.

to develop a better understanding of the landscape revealed by these technologies. Our project is: *to develop an ontology of the various roles we may adopt in creating and using robunculi and the methods of relating that typify each of these roles; and to demonstrate the utility of this ontology in the development and evaluation of robunculi, as well as in considering the character of the artifact ecologies engendered by these systems.*

In the following section we present an ontology of responsive environments describing the roles we may adopt in relating to robunculi, the interrelations between these roles and the methods of relation that typify each role. Next we will survey projects from a variety of fields incliding tangible interfaces and modular robotics that satisfy our definition of robunculi and describe them in terms of our ontology. We will then perform case studies of several projects developed by the author and others in further detail to demonstrate how this ontology can assist in identifying reusable techniques and components, and in comparing the relative merits of different projects. In the final section we will draw on these case studies to characterize different possible artifact ecologies and discuss their social implications.

Chapter 2

An Ontology of Responsive Environments

As we enter the age of ubiquitous computing (Weiser, 1999) our relationship with our artifact ecology is changing. There are several factors to these changes: we have new ways to fabricate artifacts; we have new ways of relating to artifacts; and our artifacts increasingly perform tasks that were once the exclusive domain of people. One of the key changes in an artifact ecology (that drives other changes) is the emergence of powerful computational agents that manage the explosion of relationships (and data) that arise when every artifact begins to communicate over the network. Many of these computational artifacts feed into online data stores physically situated in massive computing clusters (which we will refer to generally as *temples*[1]), managed by agents like the googlebot (which we will refer to generally as *idols*[2]).

As we enter into a cybernetic relationship with this new artifact ecology much of what we have until now considered our private personas will be determined by the behavior of the robotic devices we surround ourselves with, and by our relationship with the idols that manage these devices and mediate our interactions with other people, as we discuss in section 2.1. The character of this ecology, and what it means to be and individual within this new order, will depend largely on two factors: the transparency of these mechanisms to individuals, and their reconfigurability.

As our focus is not idols themselves but how our artifact ecology can be

[1]Because they are capable of hosting idols such as the googlebot.

[2]We chose the name 'idol' after Gibson's 'idoru'(1996), a literal AI rock star, with the accompanying cultural leverage of a teen idol; and after religious idols, to draw an analogy with the religious practice of asking powerful ethereal agents for advice and favors.

arranged to interface with them, in section 2.2 we will discuss what kinds of artifacts can be found in a responsive environment. In section 2.3 we will describe several possible responsive environment ecologies in which such artifacts could be produced and deployed. In an attempt to support the development of systems that support transparency and reconfigurability, we will focus on what we are calling a robunculi ecology: where rather than acquiring finished products people largely acquire robotic kits of parts that can either be assembled, or can self-assemble, into a variety of forms on demand. We will discuss the opportunities that this artifact ecology provides for a wide spectrum of society to play a role in shaping the behavior of their environment.

In section 2.4 we will look in more detail at the roles people can play within a robunculi ecology, and at the methods people adopting various roles can use to interact with these systems, by developing an ontology of interaction modes. We suggest that many of these interaction modes could also be usefully applied within other artifact ecologies to provide transparency and reconfigurability.

Finally in section 2.5 we describe some potential impacts of the adoption of different responsive environment ecologies, and highlight tensions that we will refer back to in our survey of robunculi in chapter 3, and in our more detailed case studies in chapter 4.

2.1 Idols

While we have related to our leveraged environments primarily as tool-users, as our environment becomes responsive this relationship is becoming more of a partnership amongst ourselves and various computational agents. For example in a leveraged environment professionals would often supplement their memory by using a notebook and appointment book, and supplement their expertise with a small private library. In a responsive environment, professionals supplement their memory through a small computer carried on their person (which we will call a *crystal*[3]) that manages notes and appointments through the interaction of a variety of software agents over a network; they supplement their expertise by using this same device to query an idol (i.e. the googlebot). Of course professionals in a leveraged environment also

[3] We call this class of handheld computers that provide a constant connection to the network 'crystals', as in a crystal ball that is used to view distant places and communicate with other agents through the ether, and as a reference to their current popular physical realization as a fragile glass-plated touchscreen.

practice division of labor, with secretaries managing appointments and engineers on call to make judgements using their personal libraries to supplement their domain knowledge. The difference is that in a leveraged environment partnerships are between people, and artifacts only effect change when operated by a person. Now when people send us invitations (from their crystals, over the network) an idol helpfully inserts them into our calendars and then buzzes us through our own crystals at the appropriate time to tell us where to be.

We suggest that the outlook for accepting these idols into our cybernetic consciousness varies from the utopian to the orwellian largeley depending on: how much control we (the citizens of idol-mediated societies) have over the behavior of our devices and idols; and how transparent (to us) the mechanisms governing these behaviors are. But before we can discuss the qualities of these computational artifacts we should discuss what kinds of artifacts we expect to see.

2.2 Kinds of Artifacts

1. construction kits vs rapid prototyping
2. robunculi, productization and reuse

[TODO: figures showing axes] (transparency - physically secured state/corp rental -¿ drm'd black box -¿ open source hardware) (reconfigurability - mass-manufactured widget -¿ bespoke popsicle -¿ kit of parts -¿ hyperform)

2.3 Examples of Artifact Ecologies

2.3.1 nodes of power

1. manufacturing
2. data transmission
3. data stores
4. shrines (high-powered computing clusters)
5. leaf node control

2.4 Robunculi: an Ontology

1. robunculi typologies

    (a) idols
    (b) tangible sketches
    (c) golems
        i. sock puppet (dumb rc golem)
        ii. avatar (golem serving as interface to idol)
    (d) hyperforms

2. morphologies
    (a) tile
    (b) block
    (c) skeleton (graph)
    (d) panel
    (e) glass (screen / projection interface)
    (f) shrine (idol-scale computing facility)

3. affordances
    (a) parallel affordances are synergistic
    (b) placing / self-reconfiguring
    (c) posing / flexing (self-posing)
    (d) commanding (pointing) / signalling (haloing)
    (e) listening (tagging) / responding (texting)
    (f) graffing (accepting drawings) / gramming (responding with drawings)
    (g) puppeteering / puppeting (present puppeteering interface)
    (h) sinks generate structured data to be accessed through idols
    (i) logging (recording interactions to data stores) (sink)
    (j) crawling (indexing data stores) (sink)
    (k) tracking (id-ing and classifying agents with sensors) (sink)
    (l) slamming (exploring and mapping environments) (sink)

2.5 Potential (Artifact) Ecological Impacts of Responsive Environments

1. radical transparency - big brother and little brother
2. means of production 2 - factories vs 3d printers

3. battle of the heavens - corporate clouds vs govt clouds vs community clouds
4. digital serfdom and device transparency

Chapter 3

A Survey of Robunculi

Chapter 4

Robunculi: Case Studies

Chapter 5

Conclusion

Appendix A

Glossary

afford a possibility for use we are able to recognize in an object; our recognition of these possibilities structures our perception of the environment (Gibson, 1979)

affordance a use afforded by an object (see **afford**)

direct manipulation introduced by Shneiderman (1983) to describe on-screen interfaces that allowed the mouse to grab and manipulate things; applied here to describe tangible interfaces that allow your hand to grab and manipulate things

ensemble a group of objects that coordinate to produce a global behavior (especially a group of robotic modules)

ensemble of robotic modules (see **ensemble**, **robot**)

golem an agent capable of performing useful tasks; from the fictional golem, an agent formed out of clay to serve and protect its creator

homunculus (plural: **homunculi**) an anthropomorphization of a cognitive process or the soul as a tiny person, often depicted as sitting inside someone's head; from the latin diminutive of man (homo)

hyperform a form that varies over time; from 'hyper-' indicating extent into the fourth dimension as in hypercube

maker a person versed in the skills necessary to craft objects

manipulative an object or kit of objects intended to engage children in discovering a particular concept or group of concepts through play

manipulative morphology one of the classes of forms developed to serve as manipulatives (see **morphology**)

modular robot a **robot** intended to serve as a member of an **ensemble** of physically coupled modules

morphology the structure and configuration of an object

purpose the broad use case an **ensemble of robotic modules** is intended to support

robot a device capable of sensing, planning and acting

robunculi the modules of a **robunculi kit**; from **robot** and **homunculi**; these 'little robots' extend our agency out into the environment by allowing us to impress behaviors upon the objects we construct out of them

scaffold (verb) to put a student in a position in which they are able to make discoveries

sensorimotor sensory integration for example between the hand and the eye

tangible interface a physical interface to digital information

tangible sketch a model built from a kit that communicates spatial information to a computational agent

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