Asimov’s Coming Back

Submitted to IET Write Around the World Competition

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1．INTRODUCTION

Figure 1 Industrial robots in car manufacturing

Source: www.businessweekly.com

Ever since the word ‘ROBOT’ first appeared in a science fiction in 1921, scientists and engineers have been trying different ways to create it. Present technologies in mechanical and electrical engineering makes it possible to have robots in such places as industrial manufacturing and assembling lines (Figure 1). Although they are essentially robotic arms or similarly driven by electrical power and signal control, they could be treated the primitive pioneers in application. Researches in the laboratories go much further. Interdisciplines are directing the evolution of more advanced robots. Among these are artificial intelligence, computational neuroscience, mathematics and robotics. These disciplines come closer as more complex problems emerge.

From a robot’s point of view, three basic abilities are needed. They are thinking and memory, sensory perceptions, control and behaving. These are capabilities we human beings have to adapt ourselves to the environment (Figure 2). Although researches on robots, especially on intelligent thinking, progress slowly, a revolution for biological inspired robotics is spreading out in the laboratories all over the world.

2．THINKING AND MEMORY

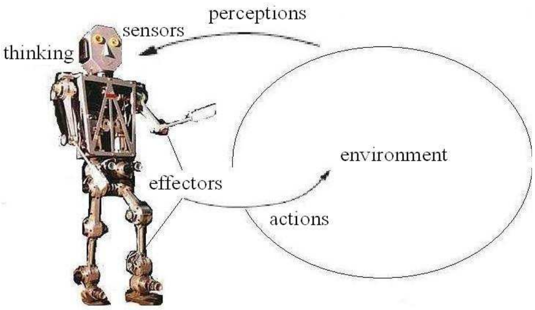


Figure 2 Robot’s three basic abilities needed

It is first-line that robot should be able to think to some extent. Researchers working on artificial intelligence have developed several algorithms on computers for intelligent machines. Almost all these methods are task-based. Machines are either programmed to perform a given task, or programmed to optimize the process of problem solving using genetic algorithm, which is called learning. Robots do not really have intelligence to understand what they are doing and will do. It’s only human engineers’ minds implemented on machines.

The secret of thinking and memory lies in the neurons’ functions and topology of the neural system. Human’s brain, for example, is composed by hundreds of trillions of neural cells. Connections between neural cells form the most complex structure in the physical world. No matter how evolution brings today’s diversity in life forms, neural networks may function in the same way on different scales in diverse existences, thus bring different degrees of intelligence. Once a life is born to the world, its neural system develops and operates the way it is predetermined, unless pathological or external attacks cause changes of neurons and connections. This is a reasonable indication that thinking abilities are determined by both single neurons’ functions and their topological structures as a whole. The only way to realize real artificial intelligence should start at the simulation of this biological structure, from the simplest to sophisticated, rough to refined.

Up to now, the only case of a neural system completely mapped at the level of neurons and chemical synapses is that of the nematode Caenorhabditis elegans [1]. More complicated neural networks such as that of mammals, are waiting to be unveiled. We will surely get lost in the complex wiring diagrams, so we seek to break them down into basic building blocks, like network anatomy (Figure 3). Knowledge on mathematics is needed, especially on graph and topology. With clear understanding of basic structural elements, we may be able to capture the global dynamic features whatever the type and size of the network is. A simplest such elements are directed graphs with n nodes, where n is small. In the case that n = 3, there are 13 types of connections, which can be found in any networks with more nodes (Figure 4). By considering pieces of various sizes (subnetworks) of the full network, it is found that the concentration of these building blocks in the subnetworks is about the same as that in the full network [2]. This is important for showing the statistical significance of the element as a function of network size. With network topological mathematics and modular connection methodology, a map addressing single neurons and links between can be expected, like genome blueprint.

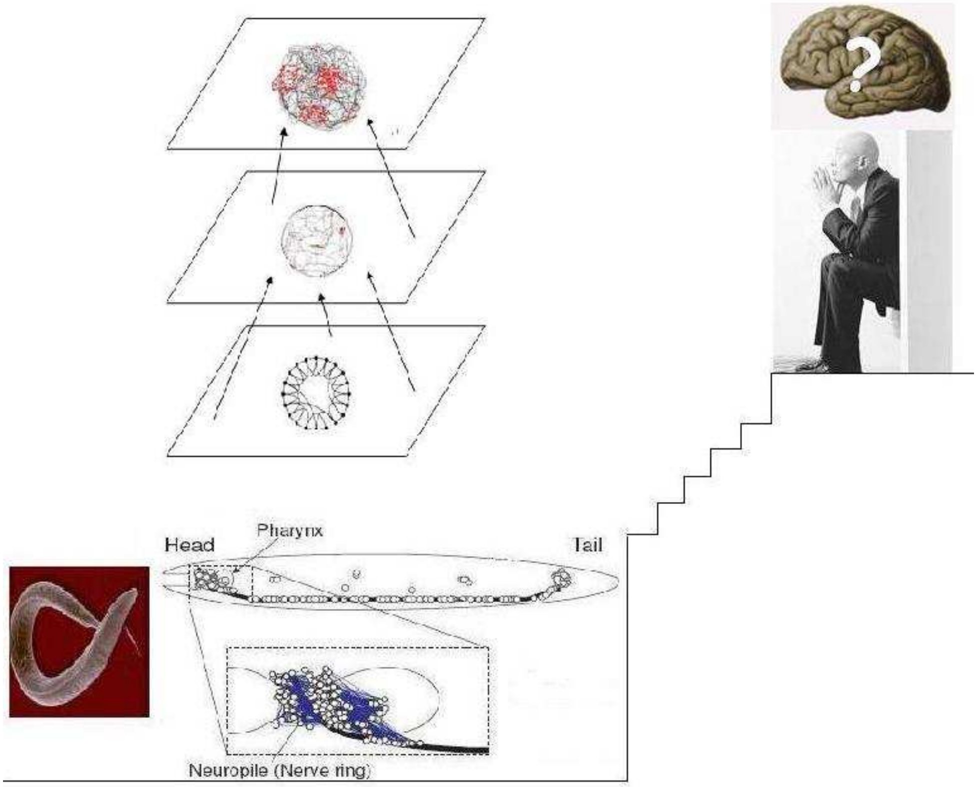
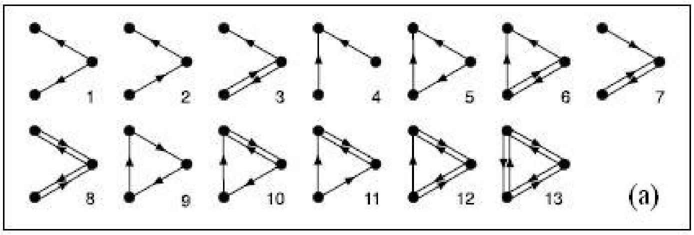


Figure 3 Structure effects function. Robot's thinking and memory abilities should be realized through imitation of natural neural system. It depends on the understanding of the complex network, which could be formed step by step, from basic simple network graphs to complex ones by mathematic analysis. Caenorhabditis elegans' neural network is the only translated network addressing single neurons and connections. What about the blueprint of that of human beings?



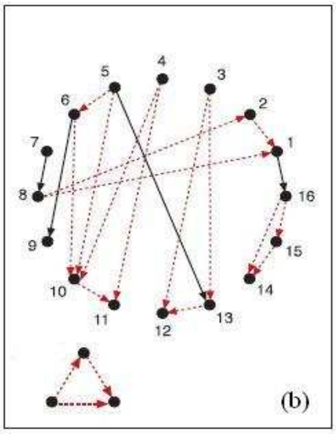


Figure 4 Demonstration of the basic structural graph elements. (a) All the 13 types of the 3-node graphs. (b)Bigger size and more complex network graph containing the 3-node basic elements.

Source: R. Milo et al. Science Vol. 298 (2002)

Autonomous Mental Development (AMD) [3] is vital for real artificial intelligence. Efficient realization methods become a hot topic of discussion. The best way is to get inspirations from natural intelligence. A realistic method is implementation on the digital computer. Although computers are totally different from the brain, they have the ability to compute. When we have found the computable characteristics in the neural system, we are able to imitate its structure and function in the computer. This will be the most popular realization method of AMD in the near future. A thorough imitation will be constructing the network responsible for thinking and memory dynamics out of analog electrical or optical circuits. This method depends on the understanding of the neural systems, thus research on network propertied bring the imitating construction of dynamical robot's brain.

3．SENSORY PERCEPTION

All species of lives have senses to acquire information from surroundings. For robot, lots of methods have been tried to make it receive information in real time. Take vision for example, Complementary Metal Oxide Semiconductor (CMOS) and Charge Coupled Device(CCD) are normally used imagers. Image data is processed by digital circuits and computers. It is frequently used for machine vision. But visual capability is restricted by the photodetector's resolution and data processing. As the complexity of data processing circuits and algorithms increases, power consumption of digital circuits quickly becomes high. Researches on biological inspired sensory configurations have convincingly demonstrated their advantages no matter in sense abilities or in power saving.

An artificial compound eye was fabricated which refined the biological inspired visual structures to a lifelike extent [4]. The artificial ommatidium consists of a refractive polymer micro lens, a light-guiding polymer cone, and a self-aligned waveguide to collect light with a small angular acceptance. The ommatidia are omnidirectionally arranged along a hemispherical polymer dome such that they provide a wide field of view similar to that of a natural compound eye. Compared with the bees' natural eyes, both the physical dimensions and optical characteristics of the artificial compound eyes achieve comparable performance. Although it is a detached artificial organ, it will be a strong competitor for robot's eyes. The vision system could contain no digital electronics, but instead use analog circuits, processing light signals by employing the innate physics of the device. In a wheeled robot moving excellent in straight lines, with visual system based on three layers of structure in the fly's eye, its power consumption stays extremely low--5 microwatts for the array, while CCD imagers on the Sojourner rover in the Mars Pathfinder mission used 0.75 watt just to acquire images [5].

Other perceptions, olfaction for example, can take inspiration from the nature too. A novel bionic neural network called KIII model is based on the topological structure of rabbit's olfactory system [6] (Figure 5):

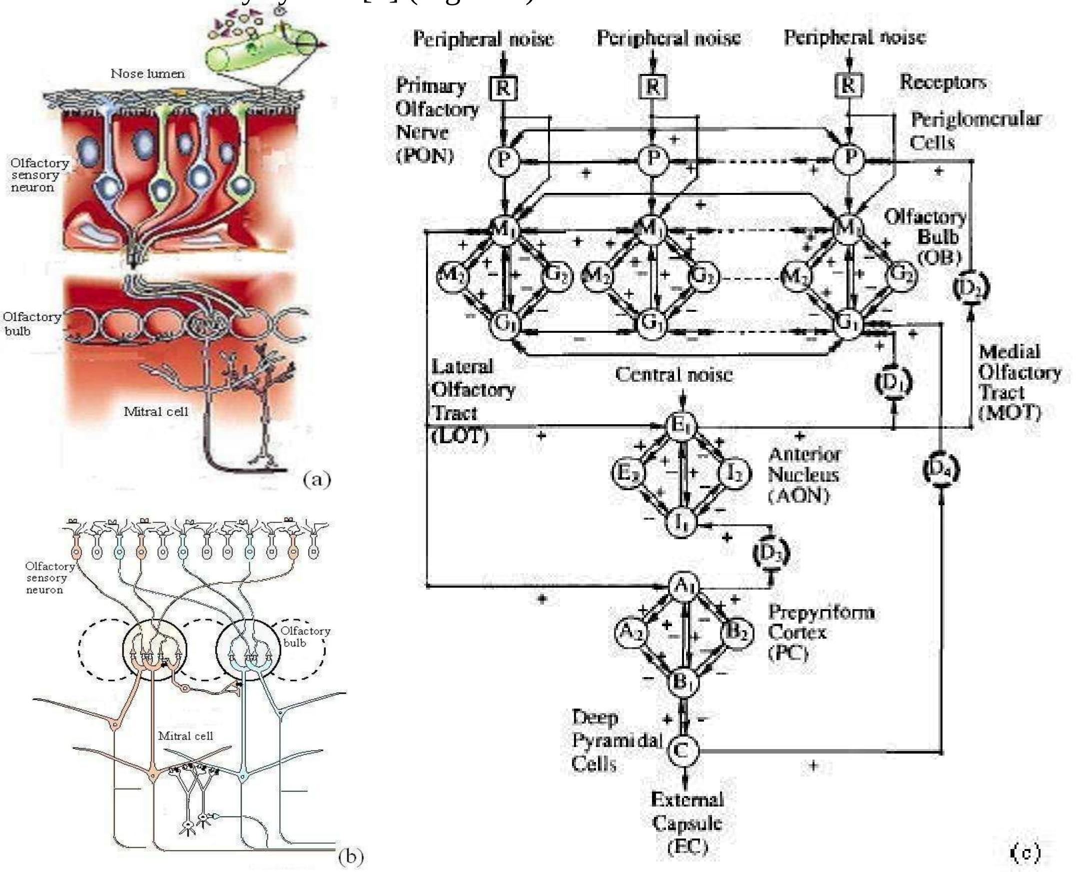


Figure 5 Topological structures of natural olfactory system and KIII model. (a) Natural olfactory system. (b) Simplified topological model. (c) KIII model topology, in accordance to the natural one.

The olfactory neural system is composed of primary olfactory nerve (PON), olfactory bulb (OB), anterior nucleus (AON) and prepyriform cortex (PC). Every node in the KIII model is described as a second order differential equation as follows:

$$\frac{1}{a\cdot b}\left[x_i''(t)+(a+b)x_i'(t)+a\cdot b\cdot x_i(t)\right]=\sum_{j\neq i}^{N}\left[W_{ij}\cdot Q(x_j(t),q_j)\right]+I_i(t)$$

$$Q(x,q)=\begin{cases} q(1-e^{-(e^{x}-1)/q}) & x>x_0 \\ -1 & x<x_0 \end{cases} \qquad \textbf{(1)}$$

$$x_0=\ln(1-q\ln(1+1/q))$$

where *xi*(t) = state variable of the *i*th node

Wij = connection strength from j to i
$Ii(t)$ = external input to the ith node
a, b, q = constants from the electro-physiological experiments on olfactory system
$Q(\cdot)$ = a static sigmoid function derived from the Hodgkin-Huxley equation

The whole model is programmed in Matlab as a collection of differential equations, so the topological structure is computable and realized on a 1024M RAM Windows XP PC. We used this bionic olfaction model programme together with an electronic odor sensor array for tea classification (Figure 6), and then made a comparison with conventional pattern classification method BP, which was not biological based. The results were recorded in Table 1 [7]. KIII performed better in our experiment for tea classification and showed the advantage of biological inspired sensory perception.

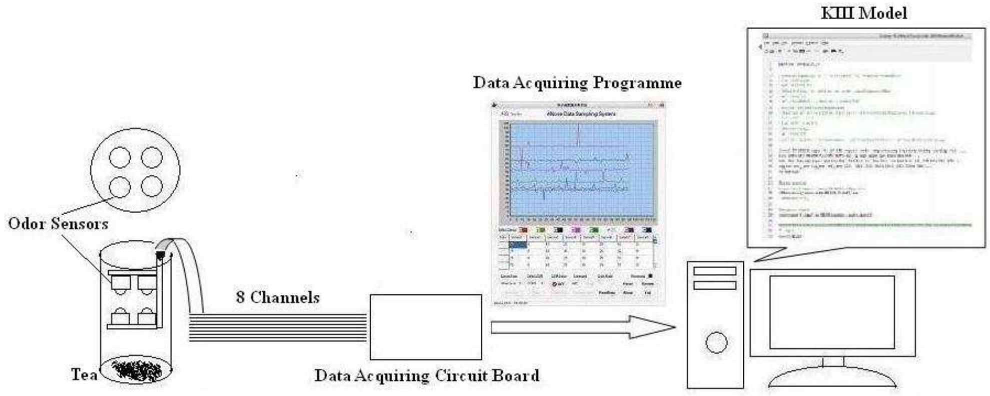


Figure 6 Our experiment system with odor sensor array, data acquiring method and KIII model in Matlab.

Table 1 Success ratio of tea classification by KIII and BP network

	Chinese Green Tea	Japanese Green Tea	Indian Black Tea	Chinese Black Tea	Average
KIII	86.7%	93.3%	93.3%	80%	88.3%
Conventional BP	100%	80%	66.7%	93.3%	85%

4．CONTROL AND BEHAVING

When artificial intelligence gives robots the ability of thinking, effectors under certain control principles make robots behave appropriately to the environment.

4．1 LOCOMOTION

Locomotion of robots on the ground could be realized using different structures, such as wheels and multiped and biped. Robots in competitions such as Robocup always have wheels for fast control and easy design. In the nature, lives on the ground rely their motor abilities on multiple or biped feet, or wiggling like snakes or worms. To us human, a bipedal robot will appear friendlier.

ASIMO is the world’s first humanoid to walk dynamically. It comes from the initial goal for a biped control mechanism to walk and turn in any direction, as well as for going up and down stairs. Researchers found that the location where the toes were attached and where the heel joint was positioned were important in determining how robot’s weight was supported. There was stability in the longitudinal direction during normal walking, and feel for surface variations in the lateral direction was enhanced when traversing a slope at an angle. With this knowledge from human body, slow walking on smooth surface was achieved. Engineers next realized fast walking and allowed their experiment model walk on uneven surface and slope. Knee joints and hip joint made ASIMO climb and descend stairs continuously without missteps [8, 9].

ASIMO brings robot to the public as it is designed for house and office use. It uses mainstream control paradigm called precise joint-angle control, in which all joints are motorized and controlled by angle rotation. It costs much power to drive the 26 servomotors throughout ASIMO’s body. The battery in its thorax can run out in 30 minutes. This control paradigm requires actuators with higher precision and frequency response than human muscles have and requires an order of magnitude more energy. Passive dynamic walkers have no actuation or control, but they can only walk downhill with humanlike gaits powered by gravitation [10]. With small amounts of substitute power added by ankle or hip actuation, they can walk on the level ground. To demonstrate efficiency of robots of different sizes, it is convenient to use the dimensionless specific cost of transport, which is defined as follows [11]:

$$C_t = E/(W \times S) \tag{2}$$

where Ct = cost of transport
E = energy used
W = weight
S = distance traveled

Take Cornell’s passive walker for example, the 12.5 kg (122.5N) robot walks at 0.44m/s, with average power consumption 10.9 Watts, average mechanical power 3 Watts. Its energetic cost of transport(Cet) and mechanical cost of transport(Cmt) are:

Cet = 10.9 / (122.5 x 0.44) = 0.2
Cmt= 2.9 / (122.5 x 0.44) = 0.055

It is very close to those of human beings, whose Cet is also 0.2, and Cmt is 0.05 [12]. Two other passive dynamic walkers’ Cet and Cmt are also calculated and shown with those of ASIMO’s in Table 2. Thus the half motorized control and half passive dynamic can reduce power consumption and also handle complex limb actions.

Besides electrical energy, other forms of energy can generate mechanical energy needed by the robot to handle the actions. Nature’s choice is to chemically power the muscles of her design with a high–energy-density fuel. Artificial muscles powered chemically came out of the inspiration [13]. These artificial muscles can either use changes in stored charge for mechanical actuation, or convert chemical energy in a fuel to thermal energy that produces actuation. They provide power density comparable to those of natural skeletal muscle and generated stresses over a hundred times higher. With these power-down methods, robots can freely prance around without any wires, and the battery carried need not be recharged frequently.

Table 2 A comparison between motorized robot and half passive dynamic walkers

	ASIMO	Passive Dynamic Walkers		
	 lower limb	 Cornell's model	 Denise	 Toddler
Degree of Freedom (hip,knee,ankle)	12 (3+1+2) x 2 legs	5 1+(1+1) x 2 legs	5 [14] 1+(1+1) x 2 legs	6 (1+1+1) x 2 legs
Cet	3.2	0.2	5.3 [15]	2.8
Cmt	1.6	0.055	0.08	0.07
Other	Servomotors on all joints	Springs driving ankles pushoff	Pneumatic hip Actuation	Learn to acquire a control policy

To realize expected control, non rigid materials could be employed on joints or connections, such as springs, rubber bands and pneumatic bags. These materials can make the movement more flexible. Structures with similar functions do exist in biological world. Human for example, there is air between bone joints. That is why sometimes we hear crack when our joints are bent. Muscle tendon is toughly tensile. Cartilage can be found in various parts of the body, such as the joints, and outer ear.

4．2 EXPRESSION

Expression abilities are what we have to pass others the messages. They include facial expression, body gesture, language etc. It is interesting that facial features have the functions for information expression, at the same time for senses. Human eyes for instance, are responsible for vision. They also give the information of one's feeling under the control of six pairs of eye muscles. This may supply inspirations to robot design to give robots intelligent behaviours.

Kismet is a robot head that can make facial expressions. The technology relies on the movement of eyes, ears and mouth. The 15-degree-of-freedom face displays a wide assortment of facial expressions to mirror its "emotional" state (Figure 7). Each eyebrow can lower and furrow in frustration, elevate upwards for surprise, slant the inner corner of the brow upwards for sadness. Each eyelid can open and close independently, allowing it to wink an eye or blink both. Each ear has two degrees of freedom that allows Kismet to perk its ears in an interested fashion, or fold them back in a manner reminiscent of an angry animal. The robot has four lip actuators, one at each corner of the mouth, which can be curled upwards for a smile or downwards for a frown. This technology makes robot sociable in the human or animal society.

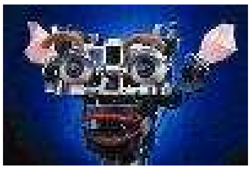


Figure 7 Kismet

Source: www.ai.mit.edu

4．3 MORE DEMANDED ACTIONS

In places where human is inaccessible or where it is not safe for men to arrive, robots are demanded to be more adaptive. As the environment may change unexpectedly,

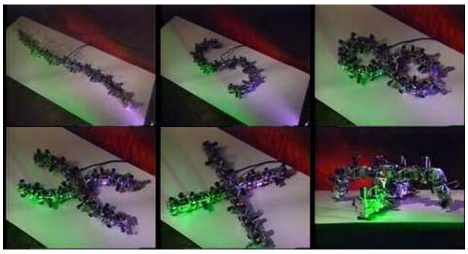


Figure 8 Reconfiguration from snake like to spider like

Source: www.parc.com/spl/projects/modrobots

robots may be demanded to have other functions, like shape shift.

Modular robot is easy for reconfiguration. It is constructed out of many "cells" of a few basic types, like living organisms. Modular robots have achieved reconfiguration without outside assistance [16]. By extending or retracting their faces, the modules can move like the squares in a two-dimensional sliding-tile puzzle. Each module carries its own computer chips and can attach to as many as four neighbors. The robot can be snake like when straight, and wheel like when bent (Figure 8). It successfully climbed fences or tunneled through pipes, and was chosen to explore an abandoned mine where bacteria found thriving in ultra-acidic water.

5．ROBOT DESIGN OBJECTIVES

To serve us human beings well, robots should be designed to satisfy our needs. Not all the robots need to have intelligence. If the tasks are sustained and specific, and the working environment is known and unchanged, like industry manufacturing process, robots could be designed only to perform the given tasks. In the situations where real time decisions are required, robots with artificial intelligence are needed. Such situations exist particularly in exploration to the unknown world, and also where robots need to respond quickly to changeful human behaviours, like in the house and office. In planet exploration, robot is assigned the mission to send back information about the X planet, preparing human astronauts' for landing afterwards. It may take the space shuttles several months to reach the destination. Since the time and asset consumption is large in such a mission, only intelligent robot can adapt itself in the unclear environment and achieve the highest performance in information acquisition.

6．A SOLUTION TO ASIMOV'S THREE LAWS

Isaac Asimov explains in his science fiction "I, Robot" his "Three Laws of Robotics":

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey orders given it by human beings except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

Although the Three Laws are described from a science fiction writer's aspect, they are treated as fundamental rules in robot design. Today's robots are far from being able to harm the human beings. But as more biological structures are introduced and robots develop sophisticated, its potential threat will surely become a

Figure 9 BHR-2 will serve 2008 Beijing Olympics

hottest topic. For robotic designers, a solution for these purposes could be that, never give the robot both powerful effectors and intelligent mind. A wireless command receiver may also be included as the ultimate control from human beings. When everything is all right, robots live their own lives. It is only in this way that robots become a helpful friend to us (Figure 9).

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