DESIGNING AN ARTIFICIAL BRAIN WITH 10,000 EVOLVED NEURAL NET MODULES

Initial Thoughts

Hugo de GARIS
Brain Builder Group, ATR, 2-2 Hikaridai, Seika-cho, Soraku-gun, Kansai Science City, Kyoto-fu, Japan. tel. (+ 81) (0)774 95 1079 fax. (+ 81) (0) 774 95 1008 http://www.hip.atr.co.jp/~degaris degaris@hip.atr.co.jp

Sung-Bae CHO
Dept of Computer Science, Yonsei University, 134 Shinchon-dong, Sudaemoon-ku, 120-749, Seoul, Korea. sbcho@csai.yonsei.ac.kr

Michael KORKIN
Genobyte Inc. 1319 Spruce St., Suite 210, Boulder, CO, 80302, USA. tel. + 1 303 545 6790, fax. + 1 303 545 9667, http://www.genobyte.com korkin@genobyte.com

Arvin AGAH
Bio-Robotics Division, Mechanical Engineering Lab (MEL), Tsukuba Science City, Japan. tel. (+ 81) (0)298 58 7088, fax. (+ 81) (0)298 58 7201, agah@melcy.mel.go.jp

Abstract

This paper introduces some early thoughts of the authors on how to humanly design an artificial brain containing 10,000 evolved cellular automata-based neural network modules.

1. Introduction

By the end of 1997, de Garis's lab, ATR, will have the technological capability of evolving neural net modules in less than a second, i.e. a complete run of a Genetic Algorithm (GA), with tens of thousands of cellular automata based neural circuit growths. Each growth is followed by a fitness evaluation of the system the grown circuit controls with its time dependent neural signaling. This approach uses new evolvable hardware (EHW, E-Hard) based on state-of-the-art FPGAs (field programmable gate arrays), namely Xilinx's XC6264 chips. The electronic device using these chips, we call a "CBM" (i.e. CAM-Brain Machine [Korkin, de Garis et al 1997]). This machine will be built by the end of 1997. Simultaneously with the development of the CBM will be the development and construction of a kitten robot called "Robokoneko" (Japanese for "robot child cat") which will be controlled off-line (by radio antenna) using an artificial brain to be built with 10,000 neural network modules evolved by the CBM.

The modules communicate with each other via an array of "tags" stored in memory. For example, a tag array might contain the message "module 437 receives inputs from modules 543, 654 and 3638. Inter module communication can be in the form of a broadcast or point to point. Each tag also includes the length of the connection in "clock ticks" and a pointer to the current position(s) of the most recent signal update. The input module numbers listed in each tag provide address pointers to binary signal arrays. These signal arrays are stored in a large module-interconnect memory. For 10,000 modules with an average connection width of 1 byte and 1000 clocks long (and assuming that each module can receive inputs from a maximum of 6 other modules), a memory of about 64Mbytes will be needed for module interconnection. However, the output of one module can still be broadcast (repeated) to thousands of other modules, even though there are only 6-8 signal busses connected to each module.

The lengths of the connections can be made "virtual", i.e. distant modules in real 3D space can have "short connections" if needed. When a module is being run, its input signal stack is loaded from the interconnect memory with the data from the array(s) whose numbers are listed in the tag for the module, and after 50-100 clocks, the output stack is saved in memory (using an address pointer for the module, to be used as a signal source for other modules).

The above paragraphs which describe some of the functional characteristics of the CBM, give only a taste of its capabilities. For further details see [Korkin, de Garis et al 1997].

Assuming now that the construction of a 10,000 evolved neural network module artificial brain will be technologically feasible in 1998, the challenge at the time of writing (March 1997) is to create the architecture for such a
brain. This paper presents some early thoughts on the functions that we want our 10,000 module artificial brain to have, and some ideas for a possible architecture to implement those functions.

The remainder of this paper consists of the following sections. Section 2 introduces briefly some suggested categories of behavior which could be generated by artificial brains which contain an increasing number of modules (in orders of powers of ten). This situates section 3, which discusses the behavioral criteria of the kitten robot having 10,000 modules. Obviously, the brain architecture will depend on what we decide we want our robot to do. With 10,000 modules, we can afford to be quite ambitious. Section 4 gives a more detailed high level architecture of the brain which meets the behavioral criteria. Section 5 takes some of the higher level subsystems of section 4 and suggests how they could be implemented with interconnected individual evolved modules. Section 6 provides further thoughts relevant to brain building, and section 7 talks about ideas for the future, including longer term plans to persuade the Japanese government to invest in the creation of a 2000 human "evolutionary engineer" (EE) plan to build a 10,000,000 module artificial brain in the so-called "J Brain Project" (J = Japanese).

2. Brains with Increasing Powers of Ten Modules

This section is a summary of a section taken from an earlier paper which discussed in very broad terms what kinds of artificial brains might be worth making when the number \( N \) of neural modules that they contain equals 100; 1000; 10,000; 100,000; 1,000,000; 10,000,000. This earlier paper also discussed some of the personnel, management and political issues involved, as the scales of the brain building projects increase, but these aspects will not be discussed here. This section situates the attempt to design a 10,000 module artificial brain, by providing a broader context of larger brain building projects which will probably be undertaken during the next 10 years.

\( N = 100 \)

A fairly detailed architecture for a 100 module brain was presented in an earlier paper [de Garis et al 1997]. This brain controlled the behaviors of a simulated 3D quadraped artificial creature which could walk straight, turn left, turn right, peck at food, and mate. It had modules to control leg motions, to detect signal strengths, frequencies, etc. and could switch motions depending upon incoming signals from its detectors. Production rules to decide when to switch were implemented with interconnected modules. This creature (called LIZZY) would orientate towards prey and mates, and away from predators, and approach or flee. In the case of a prey or mate, Lizzy would approach, stop, and eat or mate. All this was possible with less than 100 modules.

\( N = 1000 \)

By simply adding to Lizzy's behavioral repertoire, one can quickly increase the number of modules to 1000. Lizzy could be made to behave like a toy kitten, so that it could jump, chase its tail, emit simple cries, run at different speeds, etc.

\( N = 10,000 \)

With ten thousand modules, one can begin to experiment with vision and hearing. Simple artificial retinas could be built with some post retinal processing. Maybe some memory could be added. This seeing and hearing creature could avoid objects, approach or flee from slow or fast moving objects respectively, pick up things, etc.

\( N = 100,000 \)

With one hundred thousand modules, more serious versions of creatures with memory, vision, motion generation and detection, hearing, simple comprehension, and multi-sensor interaction could be built.

\( N = 1,000,000 \)

Suggested examples of million module systems might be, artificial kitten pets for children and the aged, robot "guide dogs" to help blind people cross the road, household cleaner robots, etc. These systems would include quite elaborate artificial retinas, and post retinal processing, memory processing, sound generation, even early speech.

\( N = 10,000,000 \)

With ten million modules, one can probably start thinking seriously about the possibility of building useful home cleaner robots that could do the vacuuming, the shopping, empty the garbage, wash the car, etc. Every affluent household would want a cleaner robot. A ten million module brain could probably talk quite well with the understanding level of a small child. One could begin to have relationships with such brains. Perhaps one could start implementing some of Minsky's "Society of Mind" ideas [Minsky 1986].

3. Robokoneko's (Kitten Robot's) Behaviors

This section discusses the behaviors that the authors would like the robot kitten ("Robokoneko") to have, which will require roughly 10,000 modules to implement. It seems to the authors that there are two broad approaches to mapping a set of behaviors to a given number of modules and vice versa. One approach is empirical, i.e. just keep adding behaviors and capabilities to the brain, until a given number of modules is reached, or just add more modules until a given behavioral repertoire is reached. The other approach, would be more theoretical but does not exist yet. We call it "Behavioral Set Analysis (BSA)", which attempts to provide brain architects with principles with which to estimate the number of modules needed for a given behavioral set, or for
a given number of modules, how extensive (how intelligent?) could the behaviors of such a brain be. Since brain building is entirely new, at least on the scale envisioned in this paper, BSA does not yet exist. There is not enough experience yet to create such a body of theory, but as more artificial brains are built (as CBMs and similar devices become more commonplace), this theory should be easier to construct.

Since this attempt to build a 10,000 module artificial brain is the first of its kind ever, there is zero experience to fall back on. It is possible that a behavioral set suggested here may need a lot less than 10,000 modules. When one thinks that Lizzy was implemented with less than 100 modules, imagine what one could do with 10,000 (possible in 1998), or 10,000,000 (which is less than a decade away).

We begin now with some suggestions as to what Robokoneko could do with the 10,000 modules that the CBM will be able to evolve and control in real time in 1998. Note, that this paper only presents the early thoughts of the authors. More detailed plans will be created during the course of 1997 in anticipation of the delivery of the CBM and the construction of the kitten robot by Xmas 1997.

The behavioral set of the kitten robot is partly determined by "political" considerations. Building an artificial brain is a pioneering effort, and so our first task is to show the world that such a thing is possible. ATR's Brain Builder Group needs "proof of concept". For this reason, it is important to make the brain as media friendly as possible to maximize publicity. When millions of people see a cute media friendly robot kitten displaying the many behaviors made possible by a 10,000 module artificial brain, they will be impressed, and hopefully also will Japan's top scientific research policy makers who control the purse strings to pay for a 2000 evolutionary engineer (EE) 5 year J-Brain Project (2001-2005).

Hence, the broad aim is to create an artificial brain which will be capable of making a kitten sized robot as life like as possible. Since 10,000 modules is a lot, it will be possible to give this robot many behaviors and capabilities. de Garis and Agah brainstormed together for 2 days and came up with the following desiderata for the robot. (Several items were added later).

The body of the robot kitten should be real kitten size, with of course 4 legs, a tail, whiskers, a head, with 2 color camera eyes, 2 microphone ears, and maybe (if it is not too heavy) some soft furry covering over its metal springs and frame etc, to make it cute. The kitten should be controlled by wireless modem and be battery powered to be active for about 30 minutes before needing a recharge. The robot could probably be built within a year, especially if grad students get involved.

For functionality, we thought of the following. For behaviors, we wanted the kitten to walk on its 4 legs, stand on 3 legs, manipulate with its front leg(s), jump on the floor, jump onto objects, curl, lie down, sleep, move its tail, move its head, wiggle its ears, react to whisker touching, urinate (water), avoid obstacles, purr when stroked, show hostility when its tail is pulled etc. This is only an initial list which will probably be extensively added to, considering we have 10,000 neural net modules at our disposal to put into the kitten's brain. For sound generation and detection, we want a speaker with a ROM "meow" expressing a range of emotions, e.g. attention seeking, anger, sadness, purring etc. The sound detector would be 2 microphone ears and 2 signal processing chips, so that one could call the kitten "Here, kitty kitty kitty", “Scram”, “Woof” (fear reaction), etc.

We wanted heat sensors (to detect people in the neighborhood), touch sensors (on the back, whiskers, tail etc) and force sensors on the feet. For vision, we wanted 2 color cameras for the eyes, with accompanying signal processing chips on the robot. The whole thing should weigh about 1 to 2 Kgms, so that it can jump and move at real kitten speed. It will be made as light as possible and with minimal on-board processing. Most of the intelligence of the kitten will be generated off-body by the artificial brain, whose decisions will be transmitted by wireless modem to (and from) the kitten.

A certain minimum weight will be necessary due to the weight of the modem (about 0.5 Kg) and the battery (0.5 Kg). The binary I/O of the modem could interface directly with the 1 bit signaling of the so called "CoDi model" of ATR's CAM-Brain design [Gers & de Garis 1996].

4. Behavioral Subsystem Design

The suggestions given in the previous section for the kitten robot's behavioral repertoire are probably insufficient in number to occupy 10,000 modules. Probably most of the modules will be concerned with visual and aural processing. Other modules will probably be needed in a multi-level control architecture. An interesting example of such multi-level control is given in Figs. 1 thru 4, taken from Nikolaas Tinbergen's famous book on ethology [Tinbergen 1989]. These figures show how instinctive behaviors might be controlled in various animals. They are an example of what we call "brain architectures". Fig. 1 shows a hypothesized hierarchical organization of the reproductive instinct of the stickleback. Fig. 2 shows circuits to explain the "central excitatory mechanism (CEM) which arouses male sexual behavior in rats, which (quoting Tinbergen) "is receptive to sensory stimuli and hormone influences and which dispatches impulses to the neural circuits of the behavior pattern". Fig. 3 shows a representation of an instinctive center of an intermediate level in a hierarchy of instinctual control, and Fig. 4 shows a hierarchical system of centers underlying a major instinct (in this case the reproductive
instinct of the stickleback). For details, read Tinbergen's book.

The point being made here is that brain architects will need to read the literature on brain modeling, and especially the work of the ethologists. Within less than a year, a new technology will enable such brain models to be implemented and tested. Each major instinct will have its own behavioral subsystem design. (Note, we begin with instinctual models, because they are much easier to design than learning models. Instinctual creatures with a million neurons are complex enough). As an example of hierarchical subsystems, see Fig. 4 which shows progressively - 1st level modules controlling the major instinct of reproduction, 2nd level fighting, nesting etc, 3rd level consummatory act, 4th level fins, 5th level fin rays, 6th level muscles, 7th level motor units etc.

We could make an equivalent instinctual model for the robot kitten. However, prior to making such a detailed architecture it would probably be better to have a good read of the brain modeling literature to get better inspirations. Tinbergen's ideas are just one set of many, but at least they give a taste of what could be done.

5. Implementing Subsystems with Evolved Neural Modules

Once the above architecture is specified, the next task is to translate the behavioral and control modules into CBM evolvable modules. Of course, this can only begin once the architecture is ready. It is likely that in the case of N = 10,000, there will be two types of people involved in the design and implementation effort. 10,000 modules are a lot. If the whole design and implementation task is to be carried out in one year by 2 people, then this works out at very roughly to one module definition per 20 minutes for 50 times 40 hour weeks. Probably more realistic is to have the two “brain architects” concentrate on the architecture and to delegate the specification of the fitness definitions for each module to more junior researchers (“evolutionary engineers” (EEs)), otherwise the relentless pressure on two people to specify a new module every 20 minutes or so will soon lose its charm and simply become hard dull work.

Once the modules are individually evolved, they then need to be incorporated into the global architecture and tested. To test a hierarchical architecture, one will probably start at the lowest levels and work up. To evolve low level motions for example, it will probably be necessary to simulate in software and then download the solutions into the large CA memory controlled by the CBM in run mode. (For details, see [Korkin, de Garis et al 1997]). One can imagine that once the kitten robot is built and is controlled by an memory controlled by the CBM in run mode. (For details, see [Korkin, de Garis et al 1997]). One can imagine that once the kitten robot is built and is controlled by an

6. Further Thoughts on Brain Building

At a fundamental level, we can think of a number of design principles according to which various modules can cooperate in a given task. Murre proposed three principles for the construction of small-scale multi-module networks, namely - structural compatibility and neural assemblies, replication of structure, and recurrence [Happel 1994]. These principles, although extremely limited, suggest how such subsystems might supplement each other and how they might interact to solve computational difficulties. We could make use of them at a "microscopic" stage of designing an artificial brain.

Group behavior has been studied in a variety of fields, ranging from biology and ethology to sociology and artificial intelligence. We should be able to adopt some of the techniques these fields have proposed when designing larger systems based on the modules. For example, Mataric proposed two ways to combine basic behaviors to develop more complex higher-level behaviors [Mataric 1995]. As is the case with complementary and contradictory drives, Mataric's architecture allows for complementary behaviors, whose outputs are executed concurrently, and for contradictory behaviors, whose outputs are mutually exclusive and can be executed only one at a time. She suggested that these two types of combination operators, applied to a fixed set of basis behaviors, can generate an extensive repertoire of collective behaviors.

The biological literature proposes that neural modules containing little more than a hundred neurons as the basic functional unit of the cerebral cortex [Szentagothai 1975, Eccles 1981]. The overall structure and function of the brain has resulted from a long evolutionary process which has generated a large number of specialised modules which perform the tasks necessary for survival and reproduction. Therefore one of the most promising techniques for designing an artificial brain would be to adopt such evolutionary mechanisms.

However, as the number of modules increases, it may take a very long time indeed to evolve an artificial brain which performs at the level of animal capability. Such evolution might even take several billion years, as was the case with human evolution. Biological principles could help us expedite the design process in several respects. Firstly, the main characteristic of the biological organisation of the brain is that it has a layered structure. Such hierarchical information processing can be identified in the primary visual system [Hubel & Wiesel 1965]. Secondly, multiple parallel processing streams constitute another major neural construction principle [Livingstone & Hubel 1988]. The structuring of the brain into distinct streams, leads to the
independent processing of different information types and modalities.

Last but not least, the brain architecture for consciousness and attention should be considered. This has recently become a hot topic in the neurophysiological and cognitive science fields. Consciousness can be defined as a global integration and dissemination system, which is nested in a large scale distributed array of specialized bioprocessors, and which controls the allocation of the processing resources of the central nervous system. It is posited that this global control is performed via the cortical "gating" of a strategic thalamic nucleus. A promising architecture for this problem consists of two types of network, expert networks and a gating network. Basically, the expert networks compete to learn the training instances, and the gating network facilitates cooperation by the overall mediation of this competition.

7. Ideas for the Future

Obviously, to complete a 10,000 module artificial brain architecture by the end of 1997, a LOT more work needs to be done. The first step will be to read the ethological literature [e.g. Young 1989, Ewert 1980, Tinbergen 1989] and the many books on brain modeling, for inspiration. Once an approach has been chosen, the next step will be to decide upon a full behavioral repertoire and control structure. This repertoire should be extensive enough to fill the large capacities allowed by a 10,000 module architecture. Once the behaviors and control structures are finalized, lower level subsystems can be designed, and finally to low level individual evolvable modules with their fitness definitions and target vectors [Korkin, de Garis et al 1997].

Probably by the end of 1998, it should be clear how successful the 10,000 architecture has been. If it is very successful, then it is likely that a new research field will open up, namely "Brain Building", and the field of neural networks will never be the same, because from 1998 onwards, single network papers will become unsexy in comparison with papers dealing with artificial brains containing 10,000 (and upwards) neural net modules.

It is likely that if the early brains built by ATR and other labs are a success, then governments will want to get involved. In fact, it is the ambition of de Garis to see the Japanese government finance the creation of a 10,000,000 module artificial brain in the so-called "J-Brain Project" with 2000 “evolutionary engineers (EEs)” over the period 2001-2005.

References

Note: Many brain building papers can be down-loaded from de Garis’s web site - http://www.hip.atr.co.jp/~degaris


CHASING
BITING
THREATENING
ETC.
DIGGING
MATERIALS TESTING
GLUING
ETC.
ZIGZAG DANCE
LEAD FEMALE TO NEST
SHOWING ENTRANCE
QUIVERING
FERTILIZING EGGS
ETC.
FANNING
RESCUING EGGS
ETC.

Fig. 1 Hierarchical Reproductive Instinct of Male Stickleback

ANDROGEN INCREASES/LOWERS EXCITABILITY THRESHOLDS
CENTRAL EXCITATORY MECHANISM
PRIMARY CONNECTIONS WITH SENSORY SYSTEMS
NEURAL CIRCUITS FOR MALE PATTERN
EFFECTORS
NEURAL CIRCUITS FOR FEMALE PATTERN
HORMONES
EXTERNAL MOTIVATIONAL IMPULSES
INTERNAL STIMULI
CENTRAL EXCITATORY MECHANISM (I.R.M.)
BLOCK PREVENTING CONTINUOUS DISCHARGE
APPETITIVE BEHAVIOR PATTERN (A.B.P.) CONTROLLED BY CENTER 1

Fig. 2 Central Excitatory Mechanism

LEVEL OF MAJOR INSTINCT (REPRODUCTIVE)
2nd. LEVEL (FIGHTING, NESTING, ETC.)
3rd. LEVEL (CONSUMMATORY ACT)
4th. LEVEL (FINS)
5th LEVEL (FIN RAYS)
6th. LEVEL (MUSCLES)
7th. LEVEL (MOTOR UNITS)

Fig. 4 Hierarchy of Centers for Major Instinct