Robotics as an Educational Tool

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ABSTRACT

This paper explores a new educational application of Piaget's theories of cognitive development i.e. the use, as a teaching tool, of physical robots conceived as artificial organisms. By using simple assembly kits, students at all levels are able to project and construct real robots that simulate the behaviors of animals. The process of constructing real robots helps students to understand concepts about complex dynamic systems – in particular how global behavior can emerge from local dynamics. This is done through a construction process. In order to obtain a given behavior students modify both the "mind" and the body of artificial organisms. The construction of populations of artificial organisms helps the students to realize the difference between observing behavior at the individual (microscopic) level and at the population (macroscopic) level. The development of a population of robots with a given behavior is an evolutionary process. The selective reproduction of a population of robots is a powerful tool for teaching the Darwinian theory of evolution: experiments using artificial – as opposed to biological - organisms make it possible to rapidly observe the results of selection, reproduction and mutation. The paper reviews a number of educational projects using real robots. It is shown that the use of intelligent systems to enlarge our view of biological reality could become an integral part of curricula in science, technology, psychology and biology.

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ARTIFICIAL ORGANISMS FOR EDUCATION

During the last decade, researchers and industries have proposed and developed a number of “robot construction kits” designed to stimulate the learning of concepts and methods related to the education of students in scientific fields such as mathematics, physics, computer science, and mechanics. The kits include small motors, simple sensors, wheels, gearwheels, belts, and relays - everything the student needs to construct a robot. Products like LEGO Dacta and LEGO CyberMaster include cables or radio equipment making it possible to connect the robot to a personal computer. This allows a user to control the device. The recent LEGO Mindstorms product has been developed so as to allow the user to build fully autonomous robots with all computing power located within the machine.

These kits have been built in accordance with educational principles derived from Jean Piaget's theories of cognitive development (1966) as revised by Seymour Papert (1980; 1986). This approach suggests that the center of all learning processes is the active role of the learner who enlarges his/her knowledge through the manipulation and construction of objects. This philosophy suggests that traditional construction kits are highly suitable for use as learning tools. Giving life to an object through interaction with a personal computer makes it possible, however, to develop applications which go beyond the original ideas of those who first proposed this methodology. In particular, a number of research groups have constructed small, mobile machines that simulate the behaviors of real animals. Such prototypes are essentially mobile robots. Like real animals they have a sensory apparatus (i.e. sensors which are sensible to light or heat), a motor system (e.g. mechanical arms or wheels controlled by motors) and a brain (represented by a computer programmed to control the motor system using information from the sensory apparatus). These machines can be treated as *Artificial Organisms* and are used both for educational purposes and for fundamental research in fields such as psychology, ethology and robotics.

ARTIFICIAL ORGANISMS AND NEW EDUCATIONAL TECHNOLOGIES

Artificial Organisms and the Understanding of Complexity

The molecules of a gas within a gasometer, the genetic codes of living beings, an organism's brain, the bees in a beehive and human communities are all examples of *complex dynamic systems.* A system is defined to be *complex* when it is constituted of many different elements that interact with each other. It is a *dynamic* system when the micro-laws of interaction amongst the different elements produce macro-effects which vary over time.

Scientific interest in complexity has produced more than just technological knowledge; what it has done is create a new way of observing and interpreting reality. This is based on the knowledge that in a complex system each component interacts with other components and thus that any action by one component influences the behavior of other components. As a result global behavior emerges from local dynamics affecting specific sub-systems. External disturbances or modifications in the interaction principles governing the activity of system components leads to changes in these local dynamics. These are regulated by non-linear laws. Small, random fluctuations in the behavior of a single component can produce huge changes in global behavior. At the same time however major disturbances can sometimes be absorbed, leaving the state of the system unchanged. Consequently, to study complex dynamic systems, one has to consider behavior both at the microscopic level (the behavior of single components) and at the macroscopic level (the collective, global behavior produced by the interaction of all components).

To transfer this new way of perceiving reality to children, or, more generally, to persons outside the world of scientific research, requires new teaching tools. The importance of the task is evident: we are not just talking about new notions or concepts but about new ways of observing and reasoning that might help people to evaluate the reality in which they live more attentively.

Mitchell Resnick, from MIT’s Media Lab, has developed a teaching methodology that allows the learning of concepts essential to the understanding of complex dynamic systems (Resnick, 1988, 1989, 1994; Kafai & Resnick, 1996). This work is an important part of the background to LEGO Mindstorms (see Appendix A).

Resnick proposes a work group of pupils who are to construct "artificial organisms". The pupils follow a precise construction plan but have the freedom to introduce variants. A concrete example of the potential of this approach can be found in experiments in which a group of children is asked to construct an artificial organism with the ability to move towards a light source.

The first phase in this experiment is to design the body of the machine, i.e. to construct the hardware structure of the robot, decide what kind of sensors to use and how many of them there should be, to define the motor apparatus (choosing wheels, belts or artificial legs). A simple hardware structure for a mobile robot would be a box mounted on two wheels with a light sensor on the front. Each wheel is controlled by an electric motor. In the simplest design, a motor can be on, and thereby provoke a forward movement of the wheel, or off, in which case there will be no movement. In this way, a robot with two independent motors, each connected to one wheel, can produce 4 kinds of actions: go forward (when both motors are on), turn right or left (when one motor is on and the other is off), or stay still (when both motors are off at the same time). The characteristics of the sensors are such that activation is directly proportional to the distance which separates the sensor from the light source.

Having constructed the body of the artificial organism, pupils have to give it a "mind". In this phase, pupils program the computer controlling the behavior of the robot. If they want light-approaching behavior, the pupils have to write procedures where motor activation is a function of the intensity of light perceived by the sensors. At this point a discussion arises: how can an artificial organism with only one sensor move towards a source of stimulation?

Usually, the children realize that, as with real, living organisms, there are two different solutions to the problem. In solution (a) the robot reads the light intensity perceived by the sensor at two different moments; if light intensity at moment 1 is less than intensity at moment 2, the robot is moving towards the light and the correct action is to carry on forward. A second solution (b) might be to add an extra light sensor on the rear of the artificial organism and sense whether the activation on the forward sensor is higher than activation in the rear, in which case the correct action is again to carry on forward.

At this point, the instructor suggests alternative solutions, pointing out that solution (a) requires "memory", i.e. a change in the "mind" of the robot, whereas (b) consists of a structural modification, i.e. a change in the "body" of the robot.

In a second experiment children were asked to construct a population of artificial organisms and observe their behaviors at the individual (microscopic) and population (macroscopic) level. The population consisted of two different kinds of artificial organism: one category of robot was programmed to move toward light sources while a second category was programmed to move away from any kind of light. In this way, each individual had a rather simple behavior. If, however, we place a small lamp on the "head" of each organism the behavior changes – in interesting ways. This may lead to one of two alternative patterns of global population behavior. In pattern (a) it is observed that if the two categories of robot are initially segregated into different regions of space, organisms that are attracted to light tend to meet, to bump into each other and to concentrate within a very small area; robots which avoid light tend, on the other hand, to scatter through the environment until each individual is at “a safe distance” from all other robots. In pattern (b) there is no initial spatial segregation; this implies that an individual belonging to one category can interact with individuals from the other category; in this case one observes complicated patterns of flight and pursuit. Between patterns (a) and (b) there exists a large number of intermediate solutions.

Practical experiments such as these help learners to assimilate concepts which would otherwise be abstract and obscure. The children assimilate the notions of dynamics and complexity through the construction of systems composed of a number of hardware and software components. They learn to study reality from different points of view (i.e. at different levels of analysis) by observing the behavior of individual robots and the global behavior that emerges from the interaction between these individuals.

Artificial Organisms in Undergraduate and Graduate Courses

It has been observed that engineers with a bachelor’s degree often have an excellent knowledge of fundamental theoretical concepts in their discipline but have had insufficient experience in designing and constructing industrial prototypes.

Over the last four years, Fred Martin of MIT has organized a course on "Designing and Constructing LEGO Robots" (Martin, 1994, 1996), the goal being to stimulate design and implementation capabilities in young engineering students. The students in the experiment were divided into small working groups which were given the task of designing and constructing a mobile robot to solve a task given by the teacher (e.g. to move from one point to another while avoiding obstacles of different forms and dimensions). At the end of the course, the prototypes built by the students participated in a competition; the group which produced the most efficient robot won a prize. The contest has now become an annual event at MIT, attracting strong interest and enthusiasm from the entire MIT scientific community.

The Department of Artificial Intelligence at the University of Edinburgh also uses robot competitions as part of its curriculum. In his course *Intelligence and Sensing Control,* John Hallam lectures on artificial intelligence approaches to robotics. Students are given the Edinburgh brain brick which can be used, like the MIT programmable brick, to control LEGO robots. The competitions include robot sumo wrestling and robot rugby.

At the Aarhus University Department of Computer Science we also use robot competitions in graduate level courses on *Adaptive Robots* and *Robot Modelling*. In the different competitions, the students are given a Khepera miniature mobile robot; alternatively they build their own LEGO Mindstorms robot. The competitions include the Danish Championship in Robot Soccer. Building a robot allows computer science students to learn about real world applications. Traditional computer science courses seldom teach the students about the uncertainties of real world interaction; usually, in fact, they try to abstract from the real world and build fully deterministic systems. This can cause problems when computer scientists are later supposed to design and/or program real world control systems.

Figure 1. Photo from one of the robot soccer tournaments (Copyright 1998. H. H. Lund)

While designing robot soccer players, computer science students always make a number of mistakes, usually due to an unrealistic view of their robot's effective capabilities. These problems are often due to the students' failing to view the robot from its own point of view, relying on the sort of unrealistic abstractions they have been trained to use for most of their education. Through experimentation with sensors, motors and control, the students gradually modify their view of the interaction between the robot and the real world, continuously modifying their design until it becomes a realistic one.

According to Fred Martin the success of this kind of teaching experiment is partly due to the fact that the construction kits available on the market facilitate assembly. Available construction kits allow students to find simple solutions to physical problems. The students achieve a real feel for the discrepancies between the results predicted at the design stage and those actually produced by their machines, learning to reduce this discrepancy during design and construction. In this way, the students become acquainted with the circular relationship between theory and practice that is fundamental to technological innovation.

Robotics in High School[1]

At the LEGO Lab at Aarhus University, we have used robots with high school students on a number of occasions. Recently, we arranged the FIRST LEGO League as a pilot project for a number of Danish high schools. The pupils were 12-14 years old. Each class was given four LEGO Mindstorms sets. The students worked in groups of 4-5 to plan, design, build, and program their own robot to participate in the competition. The task was focused on building a robot which could quickly navigate an arena with black tracks on the floor, a ramp, small obstacles, etc. There were awards for the best performing robot but also for the most beautiful robot and the bravest robot.

Figure 2. Robot as a "real" Pacman. (Copyright 1998. H. H. Lund)

The LEGO League pilot project ran for a short period of a couple of months in the autumn of 1998. During that time the classes worked intensively on the project. They started out knowing nothing or very little about robotics, and little about programming (no one knew the Mindstorms graphical programming language before the project started). But,

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[1] Here we use the English term high schools though these are not high schools in the Danish sense, but schools with pupils from the age of 6 to 15 years old.

with enthusiasm and help from tutors, the pupils managed to complete the work and to have well performing robots ready for the final. Boys and girls were both highly involved in the project. For instance, a group of girls decided to build a bride and a groom to run around together. After much work on the aesthetics they wanted to put specific functionality into the robots. In this way they became interested in programming and actually learnt to program the robots, though initially they had just referred to the boys when this kind of work was needed.

ARTIFICIAL ORGANISMS AND BASIC SCIENTIFIC RESEARCH.

Braitenberg Vehicles

Approximately 10 years ago, Valentino Braitenberg, one of the pioneers of cybernetics, published a small, but very interesting booklet entitled *Vehicles: Experiments in Synthetic Psychology* (Braitenberg, 1984). In the book he suggested – as a provocation – that it might be possible to gain insight into a number of typical psychological research themes by constructing small mobile robots that behaved as if they possessed sophisticated mental states. In the booklet, Braitenberg describes a number of experiments where small, vehicles of gradually increasing complexity are constructed out of simple mechanical and electrical components. Each of these machines in some way imitates an intelligent behavior; each is given a name which corresponds to the behavior it imitates. It is important to emphasize that Braitenberg never actually built real robots, but limited himself to designing and describing the robots on paper. He calls this methodology "*Synthetic Psychology*". What Braitenberg shows, with his work, is that, despite their simple mechanics, his machines (vehicles), show behaviors that an external observer would classify to be the product of mental states such as fear, embarrassment, hesitation, paranoia etc. Though Braitenberg’s ideas have produced controversial reactions, it is undeniable that they have had a strong impact on basic research, inspiring a broad range of different studies.

Using a special kit of programmable bricks, David Hogg, Fred Martin, and Mitchell Resnick from MIT Media Lab have constructed the main parts of Braitenberg’s vehicles (Hogg, Martin, & Resnick, 1991). Lund and Miglino (1995) have produced the same series of Braitenberg vehicles using the basic hardware structure presented in figure 3.

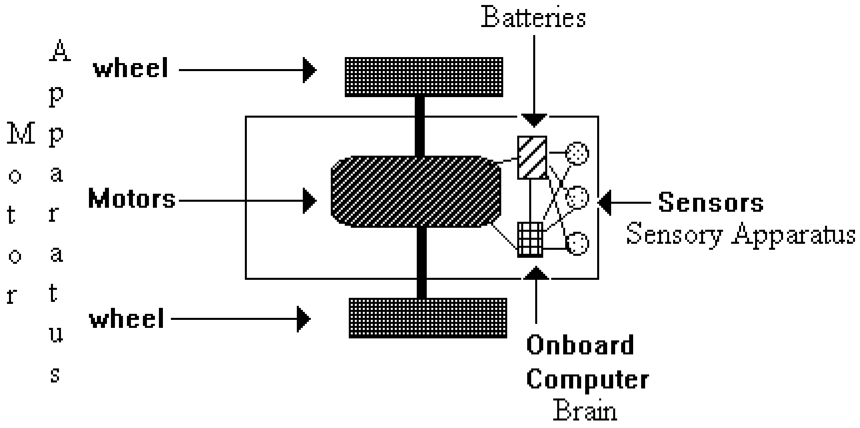

Figure 3. General configuration of the hardware of a Braitenberg vehicle.

Timid (shadow seeker). The robot has one sensor that senses light intensity. The vehicle moves forward if environmental light exceeds a pre-defined threshold, stopping if it finds itself in a shadow zone (see figure 4). Despite the simplicity of this behavior, an observer will typically attribute sophisticated mental states to the organism (e.g. "looking for shade", "hiding", etc.).

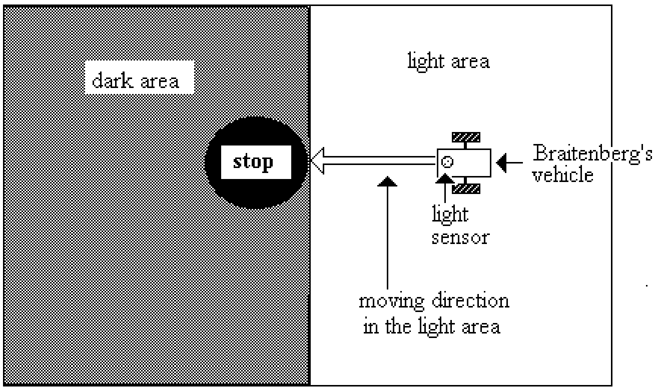

Figure 4. Timid.

Indecisive (the shadow edge finder). This machine has the same hardware structure as "timid" with the difference that when it reaches a shadow zone, instead of stopping, it reverses its direction of motion. When it finds itself next to a border between a well lit and a badly lit zone, it begins to move backwards and forwards, giving the impression that it is "indecisive" (see figure 5).

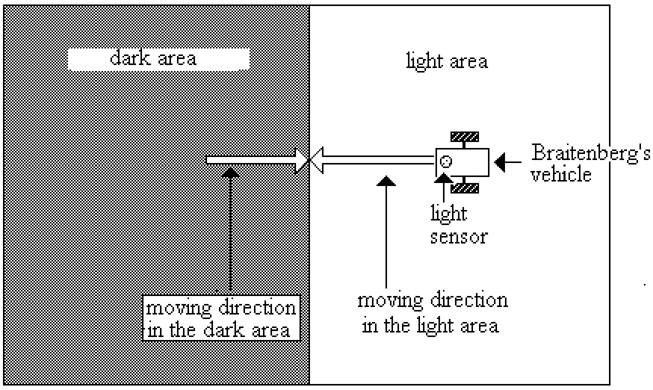

Figure 5. Indecisive.

Paranoid (the shadow-fearing robot). The structure of this robot is identical to those previously described. The "paranoid", however, when it enters a shadow zone, modifies its trajectory and turns left or right in order to return to the well lit zone (see figure 6).

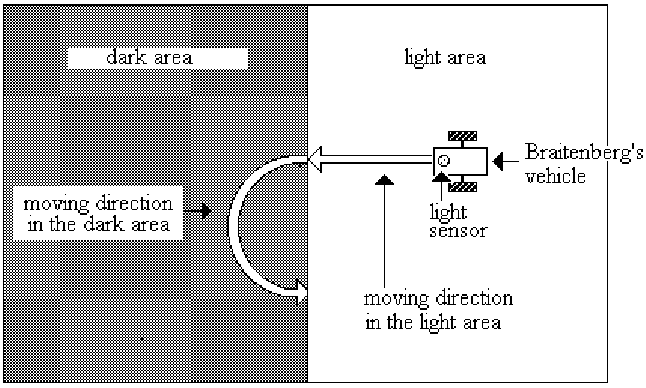

Figure 6. Paranoid.

Dogged (the obstacle avoider). This vehicle's sensorial apparatus consists of two sensors (bumpers), sensitive to physical contact with objects. The two sensors are placed respectively on the front and rear of the robot. The vehicle moves backwards if it touches an obstacle with its front sensor and forwards if it touches an obstacle with the rear sensor (see figure 7).

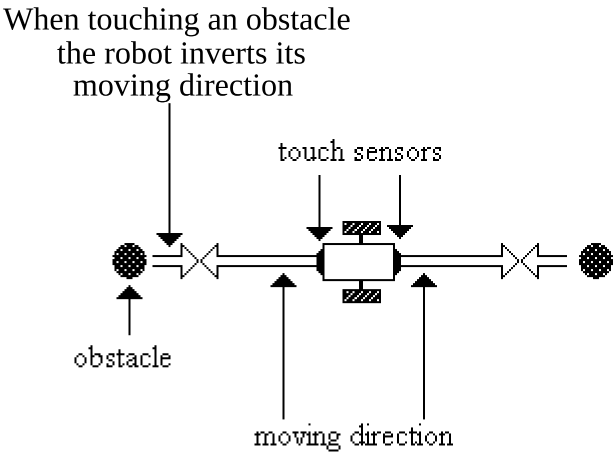

Figure 7. Dogged.

Driven (the light seeker). A sensor is mounted on the front of the robot. The sensor is sensitive to the difference in the intensity of light coming from the left with respect to light coming from the right. The vehicle turns right if the light intensity is highest to its right; otherwise it turns left. If there is no difference in light intensity it moves forward. These simple rules allow the vehicle to maneuver toward a light source by producing a zigzag trajectory (see figure 8).

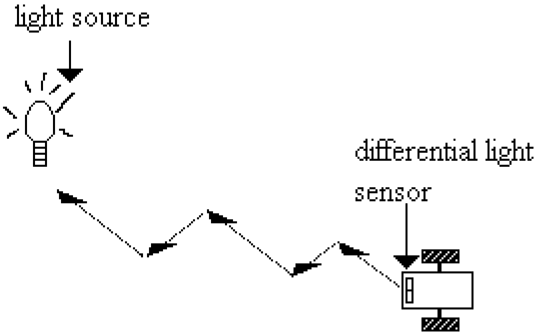

Figure 8. Driven.

Attractive and Repulsive (the leading and following pair).This experiment uses two Braitenberg vehicles. “Attractive” is an artificial organism with a light sensor mounted on its rear. If environmental light exceeds a pre-defined threshold, the vehicle moves rapidly forward; otherwise it stays still. “Repulsive” has a small lamp on the front; when it moves it proceeds slowly and continuously forward.

Imagine that “Attractive” and “Repulsive” are placed on a straight line with “Attractive” at a considerable distance in front of “Repulsive”. Initially, “Attractive” will stay still while

“Repulsive” starts to move slowly forward. When “Repulsive” comes within a distance where “Attractive”'s light sensor is activated, “Attractive” moves away with a fast forward movement. At this point, one observes a pursuit (see figure 9) characterized by a slow approach (by “Repulsive”) and rapid flight (by “Attractive”).

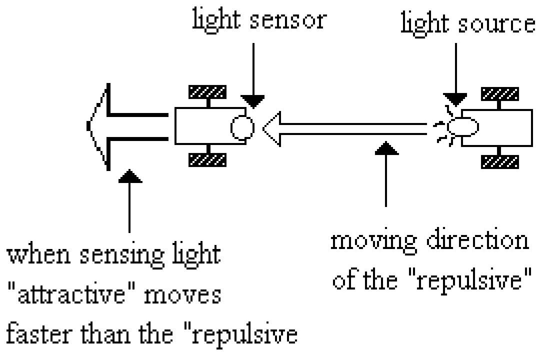

Figure 9. Attractive and Repulsive.

An artificial organism that simulates the behavior of a cricket

At the Department of Artificial Intelligence at the University of Edinburgh we have been investigating artificial organisms in collaboration with Barbara Webb, the animal psychologist, and John Hallam. The results of this work have been reported in *Science* (Bains, 1994). *Robotic experiments in cricket phonotaxis* aims to explain cricket mating behavior. In particular, we investigate the way in which the female of this insect species searches for a male based on the calls emitted by the male. This phenomenon is interesting in that observed behavior apparently requires complex mental capacities: the female has to recognize and identify the male cricket’s song from among all the noises present in the environment; she then has to efficiently maneuver towards the location the song is coming from. The task is further complicated by the fact that the male cricket's song is not continuous, but is composed by "syllables", i.e. short sounds, repeated at regular intervals. The controversial question is whether the female cricket reaches her partner because of a complex mental representation of the variables relevant to the problem or because of simple reflex behavior. Our experiment with artificial organisms suggests that the second hypothesis is indeed a real possibility. This point has been validated by the construction of a small robot that reacts very similarly to the insect.

The artificial organism has two wheels, each of which is driven by an independent motor; the sensory apparatus consists of two sound receivers placed on the side of the organism towards the front, infrared sensors, and contact sensors. Rules in the memory of the onboard computer represent the machine’s "brain". The "brain" allows the artificial organism to recognize and avoid obstacles, to identify sound stimuli similar to the male cricket’s sexual calling song and to follow these sounds. Even with this simple "brain", the robot exhibits behavior which is almost identical to the behavior of living insects. Surprisingly it also produces very efficient behavioral strategies that were not predicted from the original experimental design. If, for example,, the environment includes two loudspeakers which both emit the same calling song, the artificial organism orients itself towards, and approaches, only one of them.

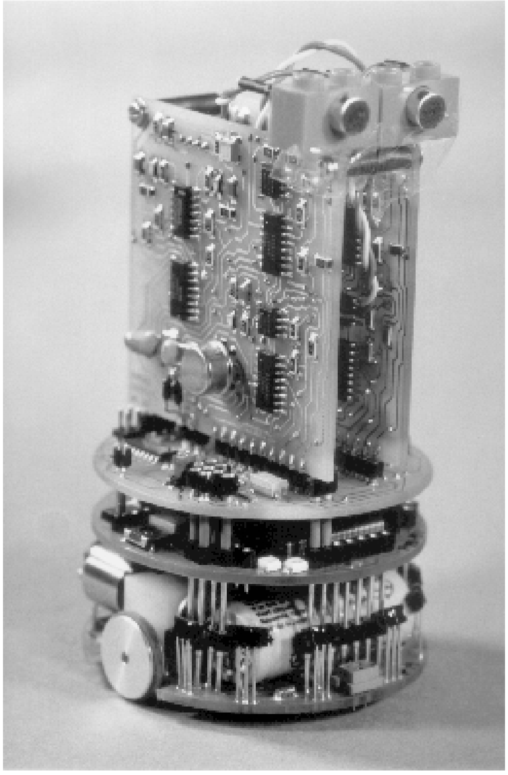

Figure 10. The cricket robot that was used in the robotic experiments in cricket phonotaxis. (Copyright 1997 H. H. Lund)

A number of researchers have criticized the work with "artificial crickets" for not demonstrating whether real crickets do, in fact, use simple rules or complex mental schemes. What our "artificial ethology" experiments have done, however, is give a concrete proof that, at least in principle it would be possible for the female cricket to identify and approach her partner using an elementary sensory-motor schema. Following our first prototype we proceeded to test the hypothesis using a smaller robot that made it possible to replicate the experiment with realistic sized organisms and environments (see fig. 10). This robot had faster processing and new hardware for its ears. This allowed us to use real male cricket calling songs and to work with live male crickets. When the cricket started its calling song the artificial organism would approach it (Lund, Webb, & Hallam, 1997, 1998).

Artificial Organisms and Evolutionary Robotics

All the mobile robots mentioned so far have been programmed by human beings. Unfortunately, although humans are very good at controlling complex processes in "ad hoc" artificial environments, we do not have the capacity to dominate and accurately predict sequences of events in the real world. We have invented automated assembly lines and computers that play nearly perfect games of chess but are still not able to produce autonomous machines that can move in space in a broad range of different environmental conditions.

Over the last couple of years, researchers have tried to overcome this limitation by drawing inspiration directly from nature. As is well known, organisms adapt themselves to different environmental conditions by modifying their body and behavior. This plasticity is shown both during the life of an individual (ontogenetic development) and over successive generations of individuals belonging to same species (phylogenetic evolution). It is this *self-organizing* capacity that researchers attempt to imitate in the construction of artificial systems. In this self-organizing approach, the rules that decide robot behavior are never made explicit by the human programmer; rather they are the product of an adaptive process during which the machines acquire experience in the world and modify themselves on the basis of this experience.

One of the most ambitious projects along these ideas is based on the new discipline of Evolutionary Robotics. The final goal of Evolutionary Robotics is to develop machines that can live, reproduce and die without human intervention. At the moment, most experiments in Evolutionary Robotics are based on computer simulations which emulate important characteristics of the environment and of the physical robots they are intended to study. The mathematical models – so called “genetic algorithms” - which govern the population dynamics attempt to reproduce biological evolution –as described below.

An initial population of robots (generation 1) is constructed by randomly giving each individual different characteristics (e.g. different numbers and types of sensors, behavioral rules, wheel positions). Each machine has to solve a given task (e.g. reach a given point in space as quickly as possible). At this point, the best-performing individuals in generation 1 are selected for reproduction. Each selected individual becomes a “parent organism” and reproduces a certain number of copies of itself – i.e. children. The parent/child reproduction process is not perfect: there are errors – genetic mutations - in the copying process. The child robots constitute generation 2. This process of selection and reproduction can be iterated an arbitrary number of times - normally via software simulation. At any point the researcher can decide to stop the simulated evolution process and try to actually build the robots represented in the computer's memory.

One of the first experiments in Evolutionary Robotics was conducted by Miglino, Nafasi and Taylor (1995) at the Biology Department, UCLA. Using a simulator, the three researchers developed a population of robots which learnt to explore a particular environment. The control system of the best-performing simulated robot was then transferred to a real robot. It was found that the behavior of the physical robot was almost identical to that of the simulated organism. Figure 11 shows the hardware architecture of Miglino, Nafasi, and Taylor’s mobile robot. The versatility of the construction kit used by the three researchers made it possible to rapidly implement and experiment with different hardware solutions. The success of Evolutionary Robotics is in fact largely based on the availability of tools (construction kits), which facilitate the construction of robot prototypes “designed” by simulated evolution.

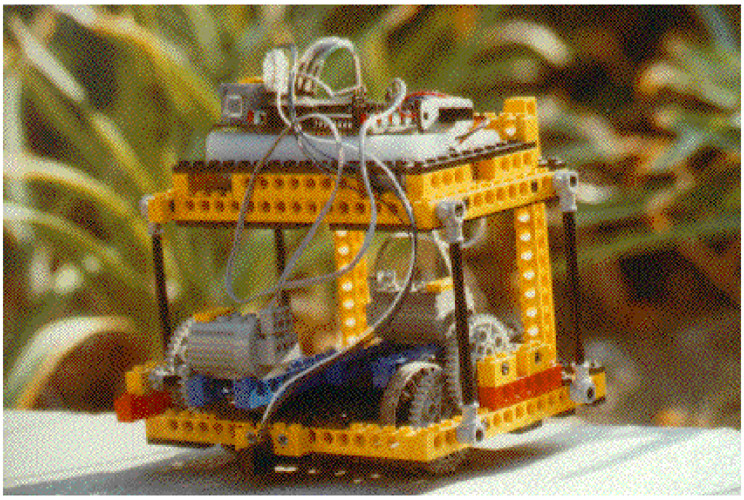

Figure 11. The artificial organism constructed by Miglino, Nafasi, and Taylor at Biology Department at UCLA.

One well-known robot often used in Evolutionary Robotics is the Khepera miniature mobile robot (figure 10). The Khepera has an onboard Motorola 68331 controller with 256 Kbytes RAM and 512 Kbytes ROM, two DC motors, two wheels, eight infrared sensors and has a diameter of 55 mm., a height of 30 mm. and a weight of 70 g.. Even though that Khepera is not, for the moment, easily modifiable, its small size and robustness make it a good tool. As a result more and more robotics researchers are using Khepera, not only in Evolutionary Robotics, but in all areas of research on artificial organisms. For instance, additional work aimed at improving the realism of the artificial cricket was done using an extended version of the Khepera robot, mainly because it is small and offers improved control of experimental parameters.

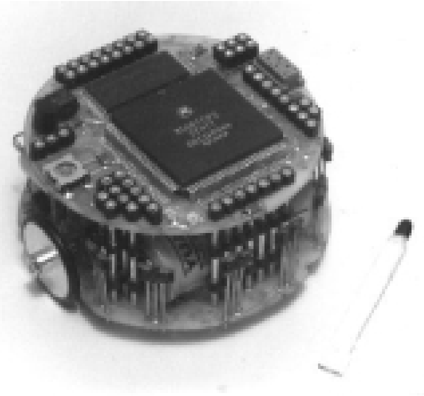

Figure 12. The Khepera miniature mobile robot.

Miglino, Lund, and Nolfi (1995) have further elaborated on the UCLA approach using Khepera. At the Italian National Research Council's Institute of Psychology in Rome, the three researchers have used simulated evolution to develop neural network control systems for the Khepera robot and have then gone on to transfer the best neural network control system to the real Khepera robot. The use of a simulator shortened the time necessary for experiments by 98 %. It was found that, by adding noise to the simulator, it was possible to obtain individuals with the same performance in simulated and physical environments. It is therefore valid to use a fast simulator before transferring evolved control systems to a real robot. This allows students to do extensive studies of evolution which would be impossible in biological settings, due to the time necessary for experiments involving many generations of real animals.

Experiments in Evolutionary Robotics show how the simulation of evolutionary processes can make it possible to automate the development of intelligent control systems for real robots. By simulating the natural processes predicted by Darwinian evolutionary theory and playing with the various components (mutation rates, selective pressure, etc.) - students achieve a much better theoretical understanding than would otherwise be possible.

As mentioned above, the techniques of evolutionary robotics force the researcher to continuously shift from simulated (digital) worlds to real environments and machines (and vice versa). In an educational perspective, this continuously shifting perspective can be used to teach a number of important points about how to build models of physical environments and how to incorporate fuzzy environmental features such as light intensity. The transfer of the controllers to real robots provides implicit feedback on the correctness of the simulation. In short, evolutionary robotics experiments force students to face a broad range of open issues in current computer science research. For this reason, the Department of Computer Science at the University of Aarhus has activated a course on Evolutionary Robotics and Adaptive Robots. The final project in this course is participation in the Danish Robot Soccer Championship

Experimenting with physical robots that have to navigate in the real world, computer science students quickly learn that there are discrepancies between a simulated world (a computer model with no uncertainty) and the real world. Students used to working with reliable data are always particularly surprised by the difficulty of interpreting sensory input. It takes many experiments with physical robots before the students change their way of thinking. Even in the final project they were often puzzled by the differences between lab conditions and conditions on the physical "playing field". This kind of experience is very important for computer scientists for when they graduate and have to design and program devices, such as space shuttles, that work with real world data.

BREEDING ROBOTS TO OVERCOME LIMITATIONS IN DESIGN AND PROGRAMMING

All the projects, ideas and experiments presented in the previous sections are based on programming-oriented philosophy. In other words, children, high school pupils, and students are expected to possess and/or learn the cognitive/manual skills necessary to pre-design and program environments and artificial organisms. In everyday life, however, individuals are often required to participate in dynamic processes and to guide these processes without having a clear idea of a final objective. In many real-life situations goals change over time. This makes it impossible to program a solution (or a machine) which will work in every possible situation. Often, the individual's role is limited to choosing between solutions that "have just happened" or to helping such solutions to emerge. This for example is what an animal breeder or a farmer does when he breeds animals or plants; it is the real sense of nursing a baby. In short what we have to learn is not how to *program* complexity but how to *manage* it.

In a recent experiment, we have been exploring what happens when we allow children to interact in an evolutionary robotics experiment in which they attempt to govern the evolutionary process.

The traditional evolutionary robotics approach would have required the children to design mathematical fitness functions. This was ruled out. We also wanted an approach which was different from traditional *LOGO programming of LEGO "robots". We therefore chose a third option: Interactive Evolutionary Robotics. In this approach children develop (or evolve) robot controllers on a simulator. At each stage in evolution the children choose among different robot behaviors shown on a screen. When they are satisfied with the simulated robot's behavior they download the developed control system to a real LEGO robot and carry on playing with it in a real environment.

The interactive evolutionary robotics approach is inspired by our previous work using interactive genetic algorithms to evolve simulated robot controllers, facial expressions and artistic images (see e.g. Pagliarini, Lund, Miglino & Parisi, 1996; Vucic & Lund, 1998). In this approach, there is no need for programming knowledge. All the end-user has to do is to choose between solutions suggested graphically on the screen. Selection is no longer based on a fitness function but is performed directly by the end-user.

Surprisingly, we observed that children, using our tool, have been able to produce most of the simple robot behaviors that have been developed by researchers in evolutionary robotics.

CONCLUSIONS

In an educational context, there are essentially two ways to exploit the computational and storage power of a computer: a) to produce knowledge-based systems (such as WWW internet services, multimedia encyclopedias, etc.) where a user navigates and retrieves texts, images, sounds; b) to build a simulated laboratory where it is possible to gain knowledge by applying a process similar to scientific method: formulating hypotheses about phenomena and testing these hypotheses by experiment. Tools built according to the first approach can facilitate learning in human sciences, the second approach is more appropriate for teaching technological and scientific subjects.

The simulated laboratory approach is a direct implementation of the constructivist perspective on education (Piaget 1966; Papert 1980, 1986; Harel & Papert, 1990). According to Piaget and Papert, individuals actively select relevant aspects of their environment, manipulate concrete objects and assimilate new knowledge through observation of the effects of these actions. In this sense the individual constructs a representation of reality. It is this active role of the learner which is the most appealing aspect of computer simulation games. At the same time however traditional simulated software environments imprison the user in an idealistic world where important, fuzzy aspects of the physical environments are often neglected. In this paper we have described how to use a computer to give life to objects in a physical world. In this sense every object in the environment is seen as a small intelligent system that can be studied in interaction with the rest of the physical world and with other intelligent systems. In this perspective, a computer can be viewed as a bridge between pure abstract formal structures (computer programs) and the key, non-deterministic aspects of the real, physical world.

APPENDIX A – ROBOT TOOLS

There are a number of hardware approaches to using robotics in an educational curriculum. In general, we can cluster these hardware approaches into two categories: 1) buying a robot with a pre-defined morphology, and 2) building a robot from smaller parts. For instance, the Khepera robot (manufactured by K-Team, Switzerland), mentioned above, is an instance of 1), though it is possible to add extra modules (e.g. grippers or vision systems) to the basic robot. With engineering skills one can also build personal modules to add to the Khepera robot as we did with the ears module. For most users, however, this robot, like most pre-assembled machines, will have a pre-defined morphology.

Because of its robustness and small size the Khepera robot is well suited for use in class. The small size means that one can fairly easy build a number of experimental set-ups (e.g. tracks and arenas) to fit into a classroom. However, the small size also means that it can be difficult to run in more realistic environments. K-Team manufactures a larger robot, called Koala, which is able to run in corridors and on a number of surfaces. Both the Khepera and Koala are programmed in the C programming language with a protocol for talking with other robot devices. This means that these robots are most suitable for use by undergraduate and graduate students and for real world control tasks. There are a large number of different robots on the market with similar properties.

Figure 13. The LEGO Mindstorms kit. (Copyright 1998. H. H. Lund)

In many cases, a robot with a pre-defined morphology is unsuitable. For instance, if the curriculum includes teaching pupils about gearing, motors, sensors, and engineering in general, it is better to give the pupils hands-on experience by allowing them to build their own physical robot. Until recently, this approach demanded that teacher and pupils should have electrical engineering skills. An excellent reference to such an approach can be found in Joseph Jones and Anita Flynn's book: "Mobile Robots: Inspiration to Implementation" (1993), in which the authors give an engineering description of the development of the Rug Warrior robot and its various components. The Rug Warrior can be purchased as an assembly kit together with the book.

To our knowledge, the easiest way to start experimenting with robotics is to build LEGO machines with sensory, actuator, and control capabilities. This can be done with LEGO Dacta systems, the LEGO CodePilot system, the LEGO CyberMaster system, and the LEGO Mindstorms system. Here we will look at the LEGO Mindstorms system. This system consists of a big LEGO brick that functions as a control unit, LEGO sensors (e.g. light sensors and switch sensors) and LEGO motors One can also use other LEGO sensors such as temperature sensors and angle sensors. Using these components it is possible not only to build traditional LEGO robots but also to give them functionality. The control unit contains batteries, so the robot can be fully autonomous with no connection to a host computer. The control unit has three input channels – which can be connected to sensors - and three output channels for the motors. The connectors follow the traditional LEGO design and are thus very easy to use; making a connection is like putting one LEGO brick on top of another. This allows the pupil to build a robot with the morphology chosen by the pupil himself/herself, and to change the morphology during the project. During experimentation the child can use the knowledge he/she acquires to modify the robot (using different sensors, placing motors in different positions, changing the gearing, etc.). LEGO Mindstorms robots are programmed using a graphical programming language (using the language is very much like putting together pieces in a puzzle), and is possible for children down to the age of approximately 11 years old. For more advanced projects, it is possible to design more advanced control programs for the robots linking with Windows compilers such as Visual Basic, Visual C++, and Visual Java++. When a control program has been compiled on a PC, the control program can be downloaded to the LEGO construction via an infrared communication link. From this point on the LEGO robot functions autonomously.

APPENDIX B – FURTHER INFORMATION

The GRAL (research group on Artificial Life) site at the National Research Council, Italy includes good information about artificial life and Evolutionary Robotics and is a good starting point: http://kant.irmkant.rm.cnr.it/gral.html.

This site includes a huge number of scientific articles about artificial life and evolutionary robotics: http://www.cogs.susx.ac.uk/users/ezequiel/alife-page/alife.html

The LEGO Mindstorms robots are described on: http://www.LEGOmindstorms.com/

and the use of LEGO Mindstorms robots in research is described on: http://legolab.daimi.au.dk/

The work by Papert and Resnick on constructionism can be found on: http://el.www.media.mit.edu/groups/el/

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