Habitabilities of Living Artefacts
A Taxonomy of Digital Tools for Biodesign

Zhou, Jiwei; Barati, Bahareh; Giaccardi, Elisa; Karana, Elvin

DOI
10.57698/v16i2.05

Publication date
2022

Document Version
Final published version

Published in
International Journal of Design

Citation (APA)
Zhou, J., Barati, B., Giaccardi, E., & Karana, E. (2022). Habitabilities of Living Artefacts: A Taxonomy of Digital Tools for Biodesign. *International Journal of Design*, *16*(2), 57-73. https://doi.org/10.57698/v16i2.05

Habitabilities of Living Artefacts: *A Taxonomy of Digital Tools for Biodesign*

Jiwei Zhou [1,*], Bahareh Barati [1,2], Elisa Giaccardi [1], and Elvin Karana [1]

[1] *Delft University of Technology, Delft, The Netherlands*
[2] *Eindhoven University of Technology, Eindhoven, The Netherlands*

This paper offers a taxonomy of digital tools for crafting habitabilities in biodesign practices. Over the past decade, interest has grown among design and Human-Computer Interaction (HCI) scholars to explore the potentials of living organisms for novel responsive behavior and interaction possibilities. Yet, to date, it remains unexplored how digital technologies can support the design of living artefacts, that is, artefacts in which the organism is alive at the time of use. Our taxonomy bridges this gap by examining and reinterpreting the roles existing digital tools can play in *the exploration of the abilities of things to provide a habitat for living artefacts both at design time and use time,* i.e., crafting *habitabilities* in biodesign. The taxonomy is grounded in a systematic analysis of ten cases of living artefacts from art, design, and HCI, and it identifies three roles for digital tools: understanding, embodying, and perpetuating the habitat. Forwarding a relational perspective through the lens of habitability, this work promotes the mutual wellbeing of both humans and non-humans in biodesign.

Keywords – Biodesign, Biological HCI, Living Artefacts, Living Materials, More-than-Human Design.

Relevance to Design Practice – This paper attempts to bridge the gap of unexplored roles of digital tools in the design of living artefacts, taking multispecies and their relationships as a focal point of biodesign practice.

Citation: Zhou, J., Barati, B., Giaccardi, E., & Karana, E. (2022). Habitabilities of living artefacts: A taxonomy of digital tools for biodesign. *International Journal of Design, 16*(2), 57-73. https://doi.org/10.57698/v16i2.05

Introduction

In recent years, design and HCI researchers have shown interest in biological materials to achieve novel functionalities and interaction possibilities in everyday artefacts, in which computer input and output can be complemented or ultimately substituted by living organisms (Aspling et al., 2016; Cheok et al., 2008; Fernando et al., 2009; Gough, 2020; Gough et al., 2021; Hamidi & Baljko, 2014; Holstius et al., 2004; Kuribayashi et al., 2007; Kuznetsov et al., 2012b; Merritt et al., 2020; Parkes & Dickie, 2013; Pataran et al., 2020; Pataranutaporn et al., 2018; Poupyrev et al., 2012; Seo et al., 2015; Yao et al., 2015).

Informed by an epistemologically pluralist commitment, the critical and sustainable HCI community has introduced a rich vocabulary for decentering humans and carefully involving non-human species (e.g., animals, plants, and other living things) in HCI (Aspling et al., 2016; Gough, 2020; Gough et al., 2021; Light et al., 2017; Liu, J. et al., 2018; Liu et al., 2019). Researchers call for a careful consideration of the ethical imperative and significance of involving non-human species (e.g., animals, plants, and other living things) in human/non-human computer interaction (Liu, J. et al., 2018; Smith et al., 2017).

Foregrounding *livingness* as a biological, ecological, and experiential phenomenon, Karana et al. (2020) have recently conceptualized *living artefacts* as ecologically and socially embedded in everyday life. Because a biodesign process is never really finished as long as the organism is alive, the authors propose the habitual relationships that develop among humans and non-humans in the space in between design time and use time have to be better understood and supported. According to the authors, the concept of *habitability* is a key element in designing living artefacts, emphasizing the need for a purposeful exploration of the abilities of both humans and non-humans to not only create a livable habitat at design time, but also to perpetuate it at the time of use of the artefacts (p. 48).

The above mentioned works depict a continuum of relationships between biological systems, computers, and humans that spans from single, one-way functional relations to a multispecies web of symbiotic relationships. In line with this continuum, we believe that in the design of living artefacts it is crucial to empower both designers and users to perpetuate the livingness of the organism through a careful crafting of habitabilities that attends to the mutual well-being of both humans and non-humans. In particular, we believe digital tools can play a key role in the future crafting of such habitabilities.

Digital technologies have been important tools in understanding the biological world we live in (Gilbert et al., 2012). In biodesign, biological systems have often been coupled with advanced digital tools to assist practitioners in the biofabrication of artefacts (Camere & Karana, 2017). But digital tools can

Received July 16, 2021; **Accepted** May 29, 2022; **Published** August 31, 2022.

Corresponding Author: jiwei.zhou@tudelft.nl

also foster communication, cooperation, and affective forms of relationality between living organisms and humans. Informed by the existing roles of digital technologies in biodesign, our paper offers a taxonomy that articulates the roles digital technologies can play in crafting habitabilities in the design of living artefacts. The strength of the taxonomy is that it is framed into the timeline of the biodesign continuum (from understanding, to embodying, and perpetuating the habitat), providing practical guidelines in terms of when and for what purposes to use certain digital tools. The taxonomy helps biodesign practitioners to attend to the well-being of both humans and other living species, and to support them in crafting habitabilities comprehensively, in both their ecological and social dimensions.

Related Works

Over the last decade, we have seen a growing interest among design and HCI scholars in the cross-fertilization of biology and design to achieve novel responsive behavior and interaction possibilities in everyday artefacts. From a historical stance, the endeavors can be concluded as several design or HCI paradigms, including DIYbio, biological HCI, biodesign (bioart and biofabrication), and, more recently, a post-humanistic paradigm manifests itself in sustainable and critical HCI, and mutualistic care practices with and around Living Artefacts. The view on the relationship between the biological, the digital, and human have been evolving towards notions and theories with ecological and social implications. In this section, we want to acknowledge the different streams of research and development within the design and HCI research communities that contributed to understanding of the particular roles that digital tools can play in designing with and for living organisms.

Jiwei Zhou is a PhD candidate at the Materials Experience Lab, TU Delft, The Netherlands. Being both a researcher and design practitioner, her work explores novel materials and materials experiences rooted in human interactions with materials from social and ecological perspectives, for better sustainability and circularity. With her material-driven and research-through-design approaches, she designs for sensitivity and care towards materials, amongst the prevailing extractivism in our society. In her Ph.D. research, she looks at the social-ecological perspective of living artefacts, exploring technologies that facilitate the constant reconfiguration of habitats and their abilities to condition livingness both physically and socially for mutualistic care with living organisms in biodesign. Before joining the Materials Experience Lab, she received a MSc in Design for Interaction from TU Delft and a Bachelor of Engineering in Industrial Design from Tongji University in China.

Bahareh Barati is assistant professor at the Future Everyday Group, TU Eindhoven, The Netherlands. Her work explores the intersection of biological and digital capabilities and their mutually-informed integrations in designing for sustainable and equitable futures. Before joining TU Eindhoven in 2021, Bahareh lead the development of a new educational module on Prototyping with/for Emerging Materials (TU Delft) and contributed to the conceptualization of Living Artefacts. In her PhD research, Bahareh developed tools and strategies to unpack the performative potential of smart material composites by engaging in material driven design processes, and disseminated her work in design and Human Computer Interaction at venues and exhibitions. Bahareh received her MSc in Integrated Product Design (cum laude) from TU Delft and was awarded the Best Graduate of Industrial Design Engineering in 2012. She is an alumnus of University of Tehran, where she received her B.A. and M.A. in Industrial Design.

Elisa Giaccardi is Professor of Post-industrial Design at TU Delft, The Netherlands. Her work focuses on the challenges that a persistent digital transformation of society present for the field of design. After pioneering work in metadesign, collaborative and open design processes, her research over the last decade has turned to more-than-human design. In this space, she engages with how things today connect and learn, and thus actively participate in design in ways that previous industrially produced objects could not. Her work has contributed significantly to the development of post-industrial and post-humanist approaches in design and HCI. She is currently leading the European network and PhD program DCODE (dcode-network.eu/).

Elvin Karana is Professor of Materials Innovation and Design at TU Delft, The Netherlands, where she founded and directs the Materials Experience Lab. Giving emphasis to materials' role in design as experiential and yet deeply rooted in their inherent properties, Elvin explores and navigates the productive shifts between materials science and design for materials and product development in synergy. In 2019, she founded the creative biodesign research lab Material Incubator, that aims at designing materials that incorporate living organisms and exploring their potential in fostering an alternative notion of the everyday. Material Incubator brings together researchers and practitioners from Avans University of Applied Sciences, The Netherlands, and TU Delft.

DIYBio

Associated with hacker cultures, DIYbio promotes tinkering and open access to biological tools, protocols, and knowledge outside of professional settings (Kuznetsov et al., 2012b). The outcomes of this work, manifested as hybrid assemblages of living and digital materials, have been used to foster public discourse around the emerging intersections of biology and computation, and to surface unexplored design opportunities and challenges (Kuznetsov et al., 2012b). In addition, a growing number of DIY toolkits (Hamidi et al., 2017; Washington et al., 2017) and open source platforms have been introduced (Fernando, 2019; Fernando & Kuznetsov, 2020; Kuznetsov et al., 2012a) that enable non-technical users to experiment with living organisms, such as yeast and bacteria, and integrate them into art and design materials (e.g., Dew & Rosner, 2018; Kuznetsov et al., 2018; Weiler et al., 2019). Well-known examples of such DIYbio tools are platforms such as DIYbio (https://diybio.org), labs such as Genspace (https://www.genspace.org), OpenPCR (https://openpcr.org), and hardware such as OpenLH (Gome et al., 2019) and Pearl Blue Transilluminator (Fernando et al., 2016; Kuznetsov et al., 2012a).

Biological HCI

The aim of a body of research in the HCI community is to examine the roles living organisms could play in human-computer interaction design. The challenges and opportunities brought about by complex control systems and observable patterns of behavior in response to the environment have made living organisms a fascinating topic for HCI and interaction design (Parkes & Dickie, 2013). For example, researchers explored the potentials of microorganisms for designing living material interfaces as sensing device (Manzella et al., 2013; Poupyrev et al., 2012), ambient displays (e.g., Cheok et al., 2008; Fernando et al., 2009; Kuribayashi et al., 2007), and for visualization of personal and social practices (e.g., Hamidi & Baljko, 2014; Holstius & Kembel, 2004; Kuribayashi & Wakita, 2006; Seo et al., 2015), and novel media for interactive artefacts (Barati et al., 2021; Groutars et al., 2022).

Within this body of research, some have proposed taxonomies. Cheok et al. identified four archetypes for using microorganisms for artistic and display purposes, and proposed a taxonomy of six design dimensions: organism, interface, control, time constant, DNA alteration, and semantics (Cheok et al., 2008). Parkes and Dickie identified areas where living organisms have been integrated into everyday life, including information display, fabrication, energy production, materials, and components (Parkes & Dickie, 2013).

In parallel, some HCI researchers proposed conceptual frameworks intended to inform HCI researchers who are new to the possibilities and challenges of working with living organisms. For example, Pataran et al. (2020) provide an analysis of research projects that integrate microorganisms as part of the computing system, and propose the notion of *Living Bits* to challenge the traditional boundaries between biological cells and computers (Pataran et al., 2020). Merritt et al. (2020) offer a definition of Living Media Interfaces (LMIs) "*as interfaces that incorporate living organisms and biological materials to take advantage of their qualities to enable different forms of interaction between humans and digital systems*" (p. 3). From this perspective, they pointed out the shared characteristics between LMIs and physical computing systems, and identified different elements for designing with LMIs (pp. 13-15).

In this type of work, the relationship between humans, technologies, and biological materials (Merritt et al., 2020) appears to be one-way. Biological materials are approached mainly in terms of exploitation rather than a mutual relationship of cohabitation (Liu, S.Y. et al., 2018; Smith et al., 2017).

Bio Art and Design

Outside of the HCI community, artists and designers too have applied biological and digital interventions for changing the appearance and traits of living organisms for sustainable material and production alternatives as well as for artistic and critical purposes (Ginsberg et al., 2014; Myers, 2012). This line of work has been documented and curated in important exhibitions such as *Alive: New Design Frontiers at Central Saint Martins (2013) and La Fabrique du Vivant | Designing the Living at the Centre Pompidou (2019). Bio art examples include the culture of microbes for creating visual imagery (e.g., Contagion, bacteria billboard; Fant, 2011); Antibiotic-responsive Bioart (Kuznetsov et al., 2018), sensory stimuli (e.g., Microbial Perfume; Evers, 2015), autonomous robots (e.g., Caravel; Henriques, 2016), musical composition (e.g., Biota Beats; Liu, 2016).*

Building on a relatively established field of biofabrication in biomedical science and engineering (Fujii et al., 2016; Mironov et al., 2009; Pavlovich et al., 2016), today, potential applications of biodesign vary from organ printing and energy production (biofuels from algae, for example), to animal-free leather and fur-like materials (such as MycoWorks' fungi-based leather, https://www.mycoworks.com), and regenerative photosynthetic materials (Balasubramanian et al., 2021) and foam alternatives (Bloom Algae Foam, for example).

Camere and Karana (2018) provided a systematic overview of design practices at the seams of biology and design, ranging from the speculative to the commercial, into four categories: (1) augmented biology, in which designers seek the re-engineering of cells to design new biological organisms that can help us cope with contemporary societal challenges, such as famine, diseases, and energy shortages (Collins, 2012; Ginsberg et al., 2014); (2) biodesign fiction, in which designers speculate on the implications of biotechnological futures before they happen through scenarios or prototypes (Ginsberg et al., 2014; Moisy & Pschetz, 2017); (3) growing design, which is characterized by hands-on practice and focused on the development of novel materials for product design (Camere & Karana, 2017; Ciuffi, 2013; Montalti, 2010); and (4) digital biofabrication (Camere & Karana, 2017), in which the researchers emphasize the unique couplings of biological tools with advanced computer technologies in biodesign (Bader et al., 2016; Smith et al., 2020; Zhou et al., 2021). Materials and artefacts have been co-created with digital technologies and biological processes, e.g., Mycelium Chair (Klarenbeek, 2014) and Silk Pavilion (Oxman et al., 2014).

In order to avoid the pitfalls of biodesign, such as possibly failing to challenge modern economic paradigms or to deliver social transformation, or leading to unexpected ecological problems, Ginsberg and Chieza (2018) suggested that future biodesign should help us identify new diverse biological, ecological, and social models that are equitable for all biologies, not just for humans and a few monoculture crops. Recently, Karana et al. (2020) have introduced the notion of Living Artefac ts—artefacts of everyday use that can sense, grow, adapt, and eventually die. Based on an extensive and in-depth analysis of existing living artefacts, the work proposes three biodesign principles as fundamental loci of designing for *livingness* in artefacts of everyday use: *living aesthetics* (i.e., the way humans experience the type, degree, and duration of change in a living artefact over time), *mutualistic care* (i.e., the reciprocal and evolving relationship between humans and living artefacts), and *habitabilities* (i.e., the various ways in which living and non-living entities condition the livingness of an artefact). As a new biodesign framework, Living Artefacts encourages a *new biological thinking* that facilitates "non-hierarchical alliances, symbiotic attachments, and the mingling of creative agents (human and non-human alike) in everyday life" (p. 49).

Critical and Sustainable HCI

Another body of work, affiliated with critical and sustainable HCI, calls for a careful consideration of the ethical imperative and significance of involving non-human species (e.g., animals, plants, and other living things) in human/non-human computer interaction (Liu, S. Y. et al., 2018; Smith et al., 2017).

Researchers engage in critical and sustainable HCI research through the lens of specific practices or with a focus on particular organisms. Part of this work has mainly considered insects, plants, and animals in built environments (Clarke et al., 2019; Forlano, 2016; Mancini, 2013; McGrath, 2009; Nyberg et al., 2019). For example, in Frankjaer's (2018) project Cyborganic, digital tools enable human beings to experience insects' perspectives in urban environments. Some HCI researchers consider plants' well-being, implicating directions like *HCI for human-plant kinship* (Ciobanu, 2019) and *HCI for plants dissemination* (Aspling et al., 2016). Informed by feminist scholarship on *collaborative survival* (Tsing, 2015) and *art of noticing* (Tsing, 2015), Liu, J. et al. (2018) have proposed speculative digital tools for detecting mushrooms in the wild, and for spores analysis. Other HCI researchers discuss how new technologies which integrate microorganisms, such as bacteria and slime mold, will increasingly rely on symbiotic relationships between the user and organisms that participate in interactive systems (e.g., Chen et al., 2021).

These works initiate a rich vocabulary reflecting posthumanist values and decentering humans to describe how HCI frames itself in relation to global ecological and societal challenges (Bardzell & Bardzell, 2011; Comber et al., 2020; Light et al., 2017; Liu et al., 2019). These positions foreground the need for non-human stakeholders such as insects, plants, and microorganisms to come into play (Aspling et al., 2016; Ciobanu, 2019; Liu, J. et al., 2018).

These intellectual provocations and speculations uncover new possibilities offered by digital technologies by extending our human sensory capacities into the biological/ecological system, thus allowing us to notice, attend to, and be inspired by non-human lives. Yet, the use of digital tools leaves non-human stakeholders still relatively passive in their participation (Liu et al., 2019), e.g., waiting *to be noticed* by humans (Liu, J. et al., 2018). In this paper, we provide a taxonomy of digital tools for purposely crafting *habitabilities* in living artefacts. We contribute to biodesign research and practices with a frame of reference that examines, reinterprets, and makes use of existing digital tools for biodesign from the new perspective of a multispecies web of symbiotic relationships. In the next section, we elaborate on *habitabilities* and explain how this notion provides a lens for understanding and analyzing the role of digital tools in the design and use of living artefacts.

Crafting Habitabilities in Biodesign

In science, living organisms are increasingly used to endow non-living materials with advanced functionalities such as the abilities to self-power, self-heal, response to biosignals, and being self-sustainable (Liu & Xu, 2020). However, self-sustaining living materials remain a challenge (Liu & Xu, 2020). Digital tools are often used for self-regulation of the habitat (e.g., auto or semi-auto bioreactor), and to prolong living organisms' life time with minimal human intervention. But digital tools can have other substantial roles to play.

The notion of *habitabilities* has been forwarded by Karana et al. (2020) as a biodesign principle when designing for livingness in artefacts, to deliberate on the ecological and social considerations for a multispecies habitat. Habitability refers to "the way the human body and other living and non-living entities condition the livingness of an artefact" throughout its life-time (p. 48), that is, from design time to use time. This principle is critical in crafting the design interventions necessary for shifting from an exploitative stance to enabling and facilitating multispecies cohabitation (Westerlaken, 2020).

In exploring the possible interplay between digital tools and living artefacts, habitability provides a useful frame of reference. A notion of habitability is not only useful for reflecting on the abilities of things to provide a multispecies habitat, it is central in acknowledging and attending to the extended role of things across design time (when a habitat is ecologically configured) and use time (when the habitat is socially sustained and thus perpetuated). Accordingly, digital tools may play a role in understanding and crafting the *habitabilities* of things, both in supporting the ecological configuration and perpetuation of a habitat, and in situating it socially. This requires biological knowledge of how habitats function in natural environments, and what relationships and entanglements naturally exist between organisms. It also requires understanding how humans may socially relate to a living artefact in order for it to thrive, and how the artefact may continue to provide humans with (functional) benefits (e.g., purifying air purifier and providing ambient light). When designing living artefacts, this ecological and social understanding of the habitat needs to be synthesized. Digital tools can help.

By exploring digital tools in crafting habitability for living artefacts, we aim to provide a taxonomy that is physically sustaining the habitat conditions for living organisms, but also socially involving human co-habitants to sustain multi-species relationships. The pillars in the taxonomy, therefore, are organized according to such continuum, from understanding the habitat which usually happens in the design time, to embodying the habitat and then extending to perpetuating the habitat in both design and use time.

Methodology

We searched across multiple existing fields at the intersection of biology, HCI, art, and design, including biodesign, bioart, DIYbio, biofabrication, biotechnology, sustainable HCI, and Bio HCI. We screened through these fields to collect example cases of physical artefacts in which (1) living organisms are kept alive in the use time of the artefact and (2) use of a specific digital tool(s) is described as part of the biodesign process, particularly in exploring and crafting the habitabilities of things (both human and non-human) which condition the livingness of an artefact.

We used the following keywords for case collection: *microorganism*, *microbial*, *microbes*, *bacteria*, *yeast*, *algae*, *fungi*, *biodigital*, *biodigital fabrication*, *bio-computation*, *biological Ai*, *growing materials*, and *living materials*. We used online google search in websites (research institutes, design related media), scientific publications, and visited design exhibitions. We gathered 77 cases. The cases were selected between April 2020 and September 2020. Based on the above mentioned two criteria, we excluded cases where digital tools were merely used in the design time, but not necessarily leading to a living artefact (e.g., Silk Pavilion by Mediated Matter Group MIT Media Lab). We also excluded cases in which digital tools are used for designing scaffolds to improve the quality of a natural habitat (e.g., Living Sea Wall by Reef Design Lab). We gave priority to the cases which suggest artefacts for everyday use, and either have been published or exhibited at HCI and design venues (e.g., CHI, DIS, Biofabricate). Thus, the cases concerning biotechnology in medicine and agriculture/food industry (e.g., human tissue engineering, micro-algae food production) were eliminated from our collection.

We selected ten representative cases of living artefacts in which digital tools are used in crafting their habitabilities across both design and use time (Table 1). Our list is not meant to be exhaustive, but representative for the taxonomy pillars we will elaborate in this section. We screened through the verbal descriptions of the cases. After an initial analysis, the following categories have emerged concerning a digital tool's specific role in crafting habitability in biodesign: Observing the organisms' behavior in artificial habitats; modeling the organisms' behavior in relation to habitat parameters; form-finding for the physical habitat that accommodates the living organisms; fabricating the physical habitat; depositing cells and chemicals in the habitat; regulating habitat conditions to maintain organisms' livingness; and help interfacing how the state of living is communicated between multi-species.

We clustered these emergent categories under three main pillars of our taxonomy of digital tools for crafting habitability in biodesign: (1) understanding, (2) embodying, and (3) perpetuating the habitat.

Table 1. Ten representative cases of living artefacts in which digital tools are used in crafting their habitability across design and use time.

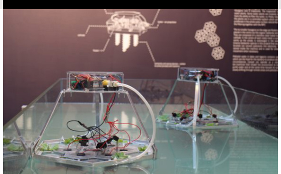
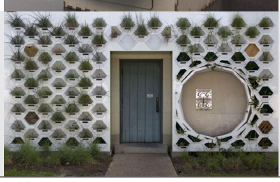
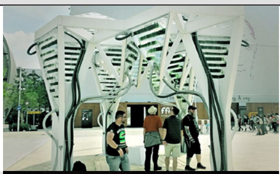
	Image	Description	Digital Tool and Role	Source
1		Vespers III by Neri Oxman and The Mediated Matter Group of MIT Media Lab, a living mask embodying habitats that induce engineered bacteria to produce pigment in response to detected chemicals	Digital Camera for image capture from microscopy Computer Aided Design (CAD) for modelling material behavior	https://www.media.mit.edu/projects/vespers-iii/overview/
2		Genesis Eco Screen by BigRep (www.bigrep.com), a 3D printed installation inhabited by green plants, embedding water supply and a drainage system in the scaffold	Agent-based Modelling on Rhino-grasshopper platform for form finding 3D printing for fabrication of the scaffold	https://bigrep.com/posts/genesis-eco-screen/
3		H.O.R.T.U.S XL by ecoLogic Studio, a 3D printed bio installation containing microalgae	3D printing used for fabrication of the scaffold	https://www.ecologicstudio.com/projects/h-o-r-t-u-s-xl-astaxanthin-g
4		Living Tattoo by Liu et al. (2017), MIT, a 3D printed living tattoo that detects chemicals on human skin	3D Bioprinting for direct writing of engineered bacteria cells, signaling chemicals and nutrients	https://doi.org/10.1002/adma.201704821
5		Caravel by Ivan Henriques, a self-sustaining environmental robot that cleans water by propelling itself on the water surface	Electronic Components for harvesting electricity produced by bacteria that are living in the water	https://ivanhenriques.com/works/caravel/
6		Living Things by Jacob Douenias, Ethan Frier, and Lena Tesone, an interior lighting installation incorporating microalgae that produces oxygen, food, and fuel through photosynthesis	Semi-automatic photobioreactor designed and embedded for harvesting biomass and regulating biomass volume	http://www.livingthings.us/
7		Rafigh by Hamidi and Baljko, a living media display incorporating mushroom growth for showing the frequency of using a therapeutic application by children with disabilities	Microcontroller to control irrigation system, to map mushroom growth to children's use of a therapeutic application	https://dl.acm.org/doi/10.1145/2556288.2557402
8		Living Wall by Danelle Briscoe, University of Texas at Austin, a vertical plant system to maintain biodiversity in a hot and dry environment	Post-installation Building Information Modeling workflow for monitoring the biological species living in the wall; making maintenance and upkeeping an interactive experience	http://www.danellebriscoe.com/utsoa-living-wall/2018/2/14/west-facing-elevation-after-3-months

Table 1. Ten representative cases of living artefacts in which digital tools are used in crafting their habitability across design and use time. (continued)

	Image	Description	Digital Tool and Role	Source
9		Urban Algae Canopy by ecologic Studio, an urban installation that is home to microalgae providing interactive shades for visitors	Sensors and controllers, electronic valves to coordinate the spatial distribution and flow of microalgae according to human position	https://www.ecologicstudio.com/projects/expo-milano-2015-urban-algae-folly
10		Living Light Lamp by Nova Innova and Plant-e, a lamp harvesting energy through the photosynthetic process of plants and metabolism of bacteria	Electronic sensors and controllers, LED mapping the action of caressing (biosensing) to signals for controlling the intensity of light	https://livinglight.info/about/

A Taxonomy of Digital Tools for Habitability in Biodesign

The type of natural environment in which a particular organism will thrive is called habitat. Some organisms are more tolerant of wide variations within a habitat, while others are very specific in their requirements (Karp, 2018). In designing a living artefact, an initial habitat is materialized by identifying the main elements, their relations, and compositions which are necessary for the organism to thrive. Designing such habitats requires an understanding of the energy conservation mechanisms necessary for the primary metabolites involved in growth and reproduction, such as photosynthesis, aerobic and (an)aerobic respiration, and fermentation processes (Jurtshuk, 1996; Voet, 2007). Corresponding to each mechanism, certain sources such as light, oxygen, carbon, and nitrogen sources, might or might not be necessary for keeping a specific organism alive. In a living artefact, living organisms continue to interact with the environment in the use time of the artefact.

Below, we present the specific roles that digital tools play in crafting habitabilities across the design and use continuum of living artefacts.

Understanding the Habitat

This pillar of the taxonomy concerns an understanding of the relations between the elements of a habitat. Herein, digital tools are used to observe, record, model, and simulate these relations between various living and non-living elements, needed in the design to migrate the organism to an artificial environment.

Observing and Recording

Digital tools have been used to observe and record living organisms in natural and controlled habitats. The two well-known digital tools used to provide real-time data on animals' location are implantable microchips and GPS trackers. The latter, particularly, can provide information on habitability of wildlife and their migration routes, according to which the built environment could be modified (e.g., Wildlife Crossings in Banff National Park by Parks Canada). Besides, diversity of organisms and their distribution in a specific natural area can be observed with digital tools. To detect and quantify diverse taxa of bioluminescent organisms off the California coast, scientists use remotely operated vehicles to record and observe in situ (Martini & Haddock, 2017). In the design of living artefacts, living organisms are often observed in a controlled environment, using both specialized lab equipment (e.g., microscopes) and DIY devices, e.g., Barati et al. (2021). An example of the latter is a shaker designed to explore the effect of specific environmental parameters (i.e., three types of kinetic stimuli) on flash qualities of bioluminescent microalgae (Barati et al., 2021).

A commonly used technique in helping humans better understand the living organisms' behavior in artificial habitats is photography. In the design of living artefacts, photography can help *cultivate designerly sensibility* of nature-culture relationships (Liu, S. Y. et al., 2018), and *situational awareness* to help understand how the observed organism interacts with its milieu on the micro-level (Ramirez-Figueroa et al., 2018). Besides, cameras for photography, digital microscopes, and microtomography are widely used in biodesign for imaging purposes and providing data on organisms' growth and other observable behavior (e.g., movement). In **Vesper III**, a mask on which engineered bacteria are inoculated to generate chemical substances useful for humans, time-lapse digital images were taken to document organism response during the incubation hours (Smith et al., 2020).

Modeling and Simulating

Modeling and simulation is a primary technique to create a tractable space (Wooley & Lin, 2005) for understanding and quantifying biological systems (Brodland, 2015). An example is biologically-informed computer aided design (bioCAD) tools to study and design cell colony behavior across spatial and temporal scales (Bader et al., 2018). A frequently implemented bioCAD method is agent-based modeling (MacAl & North, 2010), which has been increasingly applied to model cell colony behaviors as complex systems, such as in Position-based Dynamic Model for bacteria (Bader et al., 2018).

Vesper III instantiates how computational modeling and simulation could inform the habitat design by providing understanding on the various elements of the habitat and their intricate relations in a more complex geometrical setting (Figure 2). The researchers used computer simulation to estimate biological response in relation to the geometry and concentration of chemical signals in an object (Smith et al., 2020). They created a computational model to understand and predict the spatial-temporal distribution of chemically induced responsive behavior of engineered bacteria on the inoculated object based on *a digital material description in a CAD environment* (Smith et al., 2020). The modeling takes into consideration the hydrogel-mediated diffusion of chemical signals from a 3D object, the resulting bacterial response, and the geometric complexity of the 3D printed multi-material object hosting the bacteria.

Embodying the Habitat

The second pillar of the taxonomy concerns an embodiment of the artificial habitat(s) within and outside the laboratory setup. Below are ways in which digital tools are currently being used in biodesign to embody an optimum habitat in which the form of the

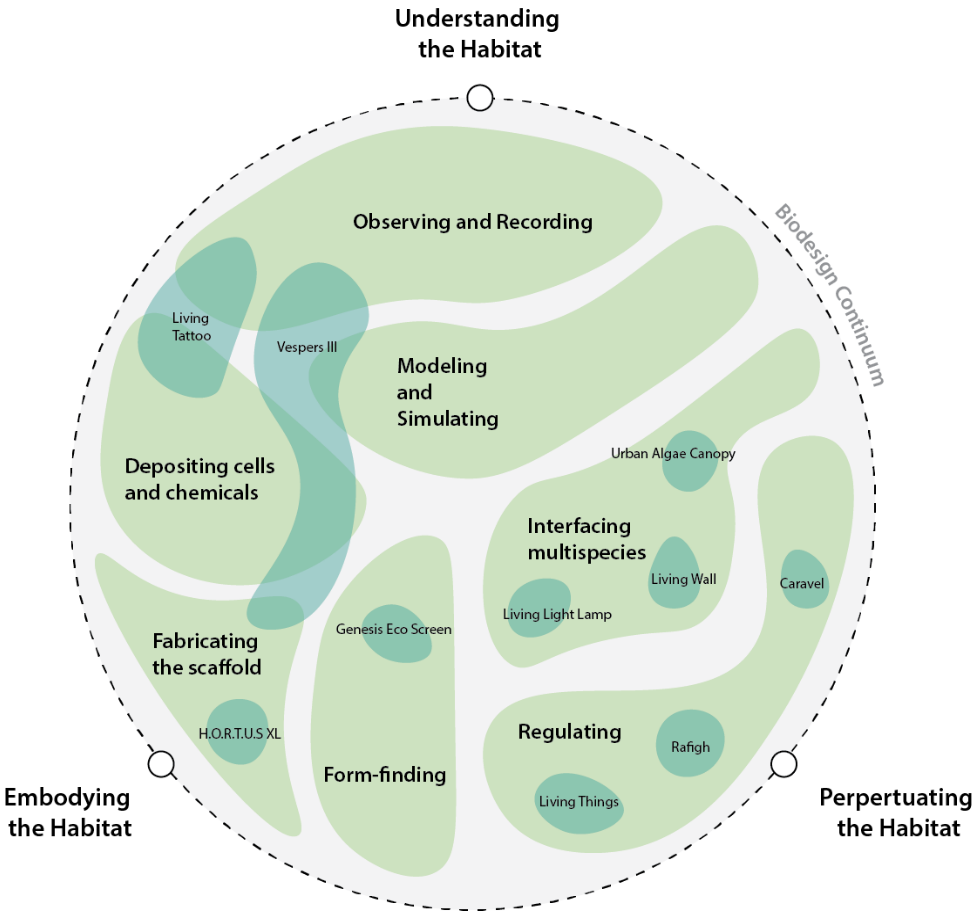


Figure 1. Taxonomy of digital tools for understanding and designing for habitabilities in biodesign.

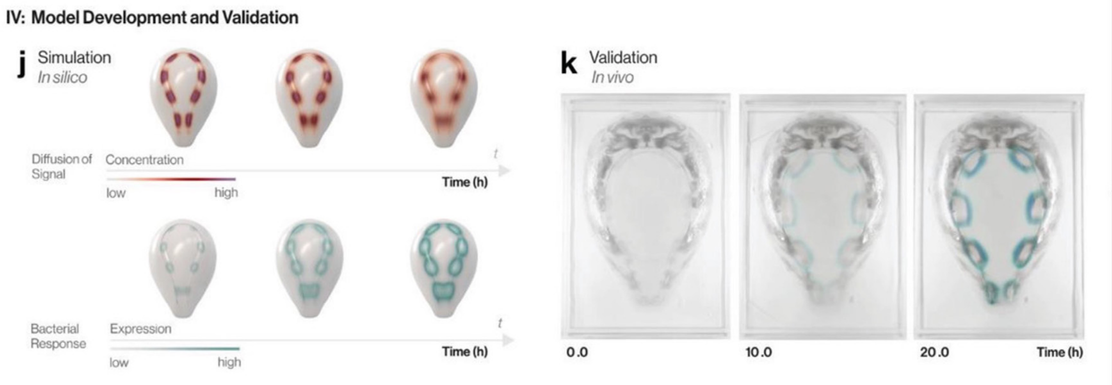


Figure 2. Computer modeling for bacteria spatial response, Vesper III.

physical artefact, its material composition, and deposition of cells, nutrients, and chemicals to the material composition collectively influence the organism's vitality and performance.

Form-Finding

Researchers have used digital tools to translate the physical, biological, and ecological characteristics of the natural habitat to artificial habitats. This starts with form-finding for a habitat, which entails negotiating complex factors within the space of formation for a given context (Oxman, 2010), which is not only determined by the living organism's needs to thrive, but also the designerly requirements for function and expression. Herein, algorithms are used to solve problems in terms of geometry (Oxman, 2010) and material composition. The design and optimization of a habitat's form is usually guided by computer aided design tools (CAD) and parametric design platforms (e.g., Rhino-grasshopper platform).

One such advancement in computer aided form finding is the development of agent-based modelling (ABM) methods and software tools. ABM has been applied to domain-specific assessment of building performance such as fire evacuation or crowd movement control (Nguyen et al., 2020), but also in the form-finding of living artefacts. In **Genesis Eco Screen**, the designers used *solar radiation analysis for agent-based modeling and parametric design* to find the form with unique characteristics tuned based on the environment that it is placed in. The agent-based modeling approach in the Rhino-Grasshopper platform also informed the arrangement of embedded irrigation channels. The outcome is a green wall for placing specific plants, with miniature internal channels for watering the plants precisely where needed with an integrated *micro-shower* mechanism (Figure 3).

Fabricating Scaffold

The material properties, geometry, porosity, and pore size of the scaffold contribute to cell seeding efficiency and cell attachment (Bancroft et al., 2002; Congdon et al., 2020; Liu et al., 2020; Mastrogiacomo et al., 2006; Olivares & Lacroix, 2012; Wendt et al., 2006). Digital fabrication has been used in biodesign for fabricating scaffolds which host living organisms (e.g., Mycelium Chair by Klarenbeek and Silk Pavilion developed by The Mediated Matter Group at the MIT Media Lab), where the biologically and digitally designed materials provide each other with structural stability (Zhou et al., 2021).

Figure 3. a) Genesis Eco Screen by BigRep (www.bigrep.com)**;**
b) internal channels for watering the plants integrated in Genesis Eco Screen.

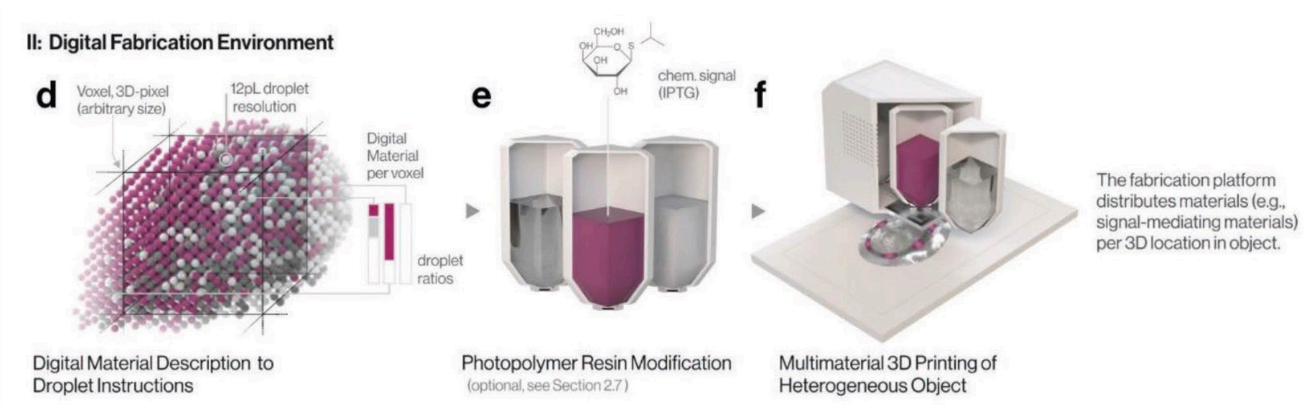


Figure 4. Scaffold fabrication process of Vespers III.

In **Vespers III**, Objet Connex500 (Stratasys, Rehovot, Israel) multi-material inkjet-based 3D printer was used to deposit hard and soft polymers for fabricating a scaffold in the form of a mask (Figure 4). Nozzles in the printer deliver droplets of two kinds of photopolymer resins and one kind of support material to targeted positions according to computer models within a macroscale build space, creating an expansive range of digital-fabricated material structures (Smith et al., 2020). This approach allowed the researchers to customize the support material for immobilizing aqueous chemical signals, which later stimulated engineered bacteria to show color changes.

In **H.O.R.T.U.S XL**, a large scale installation inoculated with microalgae, the physical scaffold was fabricated with a high resolution 3D printer through a Fused Deposition Modeling (FDM) process (Figure 5). It is printed in 105 hexagonal blocks of 18.5 cm each side producing an overall substratum that is tall enough to enclose an adult human and that reaches 317 cm in its tallest point. Microalgae converting light into oxygen and biomass are inoculated on a bio gel medium into interstitial space. The artefact's form is informed by biological models of collective coral morphogenesis. The density-value of each bio-pixel is digitally computed in order to maximize incoming light and metabolism of the organism along iso-surfaces (Pasquero & Poletto, 2020).

Depositing Cells and Chemicals

Cell seeding is the first stage of cell attachment to physical scaffolding. Its efficiency and distribution can affect the final biological performance of the scaffold and spatiotemporal pattern generation process (Bader et al., 2018; Liu et al., 2020). Computer-assisted technologies such as 3D bioprinting help precisely control spatial position of living cells (Jian et al., 2018), which has found applications in drug delivery, tissue engineering, soft actuators, and adaptive buildings (Liu et al., 2017).

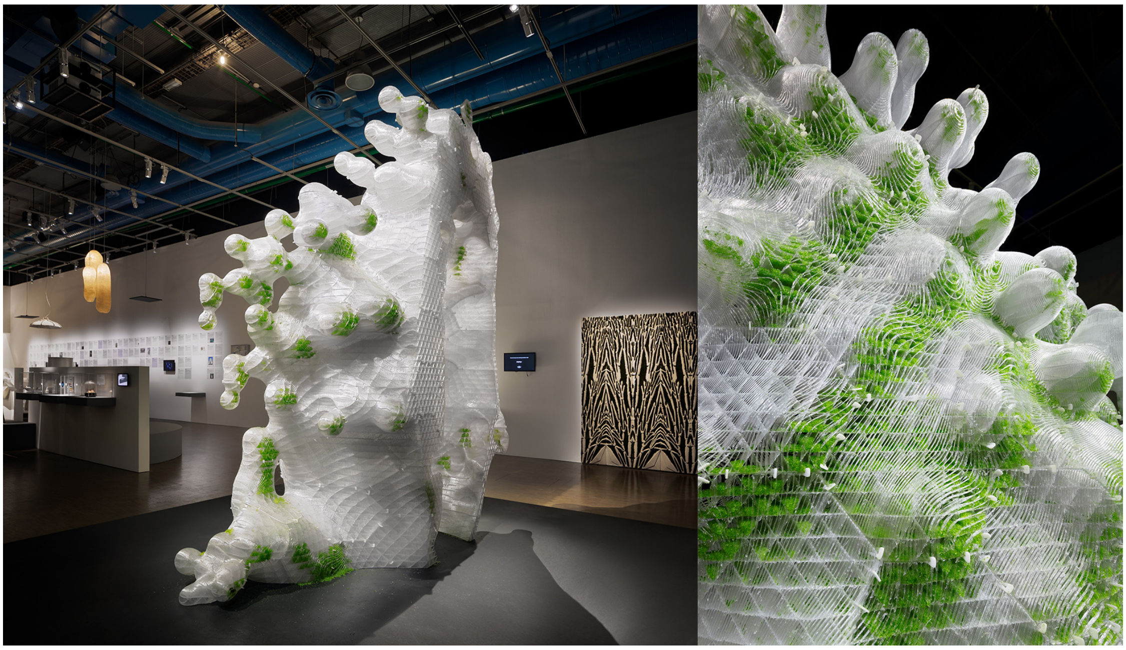


Figure 5. 3D printing process and result of H.O.R.T.U.S XL.

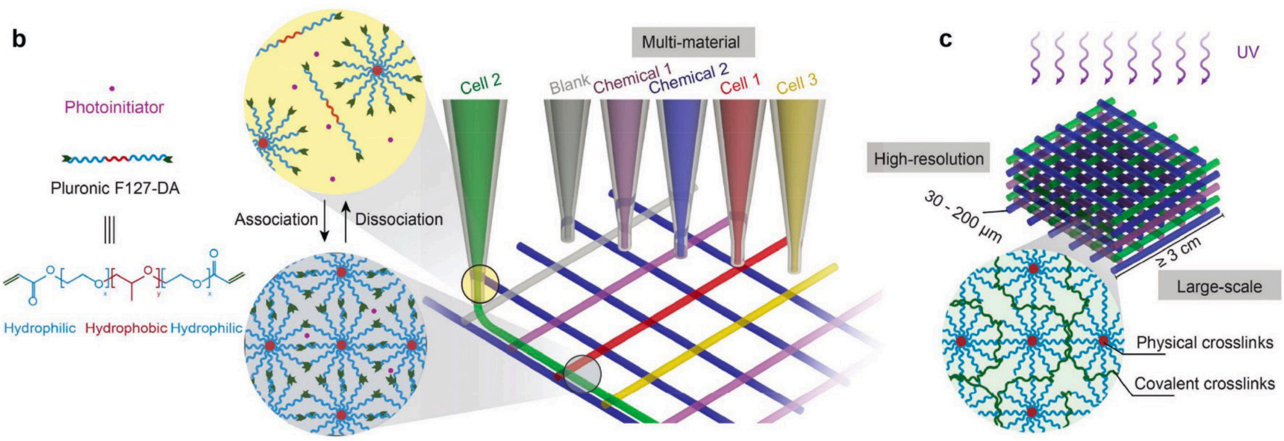


Figure 6. Schematic illustration of Living Tattoo shows direct writing of hydrogel inks.

In the design of living artefacts, 3D bioprinting has been particularly used to create templates for exogenous chemical or environmental signals in living artefacts. For example, in the case of **Living Tattoo**, a 3D bioprinted tattoo that detects chemicals on human skin (Liu et al., 2017), 3D bioprinting has enabled the integration of a collection of multiple chemical-sensing cells and chemical signals printed on the surface of a bilayer elastomeric sheet (Liu et al., 2017; Figure 6).

Although not all 3D printers are designed to deposit cells and chemicals, some can be hacked to do so. For instance, in **Vespers III**, Objet Connex 500 multi material inkjet-based 3D printer has been used to incorporate and distribute chemical inducers in the construction material of the artefact. While the two traditional print resins were used to print out the physical scaffold, one support material (usually abandoned after printing) was used in an unconventional way—to encapsulate chemical signals. In this way, living organisms were directed for desired effects by adding chemical matter to the habitat constructions in a controlled manner.

Perpetuating the Habitat

Previous pillars concern how designers can understand, model, and fabricate the habitat of a particular living organism in order to condition a certain biological behavior in the design outcome. The digital tools supporting those tasks are mainly used in the design time. Yet, digital tools can also play an important role in supporting the life of a living artefact in the use time.

The third pillar of the taxonomy concerns the perpetuation of the habitat so that the living organism can carry on its function or acquire new functionalities over time. Below, we describe ways in which digital tools are currently being used in biodesign to help regulate the care for living artefacts and to help interface living artefacts and other living things (humans and non-humans) in the context of use.

Regulating Conditions

In order for living organisms to thrive and perform stably, the internal and external elements of their habitat should be regulated. A well-known instance of digital tools regulating (human) habitats is Learning Thermostat (https://store.google.com/us/product/nest_thermostat?hl=en-US), which monitors and adjusts ambient temperature in cooperation with and by learning from people and their daily habits.

Digital tools can facilitate habitat regulation in an automated manner, to minimize human intervention, i.e., self-sustaining habitats (Karana et al., 2020). To that aim the habitat is equipped with sensing capabilities to measure the organism's wellbeing and control units to make decisions and take actions accordingly to modify and optimize. In such cases, humans have a passive role complying with convenience or need for precision. Automated regulation has been widely applied in industrial-scale bioprocessing, where fresh medium is added to the fermenter or bioreactor, while used medium and cells are harvested in automated ways. An example of such a self-sustaining habitat among biodesign cases is Caravel. It is an installation composed of a swarm of *bio-machines* that move and communicate with themselves on water while purifying organic matter in the water. The bacteria on the installation's carbon-brush-tentacles convert waste into electricity through their metabolism process. Digital components are able to make use of this electricity and move. In such a way, the installation keeps the looping process of finding waste matter and moving, thus purifying water (Figure 7).

Digital tools can deliberate human active participation in maintaining the condition of the habitat in a cooperative manner. This has been achieved through providing data-assisted control stations or predetermined mappings between quantitative data of human activities and the changes in the habitat parameters (Merritt et al., 2020). **Living Things** is an example of a living artefact where humans contribute to the regulation of the habitat directly by harvesting the excess biomass which would otherwise be more likely to sediment and attach to the walls (Huang et al., 2017). The artefact is a domestic lighting installation system, where microalgae are kept in glass vessels, sharing the light source with human residents. The mechanism of photobioreactors is for pumping air and mixing the liquid culture, while also allowing the outlet of biomass (used as agricultural fertilizer or biofuel later), from the microalgae through different valves, to keep the growth rate and volume of microalgae inside the vessels (Figure 8).

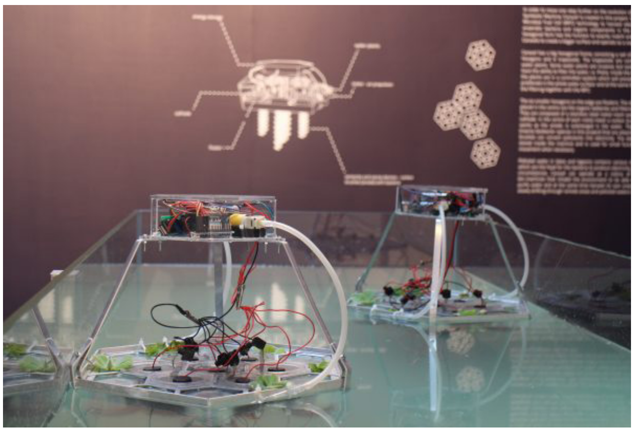


Figure 7. Caravel.

Figure 8. Living Things Light.

Regulation in **Rafigh** (Hamidi & Baljko, 2014) is enabled by the mapping of the quantitative data from human activities (unrelated to the living artefact) to a specific habitat element, namely, water (Figure 9). The control of water moderates mushroom growth depending on user behavior in their digital applications. The more time spent on target applications, the more water is administered to the mushrooms by the system, thus the more growth the mushrooms show. In this case, the digital tools help form mutually beneficial relationships between the living organism and the user through an indirect regulation of a system, which is intended to facilitate behavior change.

Interfacing Multispecies

Apart from regulation, digital tools can help interfacing how the state of living is being communicated between multispecies (humans and non-humans) which cohabitate within the same environment. Digitally interfacing human and non-human habitats is not new. Digital tools have been used by farmers for many years to ensure optimum living conditions for crops. One example is *Farmer's Helper*—developed by an engineer-turned farmer in Taiwan—a chat bot which offers information about the suitability of the season for growing certain crops and alerts extreme weather conditions and possible pest attack (Liu et al., 2019). Sensor technologies have also enabled people who have little acquaintance with growing plants to learn about house plants' habitability. A recent example is Soil Testers (e.g., Flower Monitor), which communicates real-time information about light, water, nutrients, and temperature to users via a smartphone App.

Besides a single event of communication between humans and living artefacts, communication enabled by digital tools can concern many species in a more complex manner with the aid of data technology. **Living Wall** addresses the specific challenges of maintaining a multi-species *eco-habitat façade* in an extreme climate (Figure 10). A multi-stakeholder workflow/monitoring system (Building Information Modelling or BIM in short) allows for interactively monitoring and upkeeping the situated living wall over time. According to the designer, the interactive BIM platform is informed by data from "*granular interactions between the living wall's surface, fauna habitats and specific plants, with reference to user proximity, daily water distribution and local temperature values*" (Briscoe, 2020, p. 652). The wall is designed specifically to accommodate other species (e.g., pollinators and songbirds, etc.) and increase biodiversity in the hot and dry climate, and, at the same time, deter non-native species from entering.

The interfacing is not necessarily done through numerical information. In the case of **Urban Algae Canopy**, for instance, humans and algae are interfaced through an interactive shading system. The interactive pavilion is home to living micro-algal cultures that convert solar energy into biomass and oxygen, while

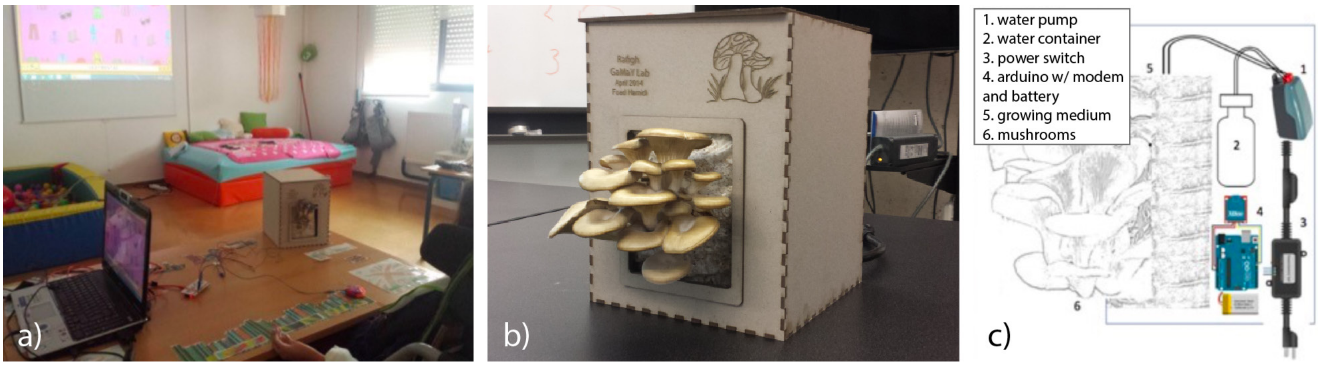


Figure 9. Rafigh: a) use scenario, b) the artifact, and c) the schematic illustration of its configuration.

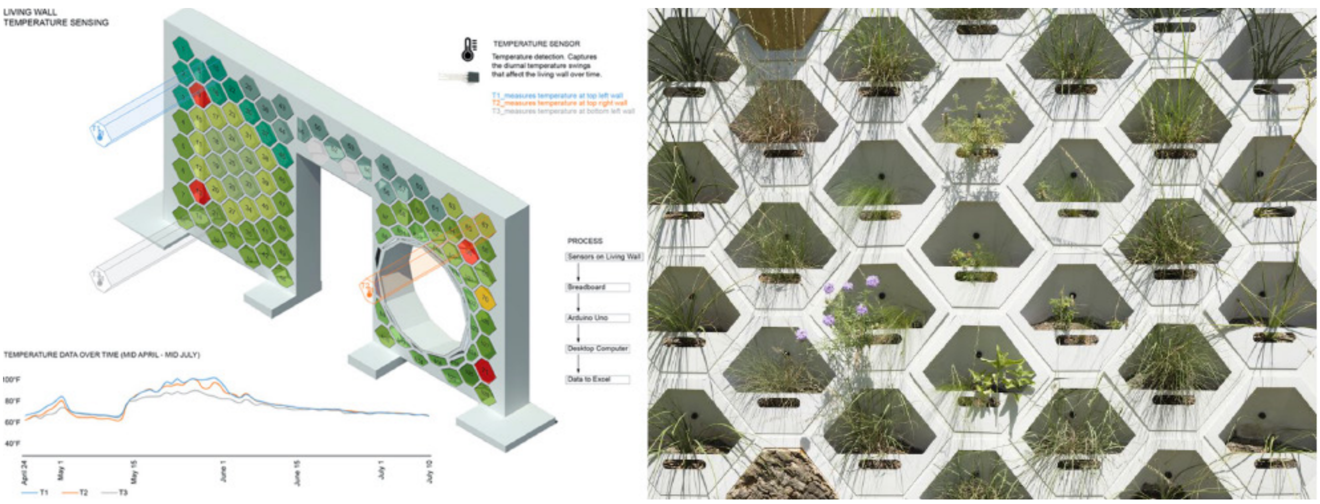


Figure 10. Living Wall's schematic illustration and close-up view.

providing shades and microclimate for humans (Figure 11). Digital camera tracking provides real-time human position mapping to the system, which then activates and adjusts the distribution of shading provided by algae. The central digital system consists of proximity sensors and controllers, computing the status of electro valves to alter the speed of algal flow through the canopy provoking an emergent differentiation across the space. Thanks to the digital tools, Algae obtains the ability to *detect* humans in order to provide shade.

In addition to interfacing humans and non-humans through data representation and functional coordinates, digital tools may help to establish symbolic relations between multispecies. For instance, in **Living Light**, a lamp which harvests its energy from bacteria in soil that feed on organic matter generated by plants through the photosynthetic process, i.e., Plant—Microbial Fuel Cell (Helder, 2012; Karube et al., 1976; Logan et al., 2006; Timmers et al., 2010; see Figure 12). The wellbeing of plants and bacteria is communicated through the amount of light it can emit. The plant leaves act as a sensing interface between human and living artefact, enabled by digital components that process bioelectrical signals (Fromm & Lautner, 2007). The action of touch and caressing suggests a *mutualistic care* scenario, even though the link is symbolic and the immediate response is enabled through a microcontroller (Karana et al., 2020).

Discussion

Our work in this paper is an invitation to engage in conversation about possible *other biological futures* (Ginsberg & Chieza, 2018), by contributing a more-than-human perspective (i.e., through a habitability lens) to understanding the contributions of digital technologies to biodesign. The presented taxonomy will guide design and HCI communities in exploring new ways of understanding, embodying, and perpetuating the habitat for living organisms, as well as foreseeing challenges that otherwise might be overlooked. To sum up, the taxonomy aims at 1) providing a conceptual framework to support the understanding of, and designing for, habitabilities through digital tools, 2) presenting case-specific practical knowledge to support new biodesign endeavours, e.g., design for perpetuation, and 3) inspiring the appropriation of the existing digital tools or their advancement as well as the development of novel digital tools to support more complicated scenarios in design and HCI (e.g., tools for empathetic interfaces between humans and living artefacts), and helping biodesigners and researchers to position the role of these tools in their specific projects.

In this final section, we emphasize two emerging directions from our taxonomy that need to take center stage in the design of such systems, and highlight the implications of our taxonomy for future biodesign and HCI research.

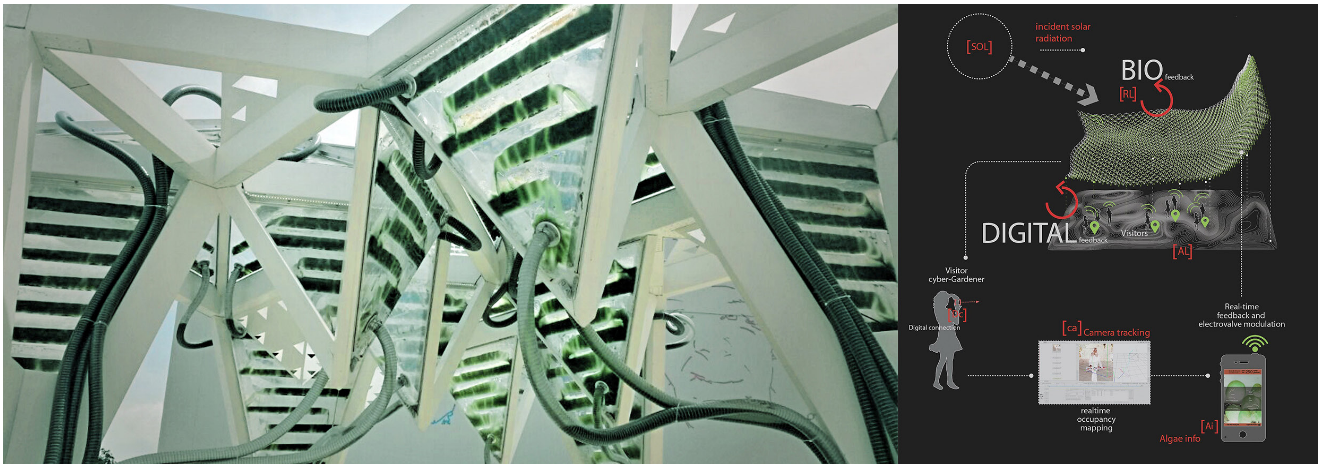


Figure 11. Urban Algae Canopy's close-up view and schematic illustration.

Figure 12. Living Light and its electronic component.

Design for Perpetuation

A key concept that underpins our proposed taxonomy is *habitabilities* (Karana et al., 2020). From a biological perspective, a habitat of a living artefact should allow the organism to maintain its biological functions, for example, replication and respiration, in a harmonious and sustainable way. Science and engineering studies offer solutions for self-sustaining habitats in the context of Engineered Living Materials (ELM), such as utilizing bacteria spores (González et al., 2020), a systematic approach to integrate different channels and compartments (Liu & Xu, 2020), and co-culturing of cooperative cells (Elias & Banin, 2012). Likewise, for living artefacts we see potential in incorporating digital technologies particularly to support self-sustaining habitats (see in the taxonomy, e.g., Caravel and The Living Things).

On the other hand, from a social perspective, the (symbiotic) relation between humans and non-humans could be considered in creating a livable habitat for living organisms throughout their life. For example, the human body may provide the habitat for a living artefact (see Biogarmentry, Aghighi, 2018; Carbon Eaters, 2018; Breathing Shoes, Help make your own shoe, while wearing it, 2019), or the artefact could live in a symbiotic relationship with another microorganism (see Living Light Lamp, Caravel, and Living Wall in our taxonomy). Future design methods should accommodate the design of such living artefacts, anticipate possible consequences, and consider the contextual significance of the symbiotic relation. *Designing for perpetuation then, as we have referred to in the taxonomy, requires designers to draw special attention, from the very beginning of the design process, to how habitability is biologically configured at design time as well as socially maintained at use time*. Envisioning scenarios of care will be central to designing for perpetuation in the design of living artefacts.

Design for Multispecies Cohabitation

When designers *hand over* the living artefact to users, the design of the living artefact is not finished: it is extended in use. It remains open to change, and over time will adapt in use, in a dynamic and unexpected way (see, for example Urban Algae Canopy). Communication between the human and non-human entities sharing the same habitat usually results in a highly dynamic interplay that cannot be fully anticipated. Similar to future algorithmic practices (Giaccardi & Redström, 2020), this will require a biodesign practice that discerns and integrates different capabilities (human and non-human) into appropriate co-performances (Kuijer & Giaccardi, 2018). Herein, we foresee the potential of digital tools in fostering co-performance in support of practices which help maintain the wellbeing of both humans and non-humans in everyday life, i.e., cohabitation. In the taxonomy, we illustrated how digital tools support cohabitation and forms of multispecies (symbiotic) relations that go beyond the deliberate actions taken by humans to keep the organisms alive (Karana et al., 2020). Examples of such a role, e.g., encouraging emotional connection, were discussed in the analysis of the Living Light Lamp case (see taxonomy), and can be found in projects such as Nukabot (Chen et al., 2021), e.g., supporting communication with other living entities through natural language (Chen et al., 2021). In designing for multispecies cohabitation, we foresee that digital tools will support the interface between humans and living artefacts to be empathetic and communicative.

Limitations of Our Work

We based our analysis and categorization on existing cases of living artefacts. The cases were selected within a certain period (April-September 2020). As biodesign is a fast-developing field, it could be that new living artefacts and new digital tools were developed after the selection period. Although our taxonomy does not mean to be exhaustive, we acknowledge this potential limitation of our methodology.

Another limitation of our work is that we have not elaborated on the actual use of the taxonomy in this paper. In our future work, we aim to conduct a study with biodesigners to explore whether the taxonomy could help them in their design process as we envision, and reveal its unexpected implications.

Conclusion

Our work attempts to bridge the gap of unexplored roles of digital tools in crafting habitabilities with and for living artefacts, taking multispecies and their relationships as a focal point of biodesign practice. Grounded in a systematic analysis of ten cases of living artefacts from HCI, design, and art, our taxonomy provides a compass of digital tools for *understanding, embodying, and perpetuating* the designed habitat. The taxonomy emphasizes the importance for designers to consider the whole biodesign continuum, and pay special attention to how habitabilities are biologically configured at design time as well as socially maintained at use time, from the very beginning of the design process. To that end, our taxonomy provides a frame of reference to enable multispecies cohabitation and co-performance in the design of living artefacts by crafting habitabilities comprehensively, instead of instrumentalizing biological materials or focusing on a single event of cohabitation. The paper concludes by discussing *designing for perpetuation* and *designing for multispecies cohabitation* as emerging biodesign practices, which creates space for more inclusive biological futures.

References

1. Aghighi, R. (2018). *Biogarmentry*. Retrieved July 20, 2022, from https://www.royaaghighi.com/biogarmentry.html
2. Aspling, F., Wang, J., & Juhlin, O. (2016). Plant-computer interaction, beauty and dissemination. In *Proceedings of the 3rd international conference on animal-computer interaction* (no.5, pp.1-10). ACM. https://doi.org/10.1145/2995257.2995393
3. Bader, C., Patrick, W. G., Kolb, D., Hays, S. G., Keating, S., Sharma, S., Dikovsky, D., Belocon, B., Weaver, J. C., Silver, P. A., & Oxman, N. (2016). Grown, printed, and biologically augmented: An additively manufactured microfluidic wearable, functionally templated for synthetic microbes. *3D Printing and Additive Manufacturing*, *3*(2), 79-89. https://doi.org/10.1089/3dp.2016.0027

4. Bader, C., Sharma, S., Smith, R. S. H., Disset, J., & Oxman, N. (2018). Viva in silico: A position-based dynamics model for microcolony morphology simulation. In *Proceedings of artificial life conference* (pp. 304-310). ASME. https://doi.org/10.1162/isal_a_00060
5. Balasubramanian, S., Yu, K., Meyer, A. S., Karana, E., & Aubin-Tam, M. E. (2021). Bioprinting of regenerative photosynthetic living materials. *Advanced Functional Materials, 31,* 2011162. https://doi.org/10.1002/adfm.202011162
6. Bancroft, G. N., Sikavitsas, V. I., van den Dolder, J., Sheffield, T. L., Ambrose, C. G., Jansen, J. A., & Mikos, A. G. (2002). Fluid flow increases mineralized matrix deposition in 3D perfusion culture of marrow stromal osteoblasts in a dose-dependent manner. *Proceedings of the National Academy of Sciences of the United States of America*, *99*(20), 12600-12605. https://doi.org/10.1073/pnas.202296599
7. Barati, B., Karana, E., Pont, S., & van Dortmont, T. (2021). Living light interfaces–an exploration of bioluminescence aesthetics. In *Proceedings of the designing interactive systems conference* (pp. 1215-1229). ACM. https://doi.org/10.1145/3461778.3462038
8. Bardzell, S., & Bardzell, J. (2011). Towards a feminist HCI methodology: social science, feminism, and HCI. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 675-684). ACM. https://doi.org/10.1145/1978942.1979041
9. Briscoe, D. (2020). Living wall: Digital design and implementation. *Journal of Digital Landscape Architecture*, *2020*(5), 646-653. https://doi.org/10.14627/537690066
10. Brodland, G. W. (2015). How computational models can help unlock biological systems. *Seminars in Cell and Developmental Biology*, *47-48*, 62-73. https://doi.org/10.1016/j.semcdb.2015.07.001
11. Camere, S., & Karana, E. (2017). Growing materials for product design. Alive. Active. Adaptive. In *Proceedings of the international conference on experiential knowledge and emerging materials* (pp. 101-115). TU Delft Open.
12. Camere, S., & Karana, E. (2018). Fabricating materials from living organisms: An emerging design practice. *Journal of Cleaner Production*, *186*(10), 570-584. https://doi.org/10.1016/j.jclepro.2018.03.081
13. *Carbon eaters.* (2018). Puma and MIT design lab. Retrieved July 20, 2022, from https://design.mit.edu/projects/puma-biodesign
14. Chen, D., Seong, Y. ah, Ogura, H., Mitani, Y., Sekiya, N., & Moriya, K. (2021). Nukabot: Design of care for human-microbe relationships. In *Proceedings of the SIGCHI conference on human factors in computing systems* (no. 291, pp. 1-7). ACM. https://doi.org/10.1145/3411763.3451605
15. Cheok, A. D., Kok, R. T., Tan, C., Fernando, O. N. N., Merritt, T., & Sen, J. Y. P. (2008). Empathetic living media. In *Proceedings of the conference on designing interactive systems* (pp. 465-473). ACM. https://doi.org/10.1145/1394445.1394495
16. Ciobanu, P. (2019). *Designing for and with care in multispecies kinship: Exploring methods of decentering the human in design*. Retrieved July 20, 2022, from https://kth.diva-portal.org/smash/get/diva2:1337125/FULLTEXT01.pdf
17. Ciuffi, V. (2013). Growing design. *Abitare Magazine, 531*, 108-111.
18. Clarke, R., Heitlinger, S., Light, A., Forlano, L., Foth, M., & DiSalvo, C. (2019). More-than-human participation: Design for sustainable smart city futures. *Interactions*, *26*(3), 60-63. https://doi.org/10.1145/3319075
19. Collins, J. (2012). Synthetic biology: Bits and pieces come to life. *Nature*, *483*(7387), S8-S10. https://doi.org/10.1038/483S8a
20. Comber, R., Bardzell, S., Bardzell, J., Hazas, M., & Muller, M. (2020). Announcing a new CHI subcommittee. *Interactions*, *27*(4), 101-103. https://doi.org/10.1145/3407228
21. Congdon, A., di Silvio, L., & Collet, C. (2020). Tissue engineered textiles. In K. Townsend, R. Solomon, & A. Briggs-Goode (Eds.), *Crafting anatomies: Archives, dialogues, fabrications* (pp. 137-148). Bloomsbury Visual Arts
22. Dew, K. N., & Rosner, D. K. (2018). Lessons from the woodshop: Cultivating design with living materials. In *Proceedings of the SIGCHI conference on human factors in computing systems* (no. 585, pp. 1-12). ACM. https://doi.org/10.1145/3173574.3174159
23. Elias, S., & Banin, E. (2012). Multi-species biofilms: Living with friendly neighbors. *FEMS Microbiology Reviews*, *36*(5), 990-1004. https://doi.org/10.1111/j.1574-6976.2012.00325.x
24. Evers, L. (2015, March 26). *Dreaming of a microbial perfume*. Retrieved July 13, 2021, from https://waag.org/en/article/dreaming-microbial-perfume
25. Fernando, O. N. N., Cheok, A. D., Merritt, T., Peiris, R. L., Fernando, C. L., Ranasinghe, N., Wickrama, I., Karunanayaka, K., Wei, C. T., & Tandar, C. A. (2009). Babbage cabbage: Empathetic biological media. In *Proceedings of the virtual reality international conference* (pp. 20-23). Laval Virtual Europe.
26. Fernando, P. (2019). Tools for public participation in science: Design and dissemination of open-science hardware. In *Proceedings of the international conference on the creativity and cognition (pp. 697-701). ACM*. https://doi.org/10.1145/3325480.3326560
27. Fernando, P., & Kuznetsov, S. (2020). OScH in the wild: Dissemination of open science hardware and implications for HCI. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 1-13). ACM. https://doi.org/10.1145/3313831.3376659
28. Fernando, P., Pandelakis, M., & Kuznetsov, S. (2016). Practicing DIY biology in an HCI setting. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 2064-2071). ACM. https://doi.org/10.1145/2851581.2892325
29. *Flower monitor.* (n.d.). Xiaomi. Retrieved July 13, 2021, from https://www.mi.com/flowermonitor
30. Forlano, L. (2016). Decentering the human in the design of collaborative cities. *Design Issues*, *32*(3), 42-54. http://doi.org/10.1162/DESI_a_00398

31. Flanagan, P., & Frankjaer, R. (2018). Rewilding wearables: Sympoeitic interfaces for empathic experience of other-than-human entities. In *Proceedings of the twelfth international conference on tangible, embedded, and embodied interaction* (pp. 611-616). ACM. https://doi.org/10.1145/3173225.3173316
32. Fromm, J., & Lautner, S. (2007). Electrical signals and their physiological significance in plants. *Plant, Cell and Environment*, *30*(3), 249-257. https://doi.org/10.1111/j.1365-3040.2006.01614.x
33. Fujii, H., Yoshida, K., & Sugimura, K. (2016). Research and development strategy in biological technologies: A patent data analysis of Japanese manufacturing firms. *Sustainability*, *8*(4), no. 351. http://doi.org/10.3390/su8040351
34. Giaccardi, E., & Redström, J. (2020). Technology and more-than-human design. *Design Issues*, *36*(4), 33-44. https://doi.org/10.1162/desi_a_00612
35. Gilbert, S. F., Sapp, J., & Tauber, A. I. (2012). A symbiotic view of life: We have never been individuals. *The Quarterly Review of Biology*, *87*(4), 325-341. https://doi.org/10.1086/668166
36. Ginsberg, A. D., Calvert, J., Schyfter, P., Elfick, A., & Endy, D. (2014). *Synthetic aesthetics: Investigating synthetic biology's designs on nature*. MIT Press.
37. Ginsberg, A. D., & Chieza, N. (2018). Editorial: Other biological futures. *Journal of Design and Science*, 1-14. https://doi.org/10.21428/566868b5
38. Gome, G., Waksberg, J., Grishko, A., Wald, I. Y., & Zuckerman, O. (2019). OpenLH: Open liquid-handling system for creative experimentation with biology. In *Proceedings of the 13th international conference on tangible, embedded, and embodied interaction* (pp. 55-64). ACM. https://doi.org/10.1145/3294109.3295619
39. González, L. M., Mukhitov, N., & Voigt, C. A. (2020). Resilient living materials built by printing bacterial spores. *Nature Chemical Biology*, *16*(2), 126-133. https://doi.org/10.1038/s41589-019-0412-5
40. Gough, P. (2020). The nature of biodesigned systems: Directions for HCI. In *Proceedings of ACM international conference on designing interactive systems (pp. 389-392)*. ACM. https://doi.org/10.1145/3393914.3395908
41. Gough, P., Forman, J., Pataranutaporn, P., Hepburn, L. A., Ramirez-Figueroa, C., Cooper, C., Vujic, A., Kong, D. S., Kim, R., Maes, P., Ishii, H., Sra, M., & Ahmadpour, N. (2021). Speculating on biodesign in the future home. In *Proceedings of the conference on human factors in computing systems* (pp. 11-15). ACM. https://doi.org/10.1145/3411763.3441353
42. Groutars, E.G., Risseeuw, C.C., Ingham, C., Hamidjaja, R., Elkhuizen, W.S., Pont, S.C., & Karana, E. (2022). Flavorium: An Exploration of Flavobacteria's Living Aesthetics for Living Color Interfaces. In *Proceedings of the SIGCHI conference on human factors in computing systems*. (pp.1-19). ACM. https://doi.org/10.1145/3491102.3517713
43. Hamidi, F., & Baljko, M. (2014). Rafigh: A living media interface for learning games. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 407-410). ACM. https://doi.org/10.1145/2559206.2574772
44. Hamidi, F., Baljko, M., & Gómez, I. (2017). Using participatory design with proxies with children with limited communication. In *Proceedings of the 19th international ACM SIGACCESS conference on computers and accessibility* (pp. 250-259). ACM. https://doi.org/10.1145/3132525.3132527
45. Haraway, D. J. (2008). *When species meet*. University of Minnesota Press.
46. Helder, M. (2012). *Design criteria for the plant-microbial fuel cell: Electricity generation with living plants—From lab to application*. Retrieved July 20, 2022, from https://edepot.wur.nl/239054
47. *Help make your own shoe, while wearing it.* (2019, April 10). Catch up PUMA's employee magazine. Retrieved July 20, 2022, from https://www.puma-catchup.com/charles-johnson-on-how-puma-creates-a-breathing-shoe-with-the-help-of-bacteria/
48. Holstius, D., & Kembel, J. (2004). Infotropism: Living and robotic plants as interactive displays. In *Proceedings of the 5th conference on designing interactive systems* (pp. 215-221). ACM. http://doi.acm.org/10.1145/1013115.1013145
49. Holstius, D., Kembel, J., Hurst, A., Wan, P. H., & Forlizzi, J. (2004). Infotropism: Living and robotic plants as interactive displays. In *Proceedings of the conference on designing interactive systems* (pp. 215-221). ACM. https://doi.org/10.1145/1013115.1013145
50. Huang, Q., Jiang, F., Wang, L., & Yang, C. (2017). Design of photobioreactors for mass cultivation of photosynthetic organisms. *Engineering*, *3*(3), 318-329. https://doi.org/10.1016/J.ENG.2017.03.020
51. Henriques, I. (2016). *Caravel*. Retrieved July 13, 2021, from https://ivanhenriques.com/works/caravel/
52. Fant, J. (2011, September 14). *Microbial marketing: Bacteria and fungi infect contagion's billboard*. Retrieved July 13, 2021, from https://www.zdnet.com/article/microbial-marketing-bacteria-and-fungi-infect-contagions-billboard/
53. Jian, H., Wang, M., Wang, S., Wang, A., & Bai, S. (2018). 3D bioprinting for cell culture and tissue fabrication. *Bio-Design and Manufacturing*, *1*(1), 45-61. https://doi.org/10.1007/s42242-018-0006-1
54. Jurtshuk, P. Jr. (1996). Bacterial metabolism. In S. Baron (Ed.), *Medical microbiology* (ch. 4). University of Texas Medical Branch at Galveston.
55. Karana, E., Barati, B., & Giaccardi, E. (2020). Living artefacts: Conceptualizing livingness as a material quality in everyday artefacts. *International Journal of Design*, *14*(3), 37-53.
56. Karp, G. (2018). *Cell and molecular biology: Concepts and experiments* (8th ed.). John Wiley & Sons.
57. Karube, I., Matsunaga, T., Tsuru, S., & Suzuki, S. (1976). Continous hydrogen production by immobilized whole cells of Clostridium butyricum. *Biochimica et Biophysica Acta (BBA)-General Subjects*, *444*(2), 338-343. https://doi.org/10.1016/0304-4165(76)90376-7
58. Klarenbeek, E. (2014). *Mycelium chair*. Retrieved July 13, 2021, from https://www.ericklarenbeek.com
59. Kuijer, L., & Giaccardi, E. (2018). Co-performance: Conceptualizing the role of artificial agency in the design of

everyday life. In *Proceedings of the conference on human factors in computing systems* (no. 125, pp. 1-13), ACM. https://doi.org/10.1145/3173574.3173699

60. Kuribayashi, S., Sakamoto, Y., & Tanaka, H. (2007). I/O plant: A tool kit for designing augmented human-plant interactions. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 2537-2542). ACM. https://doi.org/10.1145/1240866.1241037
61. Kuribayashi, S., & Wakita, A. (2006). PlantDisplay: Turning houseplants into ambient display. In *Proceedings of the international conference on advances in computer entertainment technology* (pp. 40-es). ACM. https://doi.org/10.1145/1178823.1178871
62. Kuznetsov, S., Barrett, C., Fernando, P., & Fowler, K. (2018). Antibiotic-responsive bioart: Exploring DIYbio as a design studio practice. In *Proceedings of the SIGCHI conference on human factors in computing systems* (no. 463, pp. 1-14). ACM. https://doi.org/10.1145/3173574.3174037
63. Kuznetsov, S., Taylor, A. S., Paulos, E., DiSalvo, C., & Hirsch, T. (2012a). (DIY)biology and opportunities for HCI. In *Proceedings of the designing interactive systems conference* (pp. 809-810) ACM. https://doi.org/10.1145/2317956.2318085
64. Kuznetsov, S., Taylor, A. S., Regan, T., Villar, N., & Paulos, E. (2012b). At the seams: DIYbio and opportunities for HCI. In *Proceedings of the designing interactive systems conference* (pp. 258-267). ACM. https://doi.org/10.1145/2317956.2317997
65. Light, A., Powell, A., & Shklovski, I. (2017). Design for existential crisis in the anthropocene age. In *Proceedings of the 8th international conference on communities and technologies* (pp. 270-279). ACM. https://doi.org/10.1145/3083671.3083688
66. Liu, A. (2016). *Biota beats*. Retrieved July 13, 2021, from https://ani-liu.com/biota-beats
67. Liu, J., Byrne, D., & Devendorf, L. (2018). Design for collaborative survival: An inquiry into human-fungi relationships. In *Proceedings of the SIGCHI conference on human factors in computing systems* (no. 40, pp.1-13). ACM. https://doi.org/10.1145/3173574.3173614
68. Liu, S., & Xu, W. (2020). Engineered living materials-based sensing and actuation. *Frontiers in Sensors*, *1*. https://doi.org/10.3389/fsens.2020.586300
69. Liu, S. Y., Bardzell, J., & Bardzell, S. (2018). Photography as a design research tool into natureculture. In *Proceedings of the designing interactive systems conference* (pp. 777-790). ACM. https://doi.org/10.1145/3196709.3196819
70. Liu, S. Y., Bardzell, S., & Bardzell, J. (2019). Symbiotic encounters: HCI and sustainable agriculture. In *Proceedings of the conference on human factors in computing systems* (no. 317, pp.1-13). ACM. https://doi.org/10.1145/3290605.3300547
71. Liu, X., Yuk, H., Lin, S., Parada, G. A., Tang, T. C., Tham, E., de la Fuente-Nunez, C., Lu, T. K., & Zhao, X. (2017). 3D Printing of living responsive materials and devices. *Advanced Materials*, *30*(4). https://doi.org/10.1002/adma.201704821
72. Liu, Z., Tamaddon, M., Gu, Y., Yu, J., Xu, N., Gang, F., Sun, X., & Liu, C. (2020). Cell seeding process experiment and simulation on three-dimensional polyhedron and cross-link design scaffolds. *Frontiers in Bioengineering and Biotechnology*, *8*, 104. https://doi.org/10.3389/fbioe.2020.00104
73. Logan, B. E., Hamelers, B., Rozendal, R., Schröder, U., Keller, J., Freguia, S., Aelterman, P., Verstraete, W., & Rabaey, K. (2006). Microbial fuel cells: Methodology and technology. *Environmental Science & Technology*, *40*(17), 5181-5192. https://doi.org/10.1021/es0605016
74. MacAl, C. M., & North, M. J. (2010). Tutorial on agent-based modelling and simulation. *Journal of Simulation*, *4*(3), 151-162. https://doi.org/10.1057/jos.2010.3
75. Mancini, C. (2013). Animal-computer interaction (ACI): changing perspective on HCI, participation and sustainability. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 2227-2236). ACM. https://doi.org/10.1145/2468356.2468744
76. Manzella, V., Gaz, C., Vitaletti, A., Masi, E., Santopolo, L., Mancuso, S., Salazar, D., & de las Heras, J. J. (2013). Plants as sensing devices: The pleased experience. In *Proceedings of the 11th conference on embedded networked sensor systems* (no. 76, pp.1-2). ACM. https://doi.org/10.1145/2517351.2517403
77. Martini, S., & Haddock, S. H. D. (2017). Quantification of bioluminescence from the surface to the deep sea demonstrates its predominance as an ecological trait. *Scientific Reports*, *7*(1). https://doi.org/10.1038/srep45750
78. Mastrogiacomo, M., Scaglione, S., Martinetti, R., Dolcini, L., Beltrame, F., Cancedda, R., & Quarto, R. (2006). Role of scaffold internal structure on in vivo bone formation in macroporous calcium phosphate bioceramics. *Biomaterials*, *27*(17), 3230-3237. https://doi.org/10.1016/j.biomaterials.2006.01.031
79. McGrath, R. E. (2009). Species-appropriate computer mediated interaction. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 2529-2534). ACM. https://doi.org/10.1145/1520340.1520357
80. Merritt, T., Hamidi, F., Alistar, M., & DeMenezes, M. (2020). Living media interfaces: A multi-perspective analysis of biological materials for interaction. *Digital Creativity*, *31*(1), 1-21. https://doi.org/10.1080/14626268.2019.1707231
81. Mironov, V., Trusk, T., Kasyanov, V., Little, S., Swaja, R., & Markwald, R. (2009). Bio-fabrication: A 21st century manufacturing paradigm. *Biofabrication*, *1*(2), 022001. https://doi.org/10.1088/1758-5082/1/2/022001
82. Moisy, A., & Pschetz, L. (2017). Designing with living organisms. In *Proceedings of the 3rd biennial research through design conference* (pp. 323-339). RTD. https://doi.org/10.6084/m9.figshare.4746994
83. Montalti, M. (2010). *Officina corpuscoli*. Retrieved April 27, 2021, from https://www.corpuscoli.com
84. Myers, W. (2012). *Bio design*. Museum of Modern Art.
85. Nguyen, B. V. D., Wang, T.-H., & Peng, C. (2020). Integration of agent-based modelling of social-spatial processes in architectural parametric design. *Architectural Science Review*, *63*(2), 119-134. https://doi.org/10.1080/00038628.2019.1640107

86. Nyberg, E., Hipkiss, A. M., & Sanders, D. (2019). Plants to the fore: Noticing plants in designed environments. *Plants, People, Planet*, *1*(3), 212-220. https://doi.org/10.1002/ppp3.40
87. Olivares, A. L., & Lacroix, D. (2012). Simulation of cell seeding within a three-dimensional porous scaffold: A fluid-particle analysis. *Tissue Engineering. Part C: Methods*, *18*(8), 624-631. https://doi.org/10.1089/ten.tec.2011.0660
88. Oxman, N. (2010). *Material-based design computation* (Doctoral dissertation). Massachusetts Institute of Technology, MA.
89. Oxman, N., Laucks, J., Kayser, M., Duro-royo, J., & Gonzales-Uribe, C. (2014). Silk pavilion: A case study in fibre-based digital fabrication. In F. Gramazio, M. Kohler, & S. Langenberg (Eds.), *Fabricate 2014: Negotiating design & making* (pp. 248-255). UCL Press. https://doi.org/10.2307/j.ctt1tp3c5w.34
90. Parkes, A., & Dickie, C. (2013). A biological imperative for interaction design. In *Proceedings of the conference on human factors in computing systems* (pp. 2209-2218). ACM. https://doi.org/10.1145/2468356.2468742
91. Pasquero, C., & Poletto, M. (2020). Bio-digital aesthetics as value system of post: Anthropocene architecture. *International Journal of Architectural Computing*, *18*(2), 120-140. https://doi.org/10.1177/1478077120922941
92. Pataran, P., Kong, D. S., Maes, P., & Sra, M. (2020). Living bits: Opportunities and challenges for integrating living microorganisms in human-computer interaction. In *Proceedings of the augmented humans international conference* (no. 30, pp. 1-12). ACM. https://doi.org/10.1145/3384657.3384783
93. Pataranutaporn, P., Ingalls, T., & Finn, E. (2018). Biological HCI: Towards integrative interfaces between people, computer, and biological materials. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 1-6). ACM. https://doi.org/10.1145/3170427.3188662
94. Pavlovich, M. J., Hunsberger, J., & Atala, A. (2016). Biofabrication: A secret weapon to advance manufacturing, economies, and healthcare. *Trends in Biotechnology*, *34*(9), 679-680. https://doi.org/10.1016/j.tibtech.2016.07.002
95. Poupyrev, I., Schoessler, P., Loh, J., & Sato, M. (2012). Botanicus interacticus: Interactive plants technology. In *Proceedings of the SIGGRAPH* conference *on emerging technologies* (no. 4, p. 1). ACM. https://doi.org/10.1145/2343456.2343460
96. Ramirez-Figueroa, C., Hernan, L., & Pei-Ying, L. (2018). The biological unseen. Producing and mediating imaginaries of protocells. In *Proceedings of the 5th biennial transdisciplinary imaging conference* (pp. 122-137). https://doi.org/10.6084/m9.figshare.6104687
97. Seo, J. H., Sungkajun, A., & Suh, J. (2015). Touchology: Towards interactive plant design for children with autism and older adults in senior housing. In *Proceedings of the SIGCHI annual conference on human factors in computing systems* (pp. 893-898). ACM. https://doi.org/10.1145/2702613.2732883
98. Smith, N., Bardzell, S., & Bardzell, J. (2017). Designing for cohabitation: Naturecultures, hybrids, and decentering the human in design. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 1714-1725). ACM. https://doi.org/10.1145/3025453.3025948
99. Smith, R. S. H., Bader, C., Sharma, S., Kolb, D., Tang, T. C., Hosny, A., Moser, F., Weaver, J. C., Voigt, C. A., & Oxman, N. (2020). Hybrid living materials: Digital design and fabrication of 3D multimaterial structures with programmable biohybrid surfaces. *Advanced Functional Materials*, *30*(7), 1-14. https://doi.org/10.1002/adfm.201907401
100. Timmers, R. A., Strik, D. P., Hamelers, H. V. M., & Buisman, C. J. N. (2010). Long-term performance of a plant microbial fuel cell with spartina anglica. *Applied Microbiology and Biotechnology*, *86*(3), 973-981. https://doi.org/10.1007/s00253-010-2440-7
101. Tsing, A. L. (2015). *The mushroom at the end of the world*. Princeton University Press. https://doi.org/10.1515/9781400873548
102. Voet, D. (2007). *Fundamentals of biochemistry: Life at the molecular level*. Wiley.
103. Washington, P., Samuel-Gama, K., Goyal, S., & Riedel-Kruse, I. H. (2017). *Bioty: A cloud-based development toolkit for programming experiments and interactive applications with living cells.* BioRxiv. https://doi.org/10.1101/236919
104. Weiler, J., Fernando, P., Siyambalapitiya, N., & Kuznetsov, S. (2019). Mycelium artifacts: Exploring shapeable and accessible biofabrication. In *Proceedings of the designing interactive systems conference* (pp. 69-72). ACM. https://doi.org/10.1145/3301019.3325156
105. Wendt, D., Stroebel, S., Jakob, M., John, G. T., & Martin, I. (2006). Uniform tissues engineered by seeding and culturing cells in 3D scaffolds under perfusion at defined oxygen tensions. *Biorheology*, *43*(3-4), 481-488.
106. Westerlaken, M. (2020). *Imagining multispecies worlds*. Malmö University. https://doi.org/10.24834/isbn.9789178771059
107. Wooley, J. C., & Lin, H. S. (2005). *Catalyzing inquiry at the interface of computing and biology.* National Academies Press. https://doi.org/10.17226/11480
108. Yao, L., Ou, J., Cheng, C. Y., Steiner, H., Wang, W., Wang, G., & Ishii, H. (2015). Biologic: Natto cells as nanoactuators for shape changing interfaces. In *Proceedings of the SIGCHI annual conference on human factors in computing systems* (pp. 1-10). ACM. https://doi.org/10.1145/2702123.2702611
109. Zhou, J., Barati, B., Wu, J., Scherer, D., & Karana, E. (2021). Digital biofabrication to realize the potentials of plant roots for product design. *Bio-Design and Manufacturing*, *4*(1), 111-122. https://doi.org/10.1007/s42242-020-00088-2