ABSTRACT
Today, human activities constitute the primary environmental impact on the planet. In this context, commitments to sustainability, or minimization of damage, prove insufficient. To develop regenerative, futuring capabilities, architectural design needs to extend beyond the form and function of things and engage with the management of complex systems. Such systems involve multiple types of dynamic phenomena—biotic and abiotic, technical and cultural—and can be understood as living. Engagement with such living systems implies manipulation of pervasive and unceasing change, irrespective of whether it is valued by design stakeholders or actively managed towards homeostatic or homeorhetic conditions. On one hand, such manipulation of continuity requires holistic and persistent design involvements that are beyond natural capabilities of human designers. On the other hand, practical, political, or creative implications of reliance on automated systems capable of tackling such tasks are as yet underexplored. In response to this challenge, this paper considers an experimental approach that utilized methods of critical making and speculative designing to explore potentials of autonomous architecture. Presented experiments combined knowledge of animal architecture with intelligent behaviors of robotic devices.
1 LIVING ARCHITECTURE

Does architecture have strategic challenges? What are they? In any complex and diverse discipline this question can be answered differently. In order to frame the subsequent discussion, this section outlines some key concepts in nature and design. Necessarily brief, this introduction aims to point to likely goals for future design and its technical systems.

Contemporary discourse in architecture increasingly acknowledges its temporal characteristics and its situatedness within extended, complex and dynamic systems. These acknowledgements are motivated by environmental threats but take diverse forms, from the use of landscapes—living systems—as models for urbanism (Waldheim 2006, p. 37) to the development of standards aiming to define and encourage "living buildings", and "living futures" (International Living Future Institute 2014 [2006]).

1.1 MESSY ADAPTATION

Often, these interests are underpinned by appreciation of natural systems and motivated by the desire to make buildings that "operate as cleanly, beautifully and efficiently as nature's architecture" (International Living Future Institute 2015) and the conviction that "nature produces maxi-mum effect with minimum means" (Kolarevic and Klinger 2008, p. 10). This biophilic literature suggests that animals create "environmentally sensitive architecture," and that this architecture can be seen as a positive ideal when compared with poorly optimized human performance (Halliday 2008, p. 164).

In contrast to this optimism of designers, scientists warn that:

"[e]volutionary theory provides no justification for assuming perfection in natural design—we see only a blundering trial-and-error process working against a moving target, both physical and bio-logical. Natural selection suffers from lack of foresight, near impossibility of cross-lineage trans-fer of innovations, great difficulty making anything but incremental alterations, severe lock-in of established if fundamentally inferior designs, unavoidably multifunctional devices, and limitation to locally available resources, just to mention a few of the constraints under which it labors" (Vogel 2003, p. 404-405).

Moreover,

"[h]ereditary memory can [...] include non-genetic forms of inheritance that lie outside the tradi-tionally held views of an organism's outer boundary [...]. These can sometimes lead animal-built structures in some odd, and seemingly maladaptive ways. In short, not all natural systems will live up to what biomimetic architects seek in them" (Odling-Smee and Turner 2011).

In these conditions, decisions on which specific forms, structures of functions are
worth mimicking have to be made by human designers, in reference to existing criteria, understandings, and situations. Such mimicking can be inspirational, but it is also always exploitative. When a found effect is decoupled from its context and causes and transferred into a new setting, it becomes a technology like any other, with a new set of impacts. Some of these impact will likely fit narrow human goals, others will be unpredictable and, as likely, harmful. Further, natural phenomena are mimicked because they are recognizable in reference to already known human solutions. This dependence on the existing artificial context limits opportunities for unexpected discoveries. Finally, the innovation potential of this mimicking of found effects is constrained by the expertise of designers choosing what to copy and the limits of the available scientific knowledge. Overcoming these limitations is one of the main motivations of the research discussed in this paper. What strategies might be more inclusive and open to novelty?

1.2 STRUCTURE AS PROCESS

A premise of this paper is that such strategies should focus on systems and their processes. Under this view, particular structures can be understood as effects of processes. For example, some scientists describe habitats created or modified by animals as constructed ecological niches (Odling-Smee, Laland, and Feldman 2003) or physiological extensions of animals’ organisms (Turner 2000). Speculating on designing that would mimic such physiology rather than mimicking forms, they suggest that such architecture should:

"[..] invite a radical examination of what might be called architectural epistemology: what meaning is embodied in the structures we build and inhabit? Traditionally, both architects and biologists have operated on the assumption that structure is object and function is process—structure (anatomy) is the physical venue for function (physiology). In contrast, the increasingly assertive lesson from biology, and from [the niche construction theory], is that this distinction no longer holds: living structures at any scale are not objects, but are properly regarded as process—dynamic assemblages of matter organized in a specific way by order-producing work [...]. The capability of adaptation includes the continual reshaping of the environmental context in which a process occurs. The ideal biomimetic building will incorporate this sort of dynamism into its design. In short, [the niche construction theory] opens the philosophical door to that ideal of the physiomimetic architect, the living building” (Odling-Smee and Turner 2011).

"The building-as-machine paradigm cannot quite capture this kind of seamless integration, largely because it regards structure as something distinct from function. It is therefore unlikely that the living building can emerge from this design tradition. In living systems, however, no such distinction is possible: structure is function and function is structure. At present, simply stating this offers little practical value in telling us how to realize a living building, but it at
least points us the right way: toward buildings that are extended organisms, where function and structure meld, and are controlled by the overriding demands of homeostasis” (Turner and Soar 2008, p. 234).

1.3 ARCHITECTURE AS CONVERSATION

Scientists that promote what can be grouped as the Extended Evolutionary Synthesis (Laland et al. 2014; Pigliucci and Müller 2010) suggest that selection (and the resulting effect of adaptation) occurs on multiple levels and through multiple mechanisms, not only through Darwinian variation, inheritance and natural selection (of genes). From this, Odling-Smee and Turner suggest that a “biomimetic building” should:

“incorporate into its design the possibility for similar "conversations" among structure, occupants, and function […]. This invites a radical examination of the role of the "biomimetic architect." Is the architect a specifier of a building’s apt function, imposing a particular regime of function on the building’s occupants, similar to the way (the Standard Evolutionary Theory) assumes genes impose a regime of function on the organism? Or is the biomimetic architect the mediator of a conversation between a building and its occupants in a way that puts the occupants in control of the constructed niches they inhabit? In short, is biomimetic architecture somewhat mis-named? Should it strive more properly to become physiomimetic architecture?” (Odling-Smee and Turner 2011).

Clearly, architects are not qualified to judge the validity of evolutionary theories. Whatever is the outcome of the ongoing debates on evolutionary mechanisms, experimentation with architectural ontologies and processes can proceed in parallel because even if existing theories disagree on the mechanisms of selection they seek to explain the same observed effects of biological life, such as that of gradual adaptation. While human-made habitats can be said to adapt at large scales, typical architectural ontologies and design principles do not position ongoing change at the center of design challenges. Some of the existing or past practices can be interpreted in this light and the parallel discourses are growing, for example, in regard to environmental contexts (O’Donnell 2015), architectural ecologies (Rawes 2013), or persistent representation (Ayres 2012). The ambition of this paper is to contribute to the next logical step and begin integrating such ideas into the tools and workflows of future-oriented designing.
1.4 OPPORTUNISTIC ARCHITECTURE

Can architectural design benefit from observing how biological systems tackle ongoing change without seeking to simulate actual biological mechanisms? Is it possible, instead of designing in reference to particular found effects, design in reference to the continuously ongoing change? A speculative model for such an approach would shift:

From pre-planning to ambiguity. Such a system would be able to make decisions in the process of construction, acting in the context of actual sites and in response to available information.

From central control to local diversity. Such a system would be able to take make local decisions that are not fully predetermined.

From performance thresholds to adaptability. Such a system would be able to change its mind in response to incoming information about its environment and the effects of its actions.

To enable such a shift, architectural design and construction workflows need means to observe the dynamic behaviors of host systems, understand relationships within these systems and have capabilities to react.

2 AUTONOMOUS DEPENDENCY

What might be the core properties of technical systems required to answer such a challenge? Who should direct the "order-producing work"? It is likely that encouraging results can be achieved through multiple approaches, for example through parametric, performance-oriented and designer-controlled modeling. This paper looks beyond direct-control approaches and seeks to benefit from the current architectural interest in robots expecting that robotic devices can be of use on one hand for automation of construction and on the other for amplification and rethinking of designing.

Robotics is a growing area of interest in architecture. At the moment, the attention within architecture is on industrial robotic arms that are attractive because they are common and comparatively cheap (Brell-Çokcan and Braumann 2013, p. 8). These devices belong to the subfield of manufacturing automation, or industrial robots. As such, they are intended for the environments with already existing manufacturing processes, control mechanisms, quality requirements and automation measures. In this context, their purpose is to benefit from financial opportunities that might be available through reduction of waste, improvement of quality, reduction of downtime and so on. Practical research in architecture aims to engage such robots on bespoke tasks through software and end-effector modifications. Advocates of this approach argue that employment of robotics in architecture promises "entirely new aesthetic and functional potentials that could fundamentally alter architectural design and the building culture" (Gramazio, Kohler and Willmann 2014, p. 14).
Beyond that, understandings of architecture, urban environments and landscapes as integrated, hybrid systems supported by smart environments raises questions of process automation, not dissimilar to those encountered in enterprise management: operability, quality, reliability, safety and viability. Automation of such systems calls for integrated approaches that rely on real-time data, the tools to extract information from that data, and the means for utilizing this information.

Further still, robots are not simply devices that act as programmable replacements for humans but are physically situated intelligent agents (Murphy 2000) within hybrid socio-technical ecologies, capable of more or less independent sensing, analysis, decision taking and action. Here, “an agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through actuators” (Russell, Norvig, and Davis 2010 [1995], p. 34). The “desirability of such an agent’s actions” is captured by a performance measure that evaluates any given sequence of environment states” (Russell, Norvig, and Davis 2010 [1995] p. 37).

The purpose of such agents is not in replacing people but in being better, at least in some aspects, than biological systems, projecting human capabilities into inaccessible environments or performing otherwise impossible tasks. Robotic agents can achieve these goals not because of their superior intelligence but through a combination of characteristics common to machines: ability to operate continuously and for long periods, ability to maintain speed and precision, ability to cope with large volumes of data, etc. The difference between automation and autonomy can be seen as the contrast between better tools (extension of human arms, tools with “long handles” such as drones, tools moving in bounded regions, not dissimilar to automatic weaving, such as manufacturing robots) and unsupervised agents such as mobile robots. Automation is the use of tools for the execution of precise, repetitions of actions in well-understood environments. Such environments are dealt with as controlled, closed worlds, or at least models of worlds that capture all that is relevant for a set of given operations. However, some worlds—such as typical architectural environments or construction sites—are not closed. Where models of such worlds are made, they are complex and incomplete. In such cases, complete preplanning of actions is not feasible or desirable. Instead, sensing and analytic capabilities can be employed for adaptation in response to feedback. Given this emphasis on adaptation in response to environmental conditions, autonomous agents can also, and perhaps more appropriately, described as dependent.

This ability to integrate with the surrounding environment and adapt to its changing conditions is of a particular interest here because it promises a path towards the “opportunistic architecture” discussed earlier. Like natural ecologies, such opportunistic architecture can be messy, but, like natural ecologies, it can also be resilient.

This prospect opens several research directions within architectural (and other environmental) design. Their detailed discussion is outside of the scope of this brief paper.
but some possibilities can be gleaned by the analogously motivated field of autonomic computing (Murch 2004) that aims to create systems that “know and understand” themselves; systems that can self-configure, self-optimize, self-heal, self-protect and so on. In relationship to these goals, and in extensions of currently common ambitions for robotics in architecture, one particular capability becomes important and that capability is autonomy. Indeed, this capability is recognized as intrinsic to robots, and some roboticists exclude arms that are typical in industrial automation systems from their understanding of this term.

According to ISO 8373:2010, robot is an “actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks”. The standardization effort is positioned within and within that, The Working Group 1 on Robots and Robotic devices, of the Subcommittee 2, of the ISO Technical Committee on Automation Systems and Integration, develops Vocabulary and Characteristics and defines autonomy as an “ability to perform intended tasks based on current state and sensing, without human intervention”. While related efforts, for example, those aiming to cope with imprecision of construction or human input (Helm et al. 2012), do exist, the potential of intelligent robots within architectural design is yet to be explored.

3 SYSTEM SKETCHES

In robotics, simulation can mean different things including graphic visualization of robot movements, prototypes of man-machine interfaces or numerical simulation of the dynamics, sensing and control of robots. In design, simulations, or performing models of strange ontologies (White-law, Guglielmetti and Innocent 2009), can be used to craft (Auger 2013), or at least sketch, speculative—possible but not necessarily desirable—relationships, workflows, design patterns, and use scenarios.

Seeking to merge these understandings, the metaphor of system sketches is employed here to emphasize that the persistent, living environments discussed in the first section of this paper cannot be completely pre-designed and instead need to be attempted, experienced, and adjusted. This sketching can be done during designing, through prototyping and simulation or integrated into the target environments as continuous construction.

Considering the role of architects in construction, Kieran and Timberlake argue that to retain relevance architects have to act as managers of intelligence and “the overseers of the exchange of information” (Kieran and Timberlake 2004, p. 22). In application to living environments, architects also need to engage with the biopolitics. And yet, their capabilities in such structures of power are far from clear. In response, this paper suggests that architects should seek to benefit from democratization of computational, electronic, and mechatronic tools in order to construct speculative ontologies,
workflows, and design proposals that can help them to rethink their pre-sumptions about design (green, sustainable or performance-oriented), architectural types, and the stakeholder publics. To emphasize, the primary utility of such sketches is as instruments of innovation.

### 3.1 SPECULATIVE SCENARIOS

This section outlines three speculative scenarios that employed the system sketching approach outlined above. All of these projects employed simple and yet partially autonomous robots. Their intelligence followed the biologically inspired, and common in robotic research, operational architecture that consists of a behavioral (or skill) layer, a deliberative (or sequencing and planning) layer, and an interaction layer (Gat 1997; Murphy 2000). Unlike purely reactive systems (such as boids or classic stigmery) that are only able to operate in the present, deliberative agents of this type are capable to consider the past, the present, and the future. To enable comparative analysis, these robot sketches implemented three distinct ontologies, or ways of viewing the world—as materials, objects, and fields. These metaphorical lenses can be roughly interpreted as scales: micro (material properties), midi (object properties), and macro (field properties). While these distinctions are voluntary, they are interesting as options for rethinking conventional architectural componentry and tooling because employment of autonomous systems requires encounters with computational architectures, perceptual systems, formal design patterns and other tools from unfamiliar domains.

In order to consider complete workflows, the project implemented: robotic arms with six degrees of freedom, custom end-effectors, control systems for calibration and operation, communication and coordination systems, vision and sensing systems, simulations of robot actions and graphical user interfaces, sets of planning procedures and sets of behaviors.

This approach was inspired by the way animals, such as birds, build their shelters by choosing sites and building techniques that achieve acceptable goals while minimizing energy costs.

#### 3.1.1 OBJECT PROPERTIES

This scenario explored construction from found and repurposed objects distributed on a site, for example rubble left after an earthquake or materials collected for recycling. The project focused on the strategies of birds that search for suitable construction sites, collect appropriate materials and assemble them into structures. This scenario implemented the following task sequence: 1) find an area that is suitable for construction; in this prototype, less sloping areas, as determined through the analysis of a depth camera data, were deemed to be more suitable; 2) find an area suitable for exploration; 3) find resources by analyzing vision data; 4) sort resources into types; 5) select a subset of resources within a distance threshold and generate their coordinates (Figure 2), and plot paths to these resources and compares retrieval costs (Figure 2, right); 6)
de-termine the type of object needed for the current stage of construction and retrieve it; 7) place the object into its place in the structure (Figure 3).

3.1.2 MATERIAL PROPERTIES
This scenario explored construction processes that focused on the evaluation of material properties, using earth-made structures as a case study. Earth is broadly available and interesting for its potential to 1) construct disaster relief and humanitarian aid structures in remote sites where supply is constrained or expensive and 2) to construct in sensitive environment with the goal of preserving the properties of existing habitats (Rael 2009). Earth constructions are also suggestive because their properties are similar to those found in animal architecture: local availability, reusability, amorphous shapes, non-uniform composition, material characteristics dependent on environmental conditions, malleability with simple tools, etc. The sequence implemented for this scenario involved: 1) identification of a prefabricated module in a given environment; 2) selection of sites for material testing; 3) testing of the available material for moisture and, therefore, malleability; 4) picking one of the two cooperating robots with different end-effectors in reference to the state of the available material; and 5) driving the sand with a fan or picking it with a gripper to cover the prefabricated structure (Figure 4).

3.1.3 FIELD PROPERTIES
This scenario considered the use of intelligent robots in areas and situations where autonomous remodeling of ground surfaces could be of benefit, for example, in regions affected by abrupt flooding or gradual degradation. Here robots can be employed for the construction of levee structures around flooded areas to prevent their expansion, creation of raised areas for temporary housing or execution of artificial erosion to encourage dissipation of water into newly created wetlands. In this scenario, architectural design focused on geometric and material affordances of existing landscapes, seen in the context of tendencies (for flooding or drying) developing over time. The sequence implemented in this scenario included: 1) analysis of the landscape;
2) selection of suitable site; 3) selection of operation based on site conditions: excavation or deposition (Figure 5); 4) collection of building materials, if needed; 5) excavation and/or deposition (Figure 6).

4 CONCLUSIONS

The living architecture section outlined the challenges and opportunities for managing dynamic environments highlighting some limitations of borrowing from nature and suggesting that in some cases design can learn more from natural systems and processes than from their static effects. The dependent architecture section outlined existing and potential capabilities for autonomy in architecture. It suggested that, in parallel with growing utilization in adjacent fields such as ecology (Grémillet et al. 2012) or agriculture (Zhang and Pierce 2013), autonomous systems promise useful contributions to continuous designing and management of persistent, living, systems in architecture.

The system sketches section outlined the speculative design approach in relationship to autonomous agents in architecture and the speculative scenarios section briefly described three projects for autonomous engagement with the environment. The speculative workflows assembled for these scenarios demonstrated that it is possible to sketch autonomous agents to operate in complex site conditions. With comparatively simple means, they could be made to estimate changing situations and act to autonomously direct construction processes towards designer-specified goals.

The preliminary conclusion of this work is that current software and hardware sketching tools are challenging but can be used for creative explorations by architectural designers. They can be further extended via collaboration with other disciplines and their high-end systems. However, such existing tools and methods from other domains are disconnected with architectural conceptualizations, design processes, procurement methods, goals and criteria. Ontologies and epistemologies prevalent in architecture need to be rethought with the main focus of learning the limits to autonomy, ways of implementing intelligence, methods for sharing of responsibility within hybrid systems and tactics for the inclusion of additional voices.

Resulting robotics is likely to be situated, distributed, persistent and slow. It must proceed through prototyping and testing of systems at a variety of approximations. Here, the architectural interest in using robots for full-scale building becomes complicated because “scale” in ecological systems can be understood differently and refer to geometrical size, number of elements, number of relationships, number of optimization criteria, number of dimensions in a simulation and so on. Explorations of such systems in different configurations and applications will constitute future research.
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REFERENCES


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