Living Technology: Exploiting Life's Principles in Technology

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Abstract The concept of living technology—that is, technology that is based on the powerful core features of life—is explained and illustrated with examples from artificial life software, reconfigurable and evolvable hardware, autonomously self-reproducing robots, chemical protocells, and hybrid electronic-chemical systems. We consider living technology to be secondary when its core systems are derived from other living organisms. Primary living technology is currently emerging, distinctive, and potentially powerful, motivating this review. We trace living technology's connections with artificial life (soft, hard, and wet), synthetic biology (top-down and bottom-up), and the convergence of nano-, bio-, information, and cognitive (NBIC) technologies. We end with a brief look at the social and ethical questions generated by the prospect of living technology.

Keywords
Living technology, protocell, synthetic biology, World Wide Web, autonomous robot, scientific social responsibility

1 Introduction

The concept of *living technology* has been coined to capture the technological implications of our increasing ability to engineer systems whose power is based on the core features of life. We believe the readers of *Artificial Life* may be interested in both the concept of living technology and the prospect of constructive engagement with the larger social issues raised by this new kind of technology. In this report we explain and illustrate living technology with examples from wet (wet laboratory), hard (robotic), and soft (software) artificial life; we show how the natures of technology and life complicate the definition of living technology; and we identify some of the larger social issues on the horizon. Our general message

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is that some existing technology is already very much alive, and entirely artificial organisms or other living systems are likely to be constructed soon. Living technology is still too immature to display its full potential, but significant leaps toward more mature forms will quickly happen. During our lifetimes we expect to see technology that is robust, autonomous, self-repairing, self-reproducing, evolving, adapting, and learning—a powerful combination of life's core properties that no current technology yet embodies.

There are various reasons for identifying living technology and focusing on it. One reason is that it may be seen as an essentially new form of life, and as such, it expands the realm of biological life, and may shed light on our concept of life itself and our own role within living systems. Another reason is that focusing on the lifelike properties of living technology may help us to engineer more powerful lifelike properties. Although we discuss many examples of living technology below, most of these technologies arose without much attention to their exemplification of living technology, even though their lifelike properties often provide their underlying power. The lack of living properties in technology is problematic for society in many domains where traditional technology fails or comes with the negative side effects of rigidity and mass production. These ripe opportunities for living technology include personalized medicine, environmental sustainability (e.g., protocells that metabolize industrial waste), individually adapted manufacturing and self-organizing software (e.g., personalized Web browsers that fit like a second skin). Lifelike properties are often emergent, in the sense that they are phenomena that come from strongly nonlinear interactions that prevent their prediction or derivation, and so they are difficult to engineer using conventional top-down design and engineering techniques. A focus on developing lifelike properties of technologies is already leading to the development of new engineering approaches to obtain those properties, and will continue to do so. Finally, the lifelike properties of living technology may lead to problematic interactions with existing life, as discussed below. To address these problems responsibly, and to anticipate issues before they become disastrous, it is essential to understand lifelike properties today.

Even though certain forms of living technology have existed for some time (as we explain below), living technology as a field is still very young, and identification and recognition of the concept is quite recent. The concept figures centrally in the missions of the European Center for Living Technology (ECLT) in Venice, Italy (founded in 2004) and the Center for Fundamental Living Technology (FLinT) in Odense, at the University of Southern Denmark (founded in 2007); it was also central to the original business concept of the company ProtoLife (founded in 2004), as well as a variety of European Commission and Los Alamos National Laboratory grants in 2004, 2007, 2008, and 2009. More recently, living technology has become the subject of a working group at the Initiative for Science, Society, and Policy (ISSP) in Odense, Denmark, which connects scientific knowledge and technological achievements with practical long-term social policies and broader social and ethical concerns.

2 What Is Living Technology?

Nature, and in particular life, has always been a profound source of inspiration for new technologies. Bio-inspired and biomimetic technology is ubiquitous and is more or less readily recognizable, depending on the level of abstraction and degree of combination with other ideas (e.g., in textiles, airplanes, surface coatings, computers, and robots, not to mention prosthetics from limbs to the retina). We use biological material and even whole organisms in a host of technological applications. Breeding in agriculture and animal husbandry has been extended by genetic engineering to allow rational recombinants between organisms. Now genetically modified organisms (GMOs) frequently contain gene sequences that have been separately designed, optimized, and evolved in the laboratory, allowing, for example, pharmaceuticals to be synthesized with precision in large quantities. The potential of stem cells and cloning is about to extend these technologies in many new, revolutionary directions. Automated industrial robots have for years been the standard, and increasingly autonomous robots are now also taking over routine household tasks such as vacuuming (e.g., the Roomba sold by iRobot). The flexible and adaptive behavior of these robots is generated without any complex centralized controller, by the same principles thought to underlie insect behavior. On the Web, we also find pervasive use of biological principles: Adaptive network traffic controllers, social networking services such as Facebook and Twitter, and community knowledge repositories such as Wikipedia are developing in unexpected ways through the collected efforts of a huge human population distributed around the globe. However, none of the developments in biomimicry, biomodification, or Internet-based human networks have really prepared us for the revolution that will take place when we make purely artificial technologies that embrace the core properties of life, allowing the technology itself to become robust, adaptive, self-repairing, self-optimizing, autonomous, intelligent, and evolvable.

We believe that these developments right now are converging to create a qualitative jump, as purely artificial technology itself becomes alive. We deem technology to be *living* if it is powerful and useful precisely because it has the core properties of living systems, including such properties as the ability to maintain and repair itself, to autonomously act in its own interests, to reproduce, and to evolve adaptively on its own. As our technologies increasingly embody such core properties of living systems, they will become increasingly powerful, natural, and sustainable. The key difference from mankind's earliest bio-inspired technological awakening is that we are now approaching a position to turn nonliving materials into technology that itself comes alive.

Living systems have been utilized and been part of human technology for thousands of years: horses for transportation and warfare, oxen for pulling loads and agriculture, dogs for protection and hunting, and yeast for baking bread and brewing wine and beer. Especially since the industrial revolution, many of these early living components of our technologies have been taken over by more efficient and powerful nonliving technology components. For instance, mechanized transport has largely replaced the horse. In the coming technological revolution, the technological systems themselves will become alive or very much more lifelike, bestowing the advantages of life on the wider sphere of material and technical innovation. Lifelike technology is sorely needed in technologies with a high impact on society. Today the world confronts a sustainability crisis with the help of social networks that are mediated by mobile technology, and our health is dependent on global immunization programs. These are just a couple of examples of how living technology could benefit society immensely.

A distinction between primary and secondary living technology helps clarify what is new. *Primary* living technology is constructed out of components that never were alive (nor derivable only from living organisms), so it is purely artificial. One simple example of primary living technology is artificial self-reproducing materials that may eventually be made from protocells constructed out of inert reagents [22]. Many of the issues about living technology arise in their sharpest or simplest form in primary living technology. We can also refer to the vast area of biomimetic technology that does not qualify as alive as a kind of pre-biotic (or pre-living) technology, especially when further enhancements to the technology involve acquisition of more and more lifelike properties.

Some kinds of living technology are *secondary* in the sense that their lifelike properties depend primarily on the antecedent lifelike properties of the components (e.g., living cells) out of which they are constructed. Secondary living technology can be further ranked according to what fraction of its components were previously alive. Contemporary biotechnology that has re-engineered *E. coli* to produce useful pharmaceuticals is one example of this mixed kind of secondary living technology [7] (for a recent review see [32]). Synthetic biology based on subcellular machinery such as the protein translation system is another mixed example. The World Wide Web, technologically linking up the human population of the planet, is a third. None of these examples is what we call primary living technology, because they all crucially depend on components that are already alive. Web social communities are an interesting form of living technology that is on the borderline between primary and secondary, because many of the lifelike properties of the Web communities are independent of the living properties of the human participants (e.g., the Web's evolution has very little to do with most of the living properties of particular human beings using it).

Table 1 charts a number of examples of different kinds of living technology, including those that exist today and those that are projected to exist in the near future.

Primary living technology deserves special attention scientifically for two reasons: Purely artificial things can be considered the simplest and purest forms of living technology, and they are precise

Table 1. Examples of different kinds of living technology, classified according to synthesis methods and materials. All depend on human effort and ingenuity.

Class	Living technology	
	Primary (purely artificial)	Secondary (mixture of artificial and natural)
Wetware	Protocells, self-reproducing and evolving materials	Animal husbandry (horse, wool), yeast in foods (wine, beer, bread), therapeutic use of stem cells, cloning mammals, DNA computers and nanomachines, use of bacteria for drug production, living cells expressing artificial genomes
Hardware	Reproducing and evolving robots, evolving hardware	Electronically controlled insects, optical computation with bacteriorhodopsin, human prosthetic devices, cyborgs
Software	Evolving computational processes (e.g., models of chemical or economic networks)	Autonomous decision support systems composed of evolving (learning) algorithms with human input
Mixed networks of the above	(Subject of current research and development)	Human social networks on Web, human organizations, cities, human economies

enough to be defined operationally and used in empirically testable hypotheses. For example, one can empirically test whether a given piece of a protocell system is purely artificial and devoid of previously living materials. (For example, using cell extract inside vesicles would make the system secondary, since the extract came from previously living cells.) Of course, this research is closely linked to the field of artificial life. Research in artificial life aims at understanding the fundamental properties of living systems by synthesizing and studying those properties in software, hardware, or wetware. Thus artificial life can help make technology more lifelike, using a variety of materials and methods, as displayed in Table 1.

The emerging transition to living technology is also powered by a broad convergence of the knowledge production and technology development among nano-, bio-, information, and cognitive (NBIC) technologies [19, 25]. At the center of this technological development is the desire to synthesize living or intelligent systems from nonliving components; using this technology to better understand life is the scientific core of the field of artificial life, in its chemical (wet) as well as its software and robotic forms. Thus, the frontier for the development of living technology intersects with the scientific frontier of artificial life. Research on the special advantages of living systems for technical applications has not hitherto been a central pursuit in artificial life. Conversely, artificial life research directed at understanding the nature of life through alternative constructions, whether theoretical or concrete, is not the primary locus for the best examples of living technology today.

Since this is not the proper place to enter the controversy about the connection between life and intelligence [16, 30], we will just emphasize that the foundation for intelligence is an ability to learn from trial and error, which results in processes similar to the evolutionary learning processes that underpin living systems. Thus, at the center of the cognitive and artificial intelligence part of the NBIC knowledge convergence and the emergence of the so-called *technological singularity* [31] is a similar need for a better understanding of and greater ability to synthesize living and lifelike processes.

Synthetic biology now clearly embraces two special kinds of living technology. *Top-down* synthetic biology modifies natural living systems or subsystems thereof, and *bottom-up* synthetic biology makes new forms of life in the laboratory solely from nonliving materials. The top-down versus bottom-up distinction marks an important division in technologies. Whereas the top-down approach makes heavy use of biotechnology and in particular genetic engineering, the bottom-up approach makes strong use of advances in physics, chemistry, and informational materials. Protocells exemplify the bottom-up form of synthetic biology and are an example of *primary* living technology. By contrast, genetically modified bacteria that produce pharmaceuticals exemplify the top-down form of synthetic biology, and this form of living technology is *secondary*, because it exploits components that were already alive or are derived from living organisms.

3 Examples of Living Technology Are Varied

Living technology is still in its infancy. Today research in the area is driven primarily by basic science. It should continue to unfold and expand over the next generation and beyond. The authors of this review expect that living technology will be the most transformative evolution of technology that current generations will experience.

Protocells that are being created today in the laboratory have been proposed as one basis for future living technology [23]. These include encapsulated chemical reactions inside self-assembling and reproducing vesicles (e.g., [8, 28]), vesicle-encapsulated cell extracts including artificial plasmids that produce functional proteins (e.g., [11, 29]), and oil droplets that move autonomously by metabolizing chemicals that they sense in their environment [12]. Another initiative [17] is creating an electronic chemical cell in which information processing is shared between the chemistry and electronics. Once these primitive artificial lifelike systems make the transition to life and begin to have a technological impact, they will become a new kind of primary living technology.

Taking a different tack and starting with current computer hardware, the development of reconfigurable and thereafter evolvable hardware in the 1990s [13] gave another impetus to the development of true living technology. While the hardware for electronic circuits in silicon technology cannot reproduce itself, specific circuits can: They can be configured from a generic array of wires and gates (field-programmable gate array) by a genetic digital sequence that can be loaded into memory cells, to control connections and logic (as in a digital multiplexer). Self-reproducing organisms have been designed using this technology (e.g., [6, 18]). The recent developments of self-assembling electronic circuitry (e.g., fold-up electronics [15] and solution assembly electronics [10]) will provide another major step in the direction of truly living technology. Of course, digital organisms can also be supported at a higher level in software by full-fledged processors, as in the work of Ray [24]. Furthermore, self-assembly combined with genetic descriptions appears to provide a powerful basis for problem solving using evolvable technology [9].

Moving to the realm of macroscopic autonomous robots, (pre-)living technology also includes artificial "baby seals" that autistic children cuddle and thereby come to have a satisfying emotional experience involving another being [26]. Such applications are of course distinct from (secondary) living technology involving Dolly and other cloned mammals, and from areas such as applications of stem cell research. It is interesting that there is now some consensus that it is more efficient and sometimes essential to exploit the natural information processing that comes from the material and contextual embedding of robots in the real world (embodiment) rather than to rely on complex symbolic information processing and simulation of the complexities of physical systems [21]. The ultimate step of extending embodiment to robot synthesis itself provides a convergence of this field toward living technology, beyond the common denominator of biomimicry.

The World Wide Web is an example of secondary living technology, and actually provides a living technology ecosystem that hosts many other individual forms of secondary living technology. One recent example that is growing rapidly is social networks facilitated by community-building tools such as Facebook, MySpace, and Twitter. The communities maintain themselves, grow, and evolve, largely autonomously.

It is natural to wonder what living technologies will be like in the future. All guesses about future technology are uncertain today, and unreasonable expectations and ungrounded fears (like swarms of protocells ravaging the environment) take root in this uncertainty. Still, properly qualified and empirically grounded speculation about living technology and its applications can help us imagine and prepare for our uncertain future with primary living technology. Here we simply point out a few obvious directions for such speculations.

- In the field of advanced materials, we can imagine complex materials that sustain and repair themselves autonomously from simple resources, that adopt special properties or deliver substances only on demand, or that have a life cycle ending in degradability.
- In the field of biotechnology, we can imagine organisms like bacteria with completely synthetic genomes that have been designed to produce hydrogen in fuel cells powering our automobiles [14], or wholly synthetic protocells (see below) that mineralize CO_2 and create new, sustainable building materials [1]. Looking further into the future, it is clear that living technology will play a major role in allowing us to take advantage of the diversity of environments in the solar system and beyond.
- In the field of information technology, we can imagine self-assembling, self-correcting, and adaptive software, as proposed by the organic computing community, that will solve many of the problems of lack of self-organization and robustness in software; and in the area of robotics, we can imagine autonomous and adaptive robotic infrastructure that enables the elderly to live independently with greater safety and security. We can also imagine Internet-supported collective intelligence tools that allow local communities to plan and implement local strategies for keeping their own local neighborhoods green and sustainable.

These speculations cover just a small fraction of the possible kinds of living technology, and only a few of the ways in which living technology might affect our future.

As further examples of living technology, some [2, 27] would add lifelike networks of mixed artificial and natural systems, such as firms and cities, using the concept of superorganisms for human organizations as well as for industrial metabolisms.

4 Defining Living Technology Involves the Complexity of Life and Technology

On the surface, the examples of living technology described above are quite different. So one might wonder why they should be grouped together under the concept of living technology. The details involved in understanding one kind of case are quite different from the details involved in understanding other cases. What is the conceptual benefit of grouping them together?

Each different kind of living technology is uniquely complex, and each can and should be studied on its own. But their adaptive complexity makes them especially difficult to understand scientifically. Much of the power and originality of each kind of living technology, and their useful complexity, can be traced to their lifelike qualities: growing and repairing themselves, reproducing, adapting to changing circumstances, evolving creatively. Grouping these examples together as living technology calls attention to these qualities that make them so useful and powerful. What we learn about one kind of living technology gives us epistemological leverage that can often be applied to other kinds.

Table 1 concretely illustrates one way in which the concept of living technology is complex. Living technology can be divided into different kinds of primary and secondary forms, depending on how natural or artificial it is. Living technology can also be divided into different forms corresponding to the three main synthetic methodologies in artificial life: soft, hard, and wet.

The concept of living technology is still in its infancy, and there are a number of open questions about its definition. The concept has clear positive and negative paradigm cases, but at the present it has no precise agreed-upon definition that unambiguously and uncontroversially resolves all borderline cases. We think that the distinctions between primary and secondary living technology and between simply biomimetic and pre-living technology go some way toward resolving these issues. However, from the examples above it is clearly difficult to identify clear boundaries between different categories of living technology, and there seems to be a spectrum of possibilities that range from living to nonliving, and from natural to artificial, in different ways.

Another significant reason why living technology is difficult to define is that the nature of life is itself a complex and controversial topic (see, e.g., [3]). The existence of simpler parasitic entities like viruses illustrates one kind of complication, for isolated viruses have some but not all of the properties of living systems, and most biologists do not consider them to be alive. Thus, the notion of living technology is vague where we are uncertain about the nature of life itself. As we learn more in the future and our uncertainty drops, we will also clarify the notion of living technology, and conversely, a better understanding of living technology may illuminate and clarify the nature of life in general.

A further source of complexity in the definition of living technology is the uncertainty about the nature of technology and the related distinction between the natural and the artificial. Living technologies are "artificial" in the sense of being created through intentional human activity. At the same time, they are "natural" in the sense that they grow and adapt and evolve autonomously; that is, they have a life of their own.

5 Living Technology Creates New Opportunities and New Responsibilities

The speculative future scenarios sketched above suggest some of the larger social issues that living technology will raise. This topic is only now starting to get the in-depth treatment it deserves. If we are guided by recent work on the social and ethical issues raised by protocells [4, 5], then the creation of living technology will call for us to create proper mechanisms to prevent its misuse and create safeguards to protect human health and the environment. It will also call for us to ensure that those who enjoy the benefits of living technology also bear the risks, to assess liability when living technology goes awry, and to clarify and rationalize intellectual property rights. In addition, living technology will require us to create and coordinate regulatory practices, protect personal privacy, and protect against manipulation of personal opinions. It will also require us to clarify ethical issues, develop codes of conduct, and show sensitivity toward cultural and religious perspectives.

Further, the emergence of living technology may prompt us to create new social processes to discuss the larger implications of these new technologies. Such a discussion should rest on open and easily available information about what living technology is and is not.

The prospect of living technology makes many people uneasy, and fictitious or irrelevant fears about living technology sometimes distract us from the real issues. Protocells, for example, are rather minimal life forms far simpler than the simplest modern bacteria. They have nothing to do with the creation, modification, or production of human life forms. Yet most people think about Frankenstein or Crichton's *Prey* when they hear about protocells. Because they can proliferate (even if not in the natural environment), they raise ethical concerns that overlap with those addressed in nanotechnology and biotechnology. However, given the special competence and insights of the artificial life community in particular, it would not be wise to delegate our entire social and ethical response to the advent of living technology to these fields (see [4]).

All these issues deserve careful and thoughtful attention, and they are starting to get it from new institutions such as the Human Practices Lab at Berkeley in California, the Organisation for International Dialogue and Conflict Management in Vienna, and the Initiative for Science, Society, and Policy in Odense, as well as older, more established institutions, such as The Hastings Center in New York, The Woodrow Wilson International Center for Scholars in Princeton, The Organization for Economic Cooperation and Development in Washington, the Centre for Applied Philosophy and Public Ethics in Canberra, The Royal Society in the UK, the Institute for Science and Society in Nottingham, the European Center for Living Technology in Venice, and the Rathenau Instituut in the Netherlands, among many others.

There is a strong motivation to face all these responsibilities, because the opportunities afforded by living technology are so attractive. Some existing technology is already very much alive, but it is a pale image of what is coming. During our lifetimes we can expect purely artificial technology to acquire life's core properties and thus vastly outperform all current technology. This transition will be a truly singular event in human history.

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