Introduction to Recent Developments in Living Technology

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Keywords
Living technology, lifelike technology, artificial life, artificial cells, personal fabrication, emerging technology, self-reproduction, self-organization, self-repair, metabolic materials, synthetic biology

When the scientific and technological fruits of artificial life are embodied in technology with real practical use, sometimes the result can properly be called *living technology* [6]. Technology today is becoming increasingly lifelike, and there has recently been increasing foundational discussion of the broader scientific, socioeconomic, cultural, and ethical implications of living technology (e.g., [5, 7]). This special issue of *Artificial Life* describes recent developments in living technology, and samples current progress and applications in the works. The scientific core of the volume consists of seven articles describing new advances toward living technology. The volume also contains four articles about living technology's broader social, ethical, and political implications.

Living technology is most simply defined as technology that is alive, but it is convenient to require that such technology furthermore be useful because of being lifelike [6] and not be a simple variant of existing life. We will call something *lifelike* if it has one or more of life's characteristic properties. Although there is controversy about the nature of life [4], there is a rough consensus about the characteristic properties exhibited by all typical living beings. Many also agree that a subset

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Table 1. Living and lifelike technology.

Living technology	Technology with all of life's core properties.
Lifelike technology	Technology with almost all of life's characteristic properties. Technology with only one of life's characteristic properties. Technology with properties often shared with many life forms, but not characteristic of life.

of life's characteristic properties form a small *explanatory core* that can explain the rest of life's characteristic properties, although there is some disagreement about exactly which properties constitute that core. It is common to identify three core properties: Every life form (i) autonomously creates a boundary distinguishing itself from its environment, (ii) autonomously sustains itself through the synthesis of building blocks by harvesting energy and raw materials from the environment, and (iii) autonomously reproduces itself and evolves, through inheritance with variation of reproducible internally stored information that can activate and control the life form's crucial functions [14]. In addition to properties (i)–(iii), authors in this volume focus on other characteristic properties of life, including autonomy, homeostasis, robustness, adaptability, and the ability to learn from the environment (cf. Ikegami [11], Armstrong and Hanczyc [3], Gershenson [8], Montebelli et al. [12], Ackley [1], and Whitacre and Bender [18]). Different opinions about the core properties of life can generate different opinions about which technologies are living or lifelike.

We assume that something is alive only if it has *all* of life's core properties. Once we have identified life's core properties, we can distinguish between living and merely lifelike technology (Table 1). Technologies with some but not all of life's core properties are merely lifelike, and technologies with more core properties are more lifelike, although this is only a partial ordering. Although lifelikeness cannot be measured precisely, one can still notice a general trend of more technologies becoming more lifelike; see Table 1.

It should be noted that many discussions apply the term "living technology" to technologies that are merely lifelike, even though they lack some of life's core properties. These technologies can be called *broadly living* (i.e., either living or lifelike). To keep our terminology consistent and clear, we will distinguish between living and lifelike technology as indicated in Table 1.

For example, one can distinguish between *primary* living technology, which is alive but contains no natural biological parts and did not come from a natural life form, and *secondary* living technology, which does contain some living biological parts or came from a natural life form [6]. Table 2 combines the primary-secondary distinction with the living-lifelike distinction to define four categories

Table 2. Examples of primary, secondary, and sociotechnical forms of living and lifelike technology.

Technology	Primary (uses nothing living)	Secondary (uses nonhuman life)	Secondary sociotechnical (uses humans)
Living	• Drug-producing protocells (hypothetical)	• Drug-producing yeast [16]	
Lifelike	• Movable Feast Machine (Ackley [1]) • Metabolism-driven sensorimotor droplets (Armstrong and Hanczyc [3]) • Network-buffered robot (Whitacre and Bender [18])	• Microbial fuel cell robot (Montebelli et al. [12]) • *Physarum* machine (Adamatzky [2])	• Self-organizing traffic network (Gershenson [8]) • Mind Time Machine (Ikegami [11])

of technologies: primary living technology, secondary living technology, primary lifelike technology, and secondary lifelike technology. The table applies these categories to the technological achievements reported in this volume (discussed below). For comparison, Table 2 also categorizes some additional examples of living technology. One is living yeast that was metabolically reprogrammed to produce artemisinin, an antimalarial drug [16]. Another point of comparison is a *hypothetical* living protocell [14] that self-assembles entirely from nonliving materials and self-reproduces (as well as performing some useful function such as synthesizing or decomposing a given substance).

The achievements of living and lifelike technology reported in this special issue are diverse and exemplify all of the categories of substrates for technology in Table 3. Artificial life traditionally distinguishes three kinds of substrates for life: soft (software simulations and models), hard (autonomous agents such as robots), and wet (biochemical test-tube creations produced in a wet lab). These material substrates define categories of living technology. *Wet* technologies are produced in chemical or biological laboratories. *Hard* technologies are autonomous agents created in hardware, including robots. *Soft* technologies here are software models or simulations that exist only in a computer (as opposed to *soft* matter in physics, which refers to materials sharing the soft properties of the biochemical substrate). These kinds of living technologies can be components of larger technological systems, and this creates two more categories of living technology. *Sociotechnical* technologies involve networks of humans that interact through information and communication technologies, such as social networks, and *mixed* technologies use nonhuman life forms inside a larger technological system. Three of the scientific articles in Table 3 involve wet technology, four involve hard technology, three are sociotechnical networks, two are mixed technologies, and five include soft technologies.

Various patterns in the achievements in living and lifelike technology are reported in this special issue (Table 4). All but one of the technologies are useful because they are lifelike, and many

Table 3. Examples of categories of living and lifelike technology.

	Technological substrate				
Example	Soft (simulation model)	Wet (bio-chemical)	Hard (robot)	Sociotechnical (uses humans)	Mixed (uses nonhuman life)
Microbial fuel cell robot (Montebelli et al. [12])	Y	Y	Y	N	Y
Physarum machine (Adamatzky [2])	Y	Y	N	N	Y
Sensorimotor droplets (Armstrong and Hanczyc [3])	N	Y	N	N	N
Movable Feast Machine (Ackley [1])	Y	N	Y	N	N
Network-buffered robots (Whitacre and Bender [18])	N	N	Y	Y	N
Mind Time Machine (Ikegami [11])	Y	N	Y	Y	N
Self-organizing traffic network (Gershenson [8])	Y	N	N	Y	N

Table 4. Examples of kinds of achievements in living and lifelike technology.

Example	Technological achievement		
	Useful because lifelike	Alive	Uses nothing living (primary)
Microbial fuel cell robot (Montebelli et al. [12])	Y	N	N
Physarum machine (Adamatzky [2])	N	N	N
Sensorimotor droplets (Armstrong and Hanczyc [3])	Y	N	Y
Movable Feast Machine (Ackley [1])	Y	N	Y
Network-buffered robots (Whitacre and Bender [18])	Y	N	Y
Mind Time Machine (Ikegami [11])	Y	N	N
Self-organizing traffic network (Gershenson [8])	Y	N	N

authors describe their technology as living. However, using the distinction between living and lifelike technology (Table 1), and identifying the core properties of life as above, the achievements reported here are all at most lifelike. Primary living technology that uses no living materials or components has not yet been attained. An increasingly prevalent kind of secondary living technology consists of the products of genetic engineering, biotechnology, and synthetic biology, such as drug-producing yeast. This kind of secondary living technology extends trivially, by definition, to include even human-bred crops, animal products such as wool, and animals such as draft horses and carrier pigeons.

Different categories of broadly living technology correspond to profiles of Y or N responses to the three questions in Table 4. Strictly living technology has the profile YY*, where * is a wildcard indicating that it does not matter whether the response is Y or N. In other words, any technical achievement with Y answers to the first two questions is an instance of what we are calling living technology. (The initial Y excludes a technology if being lifelike is irrelevant to its function and use.) Primary living technology has profile YYY, and secondary living technology has profile YYN. The category of "broadly living" technology (see above) has profile Y** with wildcards to fit lifelike technology whether or not it is alive, and whether or not it uses nothing living (i.e., it is primary).

One active area of development of living technology involves the marriage of wet and hard artificial life in biomechanical devices. The future of robotics and hard artificial life requires increasing energy independence, increasing autonomy from human controllers, and increasing ability to evolve and adapt to unpredictable changes in the environment. In other words, robots must become increasingly lifelike. A step toward this goal is the bio-robot hybrid system produced by Montebelli et al. [12]. The robot scavenges for food (biodegradable materials) and water to feed the bacteria in its onboard microbial fuel cell, and this fuel cell is an "artificial metabolism" that produces electrical energy for the robot's useful work. Simulations of robots controlled by artificial neural networks with weights tuned by an evolutionary algorithm show how evolution can integrate sensorimotor and metabolic signals in these robotic autonomous agents.

Another biomechanical hybrid technology is the unconventional computers constructed by Adamatzky [2] using the slime mold *Physarum polycephalum*. It its plasmodium stage, *Physarum* is a single cell with many diploid nuclei, and it is large enough to be readily visible with the naked eye. It forms an amorphous yellowish mass that includes a network of protoplasmic tubes that feed the plasmodium. The plasmodium moves like a giant amoeba and forages for food. By placing food in carefully designed channels of growth medium and inoculating the medium with *P. polycephalum*, one can create *Physarum* machines that compute various algorithms, such as solving mazes and implementing simple circuits. A *Physarum* machine is created through intentional human activity, but the living slime mold is not. The input to the *Physarum* machine is achieved by the spatial location of food and inoculations, and the result of the computation is represented by the plasmodium's spatial location and the structure of its protoplasmic network. The elementary processors in this unconventional computer are the regions of the plasmodium's active growth.

Unlike the biomechanical devices produced by Montebelli et al. and Adamatzky, the droplets produced by Armstrong and Hanczyc [3] do not depend on preexisting forms of life. This work builds on a simple system of oil and strongly alkaline water that produces highly energetic droplets that engage in sensorimotor behavior [9, 10]. The saponification reaction produces a soapy crystalline substance in the droplets, and this metabolic process digests oil and alkali to power the droplet's movement. When chemical equilibrium is reached, the droplets stop moving. In principle the droplets could be chemically programmed to do useful work, so this system is an extremely simple chemical experimental model for lifelike technologies with programmable properties.

Another example of lifelike technology constructed without employing existing life forms is the Movable Feast Machine (MFM) described by Ackley [1]. This machine is an indefinitely scalable computing device designed to maximize computational power while minimizing resources of material, energy, space, and time. The MFM tiles space with finite computational units; these tiles are interchangeable, and they can be attached or removed without interrupting the MFM's ongoing computations. The resulting robust and indefinitely scalable computer consists of distributed dynamical computational agents that are continually building, preserving, and growing their own mechanisms and relationships. The MFM is much more lifelike than traditional computer technology. Ackley explains how the MFM would tackle a demon horde sort problem, which involves sorting an endless stream of numbers moving across a grid. It turns out that the MFM continues to perform well in the face of substantial transient hardware failure, just as living organisms do.

Whitacre and Bender [18] aim to produce autonomous agents (robots) that can continue to function and repair themselves when damaged, and that can adapt to environmental changes that are unanticipated by their human designers. With the aim of constructing robots that exhibit pervasive flexibility, homeostatic robustness, and evolutionary innovation, Whitacre and Bender propose that network buffering can produce adaptable robots. Partially overlapping contexts that loosely couple many versatile and functionally redundant agents produce buffered networks in which emergent robustness can be understood and designed even though the designers do not know precisely what perturbation will be experienced or where flexibility will be needed. This kind of emergent robust behavior is among life's characteristic properties.

A number of the scientific achievements described in this issue are sociotechnical systems involving a network of humans interacting with each other and with autonomous technology. One example is the Mind Time Machine (MTM) described by Ikegami [11]. The MTM is an artificial system that interacts with humans. Humans provide input to the MTM through 15 video cameras, and the machine produces goal-oriented behavior that ultimately has the purpose of enabling the machine to survive in an open and unpredictable environment. The base software that drives the MTM is a self-organizing neural network governed by pure Hebbian learning, and including a chaotic component. Ikegami describes how the MTM achieves an important lifelike autonomy, in which the system chooses its behavior by predicting the future from past experience. One of many lifelike qualities of the MTM is that its observable behavior is mostly due to transient effects rather than the structure of attractors. The MTM is another testing ground for general design principles for living technology.

Gershenson [8] applies living technology to a wide range of problems associated with urban life. These problems are difficult in part because they are dynamic and involve mobility, logistics, telecommunications, governance, safety, and sustainability. One example involves efficient mass transportation networks that aim to decrease the use of private automobiles. Current transportation networks are designed to function rather like a clock. Gershenson advocates a self-organizing transportation network that is more like a healthy heart, instantly adapting to changing system demands. Like the decaying pheromones deposited and sensed by ants, Gershenson's adaptive transportation network uses an "antipheromone" that increases in strength over time but is erased by traffic. Computer simulations show that vehicles in self-organizing traffic networks communicate via antipheromones and balance network load as well as minimizing idle vehicles and traffic collapses.

Although the bulk of this special issue consists of scientific and technical articles on achievements in living technology, more than a third of the articles investigate and evaluate the broader social and ethical issues raised by living technology. Living and lifelike technology has already begun appearing in health care, typified by robots used in surgery, transportation, cleaning, and alleviating cognitive impairment. Lifelike robots have the advantage of being highly flexible and able to adapt to their surroundings, so they can act autonomously without external control by humans. Peronard [13] reports survey results about people's readiness to try using robots and other living technology in a health-care setting. Health care is an interesting context for investigating public acceptance of living technology for many reasons. Health is a concern for everyone, demographic trends show an increasing number of patients per caregiver, and patients are especially vulnerable and easily manipulated. Solid social-scientific survey results could indicate what factors affect how well living technology will be accepted in health care. Peronard compiled data from 200 people involved in health care, including nursing staff, managers, consultants, and a few patients. People with a high readiness to accept living technology tend to be older, involved in management, and involved in decisions about what technology to adopt. By contrast, those with a low readiness to accept living technology tend to be younger and uninvolved in management or decisions about technology.

The responsibility of government to develop and regulate new and emerging technologies is especially challenging, according to van Est and Stemerding [17], because of two bioengineering megatrends: biology becoming technology, and technology becoming biology. The second trend is the rise of living technology. Europe's troubled history with genetic engineering ensures that living technology will generate public political debate. A central challenge for good governance is to both promote and regulate living technology. Van Est and Stemerding [17] examine four models for addressing this challenge. The dominant model today is *reactive regulation*, but this model is hindered by uncertainty about scientific and technological developments, uncertainty about tradeoffs among competing social values, and uncertainty about the adequacy of current regulations. All three kinds of uncertainty arise with living technology. Modern *technology assessment* aims to anticipate the positive and negative effects of technological changes, and the results are used by the anticipatory regulation governance model. The *deliberative government* model uses the wisdom of the crowd to address scientific and technical uncertainty, and it includes the general public when assessing new technologies. The fourth model is *anticipatory governance*; this model addresses regulatory uncertainty by promoting the scientific social responsibility of the scientists and engineers on the front lines of basic research and development. Rather than affecting technology downstream through regulations that constrain technological products, anticipatory governance works upstream by encouraging scientists involved in R&D to be socially responsible about the technology they produce. If scientists involved upstream in R&D are responsible, the need for downstream technology regulation will dwindle.

Many of the dangers associated with living technology are discussed by Wills et al. [19]. Heidegger's critique of technology implies that humanity does not understand life well enough to harness its powers safely and fairly. According to Wills et al., the real danger of living technology comes from "the power it can deliver to agencies . . . to own, manipulate and control . . . aspects of nature that have until now been outside the range of human exploitation," and "the proposal to create living technology strikes at the heart of the relation between humanity and nature—indeed, at what we take each to be." Wills et al. believe that scientists have a responsibility for the broad consequences of the fruits of their scientific effort, and they think that ethical reflection about technology and society should presume the intrinsic worth of all living beings. The dangers Wills et al. see in living technology are reflected in the Prometheus myth and its modern incarnation in Mary Shelley's novel, *Frankenstein*, in which scientists create life with only the faintest inkling of the long-term harm to humanity and the natural world.

Heidegger's critique of technology is given another interpretation and application to living technology by Riis [15]. Riis uses Heidegger's evaluation of cybernetics to infer what he would say about living technology. Although Heidegger emphasizes the profound danger lurking in technology, Riis stresses that Heidegger would view living technology as the "ultimate" form of technology, for the following reason. The fundamental aim of technology is to produce something, and the "ultimate" or "highest" or "ideal" form of production avoids any external agency. The highest form of technology produces things as nature does—without external agency—and the hallmark is life reproducing itself. So, living technology refutes the typical dichotomy between the natural and the artificial, for it is both; it reproduces naturally, because of being alive, but it is an artificial construction that produces something unnatural. Riis ends up defending a perspective on technology that is informed by Heidegger but allows for and embraces the perpetual unfolding of living technology that regulates and controls itself autonomously.

The core properties of life represent functionality whose power is manifest in the natural world, but this functionality is largely absent from conventional nonliving technology. As we understand more about the nature of life, both from studies of existing life and from studies of artificial life, the lure of technologies that harness the functionality of life will grow stronger.

Some of the articles in this volume represent explorations of a variety of experimental and technological realizations that have lifelike properties. This exploration of lifelike technology helps map the landscape and identify pathways toward the realization of fully living technology. When technology becomes alive, unique new issues arise, both in understanding its nature and in understanding its relationship to us. Living technology can simultaneously be powerful, helpful, and dangerous. The articles presented here take some early steps on a socially responsible path toward living technology.

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