Evolving Robot Morphology

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***Abstract*— True evolvable hardware should evolve whole hardware structures. In robotics, it is not enough only to evolve the control circuit — the performance of the control circuit is dependent on other hardware parameters, the *robot body plan*, which might include body size, wheel radius, motor time constant, sensors, etc. Both control circuit and body plan co-evolve in true evolvable hardware. By including the robot body plan in the genotype as a kind of *Hox* gene, we co-evolve task-fulfilling behaviors and body plans, and we study the distribution of body parameters in the morphological space. Further, we have developed a new hardware module for the Khepera robot, namely ears with programmable amplifiers, synthesizers, and mixers, that allow us to study true evolvable hardware by modelling the evolution of auditory sensor morphology.**

I. TRUE EVOLVABLE HARDWARE.

The concept of evolvable hardware (EHW) or evolware has mainly been interpreted as reconfiguring Field Programmable Gate Arrays (FPGA) by using genetic learning to adapt the circuit architecture to new unknown environments [9; 10; 18; 23; 25]. However, we will argue that *true evolvable hardware* should be interpreted as hardware, where not only the primitive gates (e.g. AND, OR gates) or high-level functions (e.g. adder, subtracter, sine generator) of a FPGA are evolvable, but the whole physical morphology is evolvable.

Generally, EHW should refer to hardware that can change its architecture and behavior dynamically and autonomously with its environment: "EHW should be regarded as an evolutionary approach to behavior design rather than hardware design" [27]. Therefore, EHW should include the whole architecture of an integrated system and not only the circuit, especially when we are interested in the development of complete autonomous systems. The motivation for developing complete autonomous systems has been outlined by Malcolm, Smithers and Hallam [16], and we agree with Pfeifer [20] that complete autonomous systems should be autonomous, self-sufficient, embodied, and situated. Hence, the design of such a system must include self-organisation, and self-organisation means adaptation of *both* morphology and control architecture.

However, the EHW community has looked only at adaptation of control architectures, for example through the evolution of FPGAs. Let us, for instance, look at EHW for robot control, as suggested by Thompson [25]. In this case, traditionally, one would interpret the EHW as being the reconfigurable (evolvable) circuit, on which one can evolve a task-fulfilling robot controller for a specific task. Hence, one would evolve the architecture of the control circuit. As identified by Thompson, this might give some advantages over evolution of controllers on fixed hardware. On fixed hardware, the evolved control system will be implemented as a software simulation of a specific hardware configuration. Such a software simulation will likely slow down the processing speed. Secondly, by giving evolution control over the reconfigurable hardware, one might obtain controllers that exploit the reconfigurable circuit extensively by using designs that are traditionally prohibited by engineers, or by exploiting defects in the circuit. However, the circuit architecture is only a part of the hardware system, and ideally we would like to evolve the whole system. The hardware of a robot consists of both the circuit, on which the control system is implemented, and the sensors, motors, and physical structure of the robot.

True EHW should evolve the whole hardware system, since the evolution and performance of the electronic hardware is largely dependent on the other parts of the hardware that constitute the system. We call the latter part the *robot body plan*. A robot body plan is a specification of the body parameters. For a mobile robot, it might be types, number and position of sensors, body size, wheel radius, wheel base, and motor time constant. With one specific motor time constant, the ideal control circuit should evolve to a different control than with another motor time constant; different sensors demand different control mechanisms; and so forth. Further, the robot body plan should adapt to the task that we want the evolved robot to solve. An obstacle avoidance behavior might be obtained with a small body size, while a large body size might be advantageous in a box-pushing experiment; a small wheel base might be desirable for a fast-turning robot, while a large wheel base is preferable when we want to evolve a robot with a slow turning; and so forth. Hence, the performance of an evolved hardware circuit is decided by the other hardware parameters. When these parameters are fixed, the circuit is evolved to adapt to those

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fixed parameters that, however, might be inappropriate for the given task. Therefore, in *true EHW*, all hardware parameters should co-evolve.

II. Biological Background.

A brain does not do much without a body, while a body cannot do much without a brain to control it. Brains and bodies have co-evolved and fit almost perfectly to each other. A human brain would not be much help to a parrot, and an elephant brain would not be appropriate to control a human body. The fact that the body largely determines the performance of the brain (or rather the control mechanism) has previously been ignored by the research communities studying evolutionary computation, artificial life, robotics, and adaptive behavior, where research has been on evolving/developing adaptive control systems for agents with a fixed structure. The normal practice has been that if one were to test hypotheses in a real agent in the real world, then one would buy a robot with a predefined structure (i.e. pre-defined sensors, motors, size, etc.), or, in some cases, build one's own robot, but then with a fixed non-reconfigurable body plan.

However, the biological facts about the evolution of body plans should appeal to these researchers. Nature tells us that body plans evolve, and the biological data suggest that body plans of all animals, from fruit flies to elephants, are controlled by the same kinds of genes, namely the *Hox* genes [2]. The first multicellular animals' body plans are believed to have been largely the work of a primitive set of *Hox* genes (Antp-like genes) and descendants of these genes have been sculpting the body plans of animals ever since. When changing *Hox* genes inside embryos, cells may change and, for instance, limbs might grow in the wrong place. For example, genetic experiments with homeotic genes in mice have demonstrated that *Hox* genes are in part responsible for the specification of segmental identity along the anterior-posterior axis, and it has been proposed that an axial *Hox* code determines the morphology of individual vertebrae [11], and *Hoxa-1* and *Hoxa-2* have been shown to play a critical role in head development in both mice and *Drosophila* [5].

Further, there exist both biological data and philosophical reflections that suggest that some biological forms are impossible in the morphological space [4; 21]. Different species are clustered together in the morphological space with a long distance e.g. from insects to mammals, and we agree with Emmeche [4] that there is no direct jump from one cluster to another (see Fig. 1). The displacement in the morphological space is a long evolutionary process that is largely based on exaptations and pre-adaptations [7; 8; 15].

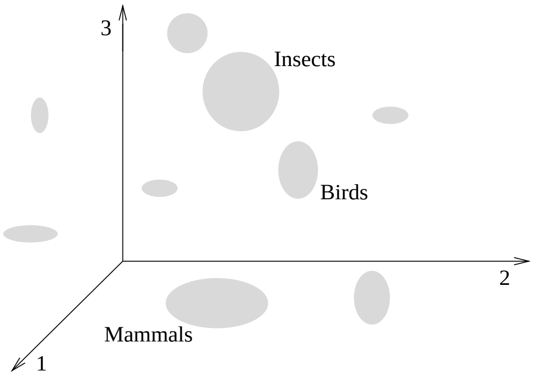

Fig. 1. The morphological space in which natural forms are clustered together. The three axes are morphological parameters. Modified from [4].

III. Evolving Robot Body Plans.

Impossible regions in the morphological space are not considered in Sims work [22], where he co-evolves morphologies in simulation. Hence, that approach might fail in real robots, since also the possibilities in the robot morphological space are limited. A more fruitful approach should combine our knowledge about robots with genetics.

The biological facts about *Hox* genes suggest that the evolution of body plans can be modelled by having parts of a genetic string to express growth of different body parts. The idea of a developmental morphogenetic model has been investigated in simulation, e.g. [1; 3], but only in order to develop the neuronal structure and not the physical structure of an agent. Spirov [24] has investigated the pattern-form interplay in a model of the early development of sea urchin. However, this simulation work does not give us indications of how to evolve real hardware structures.

Our first approach toward evolving robot body plans uses a simple direct encoding from gene to physical expression, since our immediate goal is to show the validity of evolving hardware structures rather than the validity of a developmental model. The genotype of a robot expresses a tree structure that is used as controller (and determines the number of sensors and their position) and a list of real numbers that determines the robot body plan (i.e. body size, wheel base, wheel radius, motor time constant). Hence, we co-evolve robot controllers (the traditional EHW) *and* robot body plans.

By using an evolutionary algorithm (in our case, we use genetic programming to evolve the controller and a genetic algorithm to evolve the body parameters), we can evolve robots that adapt to specific tasks, as shown in [12]. This is done in a carefully made robot simulator, and as shown in [14; 17], simple robot behaviors can be transferred from a carefully made robot simulator to reality with little difficulty. With this technique, we are currently building a simulator for LEGO robots that will allow us to co-evolve controllers and body plans in simulation before constructing and re-building the LEGO robots according to the evolved body plans.

When co-evolving robot controller and body, we can interpret the dimensions of the morphological space as being sensor number and position, body size, wheel base, wheel radius, and motor time constant. For a specific task, we can then analyze how the evolved robots cluster in specific regions of the morphological space. For practical reasons, we map only two dimensions here.

Figure 2 shows the distribution of body size and wheel base in the morphological space of a number of robots evolved to perform an obstacle avoidance task. We observe that relative small body sizes seem to be the most fit for this task and that there is an almost linear relationship between body size and wheel base (the correlation coefficient is 0.8694). These results explain that a small size robot is better at performing obstacle avoidance, and the body-size wheel base reduces the turning rate in order to keep the robot moving stably. Further,when increasing the sensor range, as in Fig. 3, the correlation between the wheel base and body size maintains approximately linearity, but the range of coverage of the evolved wheel base and body size becomes wider. This is due to the fact that the robots can sense obstacles further away, and therefore have more time to react (e.g., to turn). Hence, a larger body and a larger wheel base that means more time steps to turn the robot can evolve. In other words, the upper limit of the size and base of a robot is constrained by the sensor range.

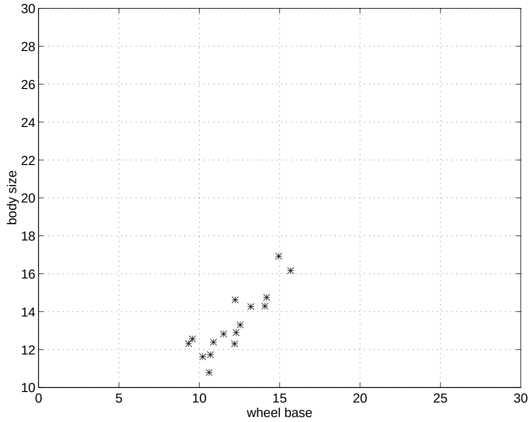

Fig. 2. Two dimensions of the robot morphological space. The plots are of the best robots from a number of evolutionary runs. There is an almost linear relationship between robot body size and wheel base in the robots that are evolved to perform obstacle avoidance tasks.

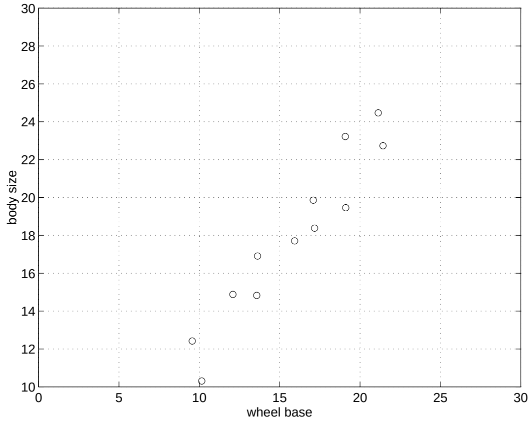

Fig. 3. The relationship between robot body size and wheel base for robots with double sensor range. The relationship is still linear, but the body size and wheel base can become larger, since the robots sense an obstacle further away and have more time steps to react.

IV. Evolving Auditory Sensor Morphology.

We have developed a new piece of hardware for the Khepera roboti [19], namely ears (see Fig. 4). This hardware is reconfigurable, and will allow us to study the co-evolution of controller and ears morphology.

As an example consider the cricket. The male cricket produces a species-specific song by rubbing his wings together, and the female is able to locate males generating her conspecific song by phonotaxis. The morphology of the cricket's auditory apparatus is crucial to the successful performance of this skill.

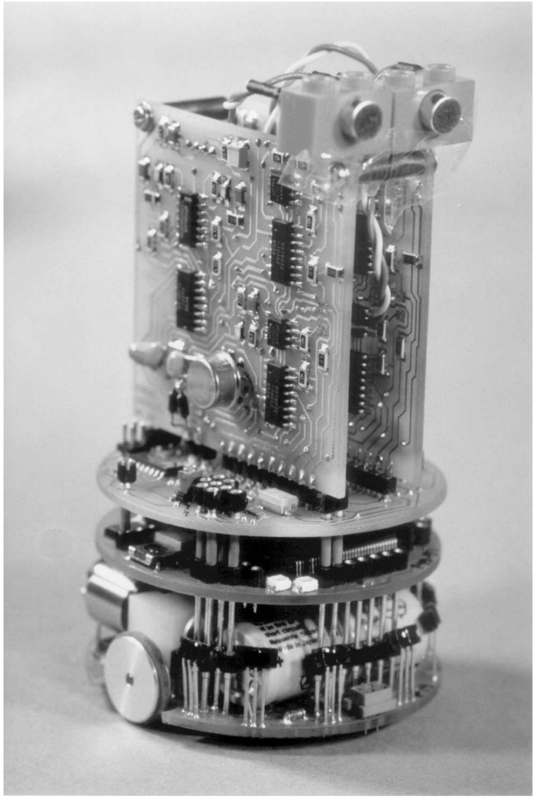

Fig. 4. The Khepera robot with ears. The ears have programmable amplifiers, synthesizers, and mixers.

The female cricket has four auditory openings: an ear (tympanum) located on each upper foreleg, and an auditory spiricle (or hole) on each side of the frontal section of her body. The four are linked internally by means of tracheal tubes. Sound reaches the tympani directly through the air and, after propagation through the internal tubes, from the other auditory openings. The sound transduced from each tympanum by the cricket's auditory receptors is thus a combination of delayed and filtered signals from the other tympanum and the spiricles arriving at the back of the tympanum with the direct sound arriving at its outer face.

The delays and filtering performed by the auditory morphology improve the cricket's ability to discriminate the arrival direction of the conspecific song since the phased combination of sounds from the different sources induces a strong directional sensitivity into the response of each tympanum. Essentially, sounds arriving from the same side as the tympanum are delayed by the internal structures to arrive in anti-phase with respect to the direct path at the ipsilateral ear and in phase at the contralateral ear. Since the sounds arriving by the two paths are subtracted (being on opposite sides of the tympanum), the stimulus intensity at the ipsilateral ear is enhanced while at the contralateral ear it is diminished.

In the cricket, the delays and filter characteristics of the internal auditory structures are species-specific. To model the auditory morphology of the cricket, we have built an electronic emulation of some of these characteristics (see Fig. 5). Sound is collected by two or four microphones whose spacing is carefully controlled. After amplification and initial filtering three delayed copies of the sound are generated with programmable relative delays, which are then scaled and added together to construct a tympanal response. The intensity of the resultant signal is transduced using an analogue-to-digital conversion system for use by the control program. This hardware allows us to approximate the auditory morphology of various crickets by adjusting the programmable delays and the summing gains. It is not a perfect emulation of the insect, however: two programmed delays allow us to sum signals from each tympanum and both spiricles, but not from all auditory openings; and the summation system allows us to program relative gains, but not frequency dependent gains.

Nevertheless, the emulation circuitry is able to model a variety of specialised morphology auditory systems, and allows us to investigate the relationship between the auditory morphology, the conspecific song, and the internal control system that generates the phonotaxis behaviour shown by the female cricket in response to the call of a mate. One possible investigation is then to co-evolve controller and auditory morphology to give good phonotaxis to a specific song while giving good discrimination between different kinds of songs.

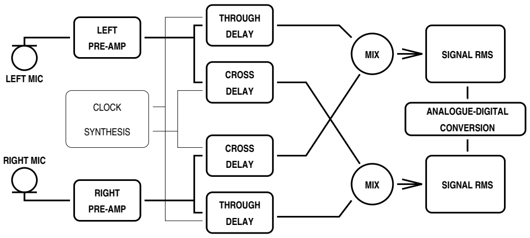

Fig. 5. Simplified diagram of the ears circuit. When sound arrives at each microphone (the analogue of the cricket's tympanum), the received signal is pre-amplified. The signal is then sent with a 'through delay' to the mixer at the same side, and with a 'cross delay' to the mixer at the opposite side. The mixed signal is sent through an RMS and an A/D converter to one of the Khepera's input channels. The same happens on the opposite side.

As a test of the reconfigurable hardware, we look at fixed amplifications, delays, scaling, and adding (i.e. we model a specific morphology (of *Gryllus bimaculatus*)). With these fixed parameters, we can verify that the hardware works as intended. We do so by designing a control system that models the female cricket's control mechanism, and by emitting recordings of male cricket song from a loud speaker. We would then expect the robot to navigate toward the loud speaker.

Figure 6 shows the result of five such runs where we have modelled the control mechanism and the ears morphology of the female cricket *Gryllus bimaculatus*, and used recordings of the male *Gryllus bimaculatus*. In this case, the robot navigates toward the male song emitted from the loud speaker. Initially, there is no sound present, and the robot moves forward in a straight line. When we start to emit the cricket male song from the loud speaker, the robot will turn and move toward the loud speaker. The result is significantly different from our previous results with a LEGO robot prototype in that we are now able to use real cricket songs where we previously had to use computerized songs with syllables much longer than in the real cricket song, though we expect to be able to demonstrate the same statistical properties of the robot behavior relative to the cricket as we have done for the LEGO robot version [26].

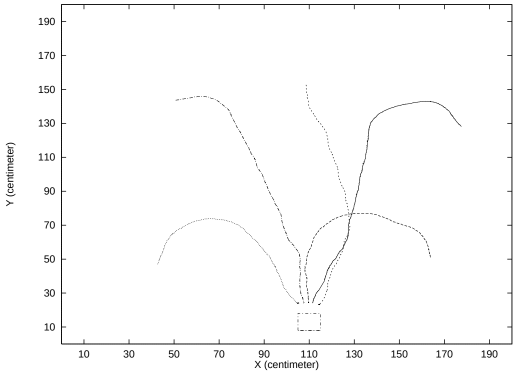

Fig. 6. The trajectories of the Khepera robot with ears parameters set as in *Gryllus bimaculatus*, and with male song from the same species being emitted from the loud speaker at the bottom. Data are collected by putting a LED on the robot and then using a video-tracking system [13].The robot hits the speaker, but the shown trajectories stop before, because the LED is placed in the center of the robot.

V. Conclusion and Future Work.

We have outlined here the framework under which one can investigate the co-evolution of reconfigurable control systems and reconfigurable body plans. It is our view, that, at least in robotics, the concept of evolvable hardware should be extended to include the robot body plan, since the evolution of the circuit architecture is highly dependent on the specific body plan. Analyses of the robot morphological space tell us that some body plans are impossible or impracticable, so evolved control circuits might fail if this is not taken into consideration. It might be difficult to imagine how to obtain reconfigurable robot body plans, yet LEGO robots are one possibility. We are currently designing a LEGO robot simulator that allows us to co-evolve LEGO robot brains and bodies before assembling a LEGO robot accordingly and down-loading the control system. Fukuda [6] has also suggested a Cellular Robotic System that consists of many robotics units that can be reconfigured depending on given tasks and environments. Another possibility is to use devices similar to the ears that we have developed for the Khepera robot. These do indeed allow on-line reconfiguration, and we can use them to study the co-evolution of controller, song, and morphology.

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