

Hybrid Biological-Digital Systems in Artistic and Entertainment Computing

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During World War II, the famous behaviorist B.F. Skinner proposed to develop accurately guided missiles that could not be jammed by enemy devices, by putting pigeons in the nose of the missile (Fig. 1). In the so-called Project Pigeon [1], later named ORCON (from the words “organic control”), pigeons were trained to peck at the target on a forward-looking lens-based projection, steering the missile and keeping it on course. Although tests were quite successful, the program was abandoned in favor of more conventional technology.

Since Project Pigeon, the integration of real, living biological organisms within mechanical systems has spread into the digital realm. In digital environments, this approach constitutes a challenge to both preprogrammed and nondeterministic approaches to behavior generation. Biological systems can create highly complex patterns and behaviors, as seen for example in the coordinated movements of a school of fish, pattern formation in bacteria and slime molds or trail formation by ants. Simulation of such complexity in real time from computer code requires considerable processing power and depends greatly on the simulation’s algorithmic and parametric characteristics.

More importantly, organic perception and processing of surroundings and events can be applied to integrate digital systems with complex situations in the real world. In this manner, the difficulties of pattern recognition and decision-making are dealt with not via algorithmic design but through the intermediation of biological organisms—as attempted by Skinner in Project Pigeon.

Furthermore, biological systems can in principle be applied at more fundamental levels of modern computing. Instead of serving only to create interfaces between digital systems and the outside world, they could replace or enhance pattern-based computation itself, as was demonstrated by Leonard Adleman’s DNA computing experiment [2]. There, he

coded a seven-city shortest-path problem in actual DNA. Then, using only bioengineering manipulations of that same DNA, he was able to solve the problem. Alternatively, biological systems could be applied to create new forms of memory for computing systems, perhaps with characteristics more similar to our own memory than to digital RAM.

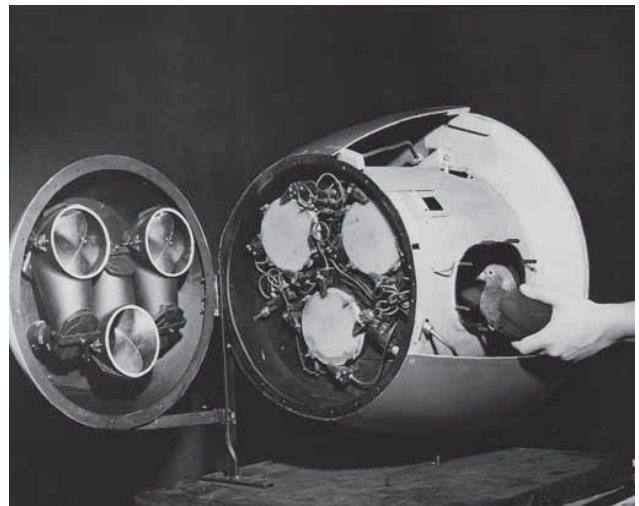
Certainly, experiments by Saigusa and colleagues [3] on periodic memory in the unicellular *Physarum polycephalum* (slime mold) suggest this as a path worth exploring.

Lastly, biological systems may exhibit unexpected or unanticipated patterns of behavior from which digital applications may also benefit. In principle, the concept of partially replacing computer code with a biological system could be applied to computer applications in general, but unlike many other applications (such as Microsoft Word or Airbus A380 flight control software), computer art and entertainment applications can in many ways benefit from the possible unpredict-

ABSTRACT

The authors give an overview of existing incorporations of biological systems for behavior generation within digital systems. The authors investigate digital systems that have artistic and/or entertainment goals, including computer games. The overview concludes with a reflection on the overall state of this hybrid approach.

Fig. 1. Pigeons in a Pelican: Demonstration model of B.F. Skinner’s three-pigeon missile guidance system [43]. (©The B.F. Skinner Foundation)



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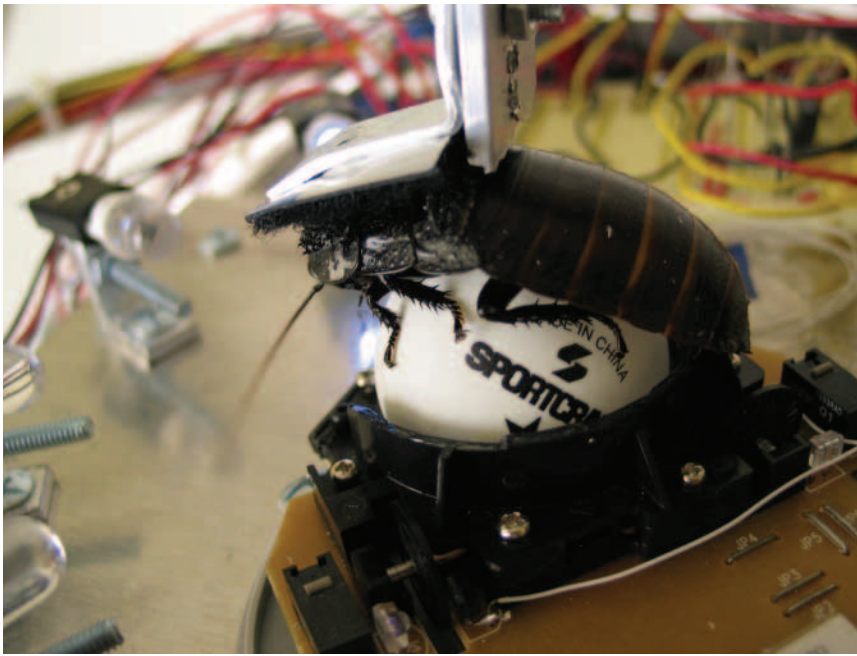


Fig. 2. Garnet Hertz, *Cockroach Controlled Mobile Robot*, custom robotic device, 56 × 56 × 56 cm, 2004. Close-up showing the cockroach placed above the trackball device. (©Garnet Hertz)

ability of organic components. Also, the conceptual blurring of boundaries between digital and biological worlds is a welcome theme in artistic practice. By their nature, entertainment computing applications encourage two-way interaction between computer and user. Moreover, experiments by Weibel et al. [4] showed that subjects who falsely believed they played online games against human-controlled opponents experienced more enjoyment, presence and flow in doing so, as opposed to subjects aware of the opponent's true non-biological control. Although not yet studied, these observations may likely generalize to awareness of other biological entities and different application domains. The substitution of computer code with organisms suggests possibly interesting interactions between user and biological system.

Below we present a review of existing works that integrate or combine biological systems with digital systems for artistic and entertainment goals. We

Fig. 3. Ken Goldberg, *The Telegarden*, 1995. This installation by Ken Goldberg was online at the Ars Electronica Center in Linz, Austria, from 1996 through 2004. (© Ken Goldberg)





Fig. 4. Philip Ross, *Junior Return*, mixed media, 17.5 × 17.5 × 17.5 cm, 2005. A seedling is kept in a dwarf state for years by a computer-controlled hydroponic environment. (© Philip Ross)

have grouped these works according to the following categories: biological control of digital systems, digital control of biological systems, digital nurturing of biological systems, computing and creation, and biological systems in digital games. We do not claim this paper to be a complete overview of all works in the field but we do aim to represent the range of practices to be found therein. Aiming to provide ourselves and others with inspiration for further research, we conclude this overview with a reflection on the overall state of this hybrid approach.

First, however, some delineation is in order. We describe a biological system as any operational living system that is part of nature, ranging from cells to microorganisms, plants, animals and even whole ecosystems. Although humans are also biological systems, we do not include humans in our study, because they commonly interact with digital systems. By the term “digital system,” we mean a programmable machine that receives

input, stores and manipulates data and provides output in a useful format. We focus on hybrid systems in which a biological component fulfils a specific task within a digital system or where digital and biological components collaborate to form a surprising interaction.

BIOLOGICAL CONTROL OF DIGITAL SYSTEMS

The capacity of animals to perform computerized tasks has been researched extensively, usually by applying reward-based training methods developed by Skinner. The results have allowed researchers to compare task performance among different kinds of animals. For example, Rhesus monkeys [5] and albino rats [6] have been trained to respond to computer-generated stimuli by manipulating joysticks. Moreover, Duke University Medical Center researchers taught a Rhesus monkey to consciously control the movement of a robot arm in real time, using only direct signals from

its brain and visual feedback on a video screen [7].

Artists have also investigated how biological systems can be used to control digital systems. Ken Rinaldo’s *Augmented Fish Reality* [8] is an interactive installation of five robotic fishbowl sculptures, each inhabited by a single Siamese fighting fish. By swimming to an edge of its bowl, the fish moves its sculpture in the corresponding direction. This lets any fish approach within 1 centimeter of another, allowing the normally aggressive fish to interact without killing one another and explore their environment beyond the limits of the fish-bowls.

Garnet Hertz’s *Cockroach Controlled Mobile Robot* [9] consists of a giant Madagascan hissing cockroach that controls the movements of a three-wheeled robot on which it is housed. The cockroach is placed on top of a trackball device, which it spins with its feet (Fig. 2). The trackball motion induces movement in the robot. When the robot detects an object ahead through infrared distance sensing, some of the many LEDs that encircle the cockroach’s field of vision light up. As the cockroach tries to scuttle away from the light, the robot moves away from the obstacle. A similar interaction path is used by Tsuda and colleagues in “Robot Control: From Silicon Circuitry to Cells” [10], which interfaces a *Physarum polycephalum* with an omnidirectional hexapod robot. As with Hertz’s robot, it is difficult to state whether the organism is controlling the robot or the robot controls the organism.

Rather than using whole organisms, neurons from animal brains can also be used to control digital systems. DeMarse and Dockendorf connected a grid of 60 electrodes with a network of roughly 25,000 rat neurons and trained this assemblage to act successfully as a consumer flight simulator autopilot [11]. Electrodes recorded the activity of individual neurons and provided “feedback” on their performance in the form of electrical stimuli. The neural network slowly learned to control the simulator’s pitch and roll while receiving feedback about deviation from level flight, up to the point that straight and level flight could be maintained.

MEART: The Semi-Living Artist [12] (Color Plate C No. 1) by Bakkum et al. is an installation distributed over two locations. Its “brain” consists of cultured rat neurons that grow and live in a neuro-engineering lab. Its distant “body” is a robotic arm that holds colored pens capable of producing 2D drawings in response to the real-time activity recorded



Fig. 5. Amy Youngs, *Rearming the Spineless Opuntia*, live spineless opuntia cactus, electronic components, motor, copper, steel, aluminum and rubber, 60 × 30 × 30 in, 1999. A spiked copper shell cover is activated when the plant is approached. (© Amy Youngs)

from the neurons. A camera aimed at the drawing provides sensory feedback to the neuronal network. Interestingly, when *MEART* stopped moving during a public presentation because the neuronal culture died, the gallery went silent with the apparent sudden realization that *MEART* had been somehow alive [13].

DIGITAL CONTROL OF BIOLOGICAL SYSTEMS

It is also possible for a digital system to control a biological system. Bio-roboticist Isao Shimoyama [14] developed a method to control the movements of a live cockroach remotely through a surgically implanted micro-robotic backpack. Pulsing electrodes make the roach

turn left, turn right, scamper forward or spring backward, although the controls are not yet very precise.

Small Work for Robot and Insects [15] by artist Andy Gracie features a robot that attempts to establish meaningful dialogue with a colony of live crickets. The robot is able to analyze the chirping of the crickets and attempts to devise a unique language with which to communicate with them or provoke them into certain behaviors.

Despite our intent not to include humans as biological systems in this study, we do choose to mention the work of artist Arthur Elsenaar. In his research project “ArtiFacial Expression” [16], he uses precisely controlled electrical impulses to trigger the facial muscles of a

live human into rendering involuntary facial expressions. This research shows how external digital control allows a biological entity to behave in fundamentally unnatural ways due to the intrinsic qualities of the neural and digital control systems.

DIGITAL NURTURING OF BIOLOGICAL SYSTEMS

Digital systems are also used to nurture biological systems, either acting autonomously or mediating for human users. *Teleporting an Unknown State* [17] by artist Eduardo Kac enables a user to upload a photograph of the sky to Kac’s installation. The image is used to illuminate a single seed that is placed upon a pedestal in a dark room so that it can photosynthesize and grow.

Similarly, the concept of telepresence is explored by Ken Goldberg in *The Telegarden* [18] (Fig. 3), which enables users remotely to view and take care of a real garden. Being able to control an industrial robotic arm through a web interface, participants can plant, water and monitor the progress of seedlings.

The goal of telepresence aside, digitally controlled nurture of biological systems has inspired many works—mostly those relating external factors to nurture conditions. For example, *Junior Return* by Philip Ross [19] (Fig. 4) houses a seedling in a computer-controlled hydroponic environment built from a set of glass capsules. LED lights supply the necessary illumination, and a small pump supplies air to the nutrient-infused water into which the plant’s roots are submerged. The system supplies just enough resources for the plant to survive but not to thrive, which keeps the plant in a dwarf state for periods of up to three years.

In *It’s Raining, Naturally: Making Good and Bad Weather* [20] by Nicola Toffolini, a water hyacinth was placed inside an enclosed glass-and-aluminum case. Users can cause meteorological and climatic variations inside the case; they can make night fall or day break and make rain fall or cease.

Spore 1.1 [21] by Matthew Kenyon and Douglas Easterly features a rubber tree plant that was bought at retailer Home Depot and is watered only when the multinational company’s share values are rising. The health of the plant thus functions as a visualization of Home Depot’s financial health. Home Depot provides a 1-year unconditional replacement guarantee for the plant in the case of its death.

Tardigotchi [22], by the same artists, features a living tardigrade (a microscopic, water-dwelling organism) and a digital caricature thereof. Housed in a brass sphere, the digital creature is visualized on an LED screen on the device, while the tardigrade can be seen through a monocle on its other side. While partly autonomous, the digital creature also reflects activities by the tardigrade. Viewers can feed the digital creature by pushing a button on the device (much as with a Tamagotchi toy), which simultaneously causes the tardigrade to be fed. Sending an email to the digital character activates a heating lamp provided for the tardigrade.

Within her project *Rearming the Spineless Opuntia* [23] (Fig. 5), Amy Youngs focuses on the spineless *Opuntia*, a cactus whose protective needles have been removed through cloning and micropropagation technologies. Youngs outfitted the defenseless plant with a proximity sensor, which activates a protective spiked copper shell around the plant when it is approached.

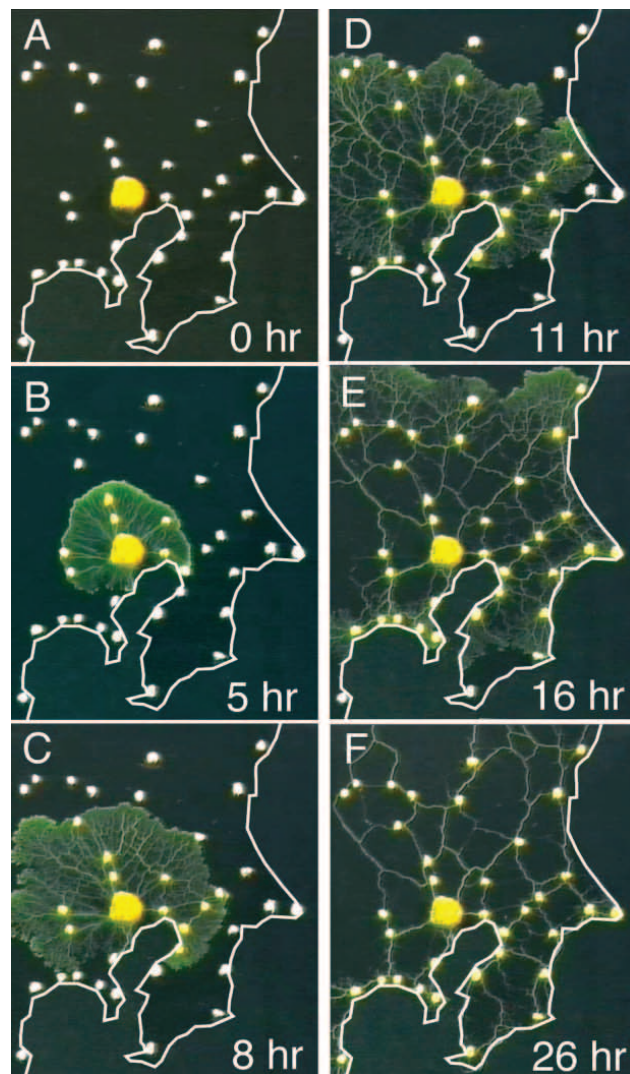
COMPUTING AND CREATION

Biology has provided considerable inspiration to the science of computing—neural information processing, evolutionary mechanics, swarm dynamics and many more biological systems have inspired artificial counterparts aimed at computing, simulation and information-processing tasks. Biological systems have also been applied to computing problems that are typically the domain of digital computing systems. One example is DNA computing, as mentioned in the introductory section of this paper.

There are several instances of computing and creation work with *Physarum polycephalum*, the amoeboid unicellular slime mold that we encountered above and which appears to be popular in scientific and artistic work. Nakagaki and colleagues used *Physarum* to find the shortest path between two selected points in a labyrinth [24]. When nutrients are supplied at these points, the organism forms a single tube that connects the two locations via the shortest route. Using the same approach, Tero et al. [25] (Fig. 6) had *Physarum* design alternative routing for the Tokyo rail system, yielding comparable or even greater efficiency and fault tolerance than the actual rail system.

In addition to computing, artistic creation is another task to which living systems can be applied. *Meadow Piano* [26] by Leif Brush is an installation that uses

Fig. 6. Toshiyuki Nakagaki, Tokyo rail network designed by *Physarum plasmodium*. The growth of *Physarum polycephalum* shown in different stages while forming alternative routing for the Tokyo rail system [44]. (© Toshiyuki Nakagaki)



a grid of sensors to sonify normally inaudible natural sounds such as wind, rain and motion by plants and animals.

The question whether a computer can be programmed to respond intelligently to unexpected events was explored in *SEEK* [27], a project by Nicholas Negroponte and his Architecture Machine Group at MIT. *SEEK* consists of a toy-block city placed in a Plexiglas-encased environment inhabited by gerbils that bump into the blocks and thus destroy the arrangement. A computer-controlled robotic arm is programmed to either correct or amplify these dislocations.

In their series of “Debug” [28] projects, design studio EDHV uses a variety of insect types to generate graphic designs and 3D objects. Insects are placed inside a logo-shaped mould or on a 3D object, and their movements are tracked by a computer and translated into line patterns. The different types

of insects each have different behaviors, resulting in diverse designs of logos and furniture.

Life Support Systems: Vanda [29] is an installation from the hand of Mateusz Herczka that registers electrical charges emitted by a *Vanda hybrida* orchid that are subsequently digitized and transferred into a computer, with the goal of creating a digital copy of the plant that can be sustained indefinitely. This virtual organism will continue to generate signals that mimic the patterns of the original orchid, even after the real plant has died.

Likewise, in *ENKI* [30], Antony Hall uses bioelectric information from an electrogenic fish to trigger human brainwave entrainment. Flashes of light and tone pulses guide the human brain into various states of brainwave activity generated from the electric field of the bioelectric fish.

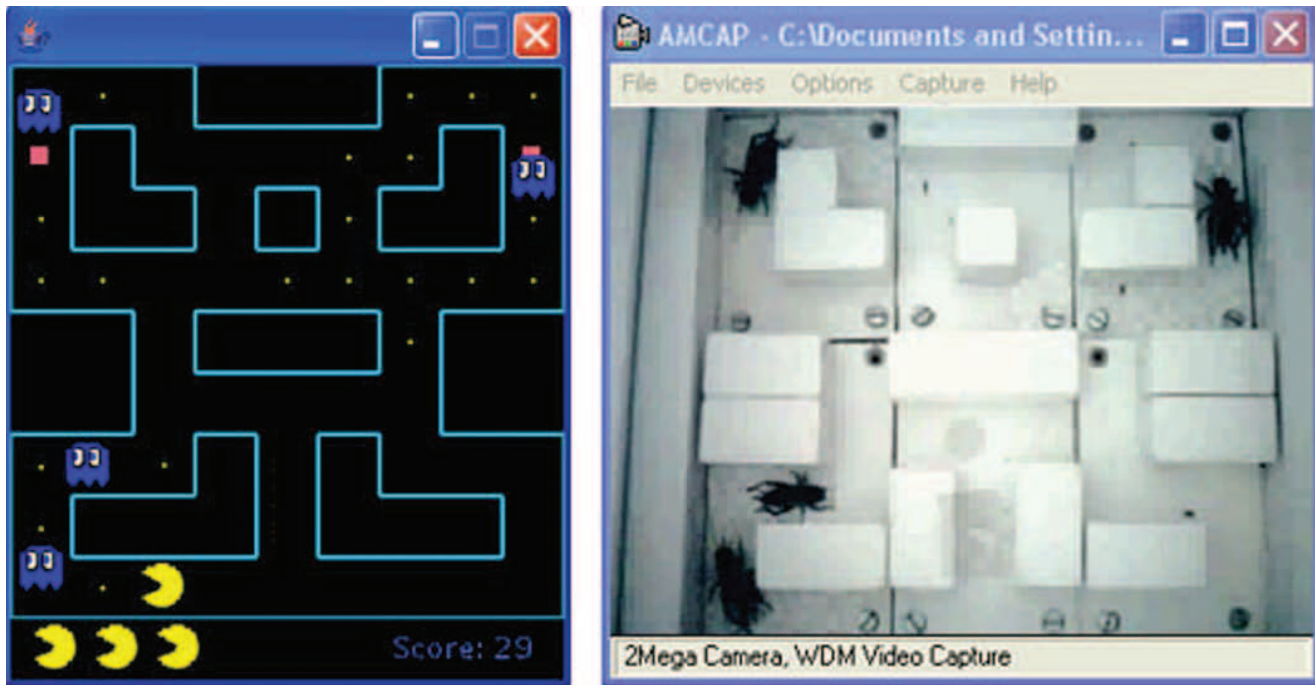


Fig. 7. Wim van Eck and Maarten H. Lamers, *Animal Controlled Computer Games: Playing Pac-Man against Real Crickets*, screen capture, 2006. (left) Player view of the computer game; (right) camera tracking the crickets. (© Wim van Eck)

BIOLOGICAL SYSTEMS IN DIGITAL GAMES

We discuss digital games separately because this is a popular contemporary application domain for combining biological and digital systems, although some of these projects may overlap with categories mentioned above.

In *Biomodd* [31], by artist Angelo Vermeulen, a game server and its monitor are integrated within a greenhouse. The heat generated by the overclocked computer is used to heat the greenhouse's ecosystem, which contains a variety of plants, animals and microorganisms, while the monitor is used to illuminate the plants. The game server hosts a computer game in which players must grow plants and protect them. Playing thus actively modifies the interior ecosystem through the generation of heat and light.

Stephen Wilson's *Protozoa Games* [32] uses a digital microscope to track the activities of a variety of live single-celled organisms and projects the captured images on a projection screen. Simultaneously, visitors are invited to engage in various movement games in front of the screen, such as mimicking the movements of the live organisms. Another game objective is to move the organism toward a target area in the petri dish. The player can turn on lights or talk via speakers on the edges of the petri dish to

influence the phototactic and phonotactic organism.

The *Metazoa Ludens* [33] team concluded that pet owners spend too little time with their pets; hence they created a remote human-animal computer interaction that allows humans to interact with a hamster over distance. The hamster is located inside a closed environment where its position is tracked via an infrared camera and shown inside the owner's computer game. The position of the player's avatar is represented by the movement of bait in the hamster's environment, which tempts the hamster to chase it. The terrain of the hamster's environment can be manipulated by an actuator so that it mimics the virtual terrain of the computer game.

After an extended trial test, the team reported that regular play in *Metazoa Ludens* increased overall body fitness in the hamsters and that over the study period the hamsters increasingly chose to play, indicating a positive desire to play the game.

In *Lumberjacked* [34] by artist Dan Young, players compete against a real tree via a computer game. With the aid of sensors, movement of the tree's leaves is translated into movement within the game. The player controls a virtual lumberjack character who must defend himself from virtual trees, which are controlled by the real tree. Although it is the

wind, rather than the tree, that actually controls the virtual trees, we include this work because the living tree is an integral part of the concept and game mechanics.

The Tic-Tac-Toe Chicken Challenge [35] installation by Bunky Boger challenges spectators to play a tic-tac-toe computer game against a live chicken that pecks at a touchscreen monitor to determine its next move. The chicken was supposedly trained to play tic-tac-toe using reward-based methods developed by Skinner, but it is more likely that a computer calculates each move, with the chicken merely triggering this move by pecking at the screen. Because a panel occludes the actions of the chicken, this is difficult to verify. If we are correct, then this project is an inverted version of the late-18th-century Mechanical Turk hoax chess-playing automaton, inside which a human chess master was hidden [36].

Animal Controlled Computer Games: Playing Pac-Man against Real Crickets [37] (Fig. 7), by the authors of this paper, explores the possibilities of replacing behavior-generating code in computer games with the real-time behavior of live animals, raising the question whether one can play computer games against animals. Players experience a normal Pac-Man game, in which the four ghosts are controlled not by computer code but by live crickets running around a physical

replica of the virtual game maze. Players control Pac-Man as usual, but its position is translated into vibrations within the cricket's playing field. In this manner, crickets are stimulated to approach or flee from Pac-Man, depending on gameplay mechanics.

With the aim to advance bioengineering research through the concept of crowdsourcing, Ingmar Riedel-Kruse and colleagues developed a series of "biotic games" [38]: digital games that incorporate biological processes of real microorganisms. These include variations on Pac-Man, Pong and pinball games. Crowdsourcing principles would allow the actions of individual game players to contribute to realizations of complex bioengineering tasks, according to Riedel-Kruse.

DISCUSSION

Above we have presented an overview of works that integrate living biological organisms and systems with digital systems. Our survey demonstrates that there is interest among both scientists and artists in creating such hybrid systems, yielding technically and artistically interesting results. Within science, however, the results so far have remained in the research phase and are hardly used in practice. In his 1960 paper on Project Pigeon, B.F. Skinner provided an early hypothesis why this might be—in his view, ideas that are too different from traditional solutions are not always given the chance they deserve [39]. Although Project Pigeon yielded remarkable results, the idea of pigeons guiding a powerful bomb was seen, as Skinner remarked emotionally, as a *crackpot idea*.

Artists, however, are keen to stretch the boundaries of acceptance. Judging by the positive responses many of the biological-digital hybrid works receive, this subject is welcome within the arts. Through artistic practice, scientific results are exposed to a larger audience; *MEART*, for instance, showed the public how the cultured neurons of a rat could be used as a "brain"; the work thus serves as a commentary on the creative capacity of biological and digital systems. Naturally, science can only benefit from such public exploration of scientific questions through artworks.

Commercial implications arising from biological-digital hybrid systems in entertainment computing are rare. There may exist multiple reasons for this, including hygiene and safety concerns, cost of required materials and, above all, ethical concerns. The only commercially avail-

able product mentioned in our overview, *The Tic-Tac-Toe Chicken Challenge*, was indeed heavily criticized by animal rights groups. Interestingly, one could also argue that the project uses the animal solely as a gimmick, since the animal does not contribute to the digital system on a technical level; its presence seems intended merely to excite consumers. Apparently the *crackpot idea* aspect is appreciated as entertainment.

We the authors are particularly intrigued by projects that manage to create a two-way interaction between biological and digital systems. Such *duplex* interaction was illustrated in a later version of Project Pigeon, in which three pigeons were placed inside the bomb rather than one [40]. All three pigeons guided the bomb toward an intended target, but if one of the pigeons pecked at a different target than did the others, it was punished and corrected by the mechanical systems of the bomb. Such closed-loop feedback systems can also be found within the above-described works [41].

The inclusion of a living element within a normally lifeless machine has a natural appeal to many and raises exciting questions that were also often formulated in the context of robotics, such as whether it might change the way in which we interact with machines and care for them. This particular question is clearly part of the *Tardigotchi* project, as the care given to the virtual character is required to keep the tardigrade organism (and in effect the whole work) alive.

Ethical concerns for the well-being of organisms in hybrid works obviously exist, although the reviewed literature mentions them marginally. Scientific communities have instituted frameworks for ethical review of research, but similar models are not applied to artistic practice. Current boundaries of ethical acceptance are set only in applicable legal systems. Strikingly, most works in our overview use invertebrate and plant organisms, which commonly fall outside the scope of ethical research models. For a discussion on this topic we refer the reader to lecture notes by Garnet Hertz [42]. Interestingly, such ethical concerns can also constitute the theme of hybrid works, such as in Youngs's *Rearming the Spineless Opuntia*.

Given that we began this paper by discussing a project by B.F. Skinner, it seems appropriate to conclude by noting a behavioristic advantage in hybrid systems: namely, the unpredictability that biological systems can add to digital systems. By studying biological systems

carefully, one can predict the possible behaviors, but the results will never be precisely reproducible. Hybrid systems may create value through outcomes that are unpredictable without being fully nondeterministic. This is a particularly valued feature within the realms of artistic and entertainment computing, where behavioral modeling is a key approach. This point was illustrated in *Animal Controlled Computer Games* when, entirely unexpectedly, a cricket moulted its skin and thereby added an extra, albeit stationary, ghost character to the computer game, surprising the player and creators.

As the authors of this paper, we naturally feel an interest in pursuing the hybrid approach. It can be expected that, through research effort in this field, other instantiations, views and realizations will be encountered in the very near future. We invite you, the reader of this work, to contribute to this emerging field in the spirit of what Skinner described as valuable crackpot ideas.

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42. Garnet Hertz, "Ethology of Art and Science Collaborations: Research Ethics Boards in the Context of Contemporary Art Practice," *Lecture Notes (2002)*. Accessed 12 Jan. 2011 <www.conceptlab.com/ethology/hertz-ethology-notes-v20081124.pdf>.
43. From Skinner [1]; content is public domain.
44. From Tero et al. [25].

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