Bioinspired Miniaturization – Stretching Information from Coherence to Dissipation for Nano-to-Micro Integrated Intelligent Systems

Salvatore Santoli
INT – International Nanobiological Testbed Ltd.
Mail Contact: via A. Zotti 86, I-00121 Rome, Italy
E-mail intitsnt@uni.net URL http://www.nanobiology.com

ABSTRACT

Thermodynamic, statistical physics and mesoscopic physics considerations, and the proof that Shannon information concept is a stumbling block in describing biosystems, show that the ambitiously sought-after goal of building biomimetic evolvable, intelligent and self-reproducing automata cannot be reached through Artificial Intelligence (***AI***) concepts and their *hard-wired* implementations. Biosystem metaphors much closer to reality than those attainable through ***AI*** ask for highly nonlinear, dissipative hierarchical dynamics from the nano- up to the macro- (thermodynamic) level. Mimicking the biological *structure-function* solidarity is shown to imply hardware-software hierarchical chains whose energetic dynamics (*hardware*) is indistinguishable from symbolic dynamics (*software*). It is shown that biological information processing metaphors can be synthesized and analyzed through the physics and topology of the emerging science of *Quantum Holography* to develop a nano-to-micro integration technology for bioinspired intelligent systems.

Keywords: nanobiomimetics, information, quantum holography, coherence, dissipation.

1 INTRODUCTION

Metaphors are a way to help our minds process the unprocessible.The problems arise when we begin to believe literally in them.
D. Brown, The Da Vinci Code

Smart systems and bioinspired intelligent robots are now experiencing a continuous and impetuous growth, supported by the recent advances in material science, micromechanics, microengineering and nanotechnology. Successes in integrating sensing and actuating on the microscale, and the introduction of composite multi-functional materials, e.g. those employed with **E**lectro**A**ctive **P**olymer **A**ctuator **D**evices (**EAPAD**s) [1] are furthering the embodiment of the concept of system smartness as the mimicking of biological structures and intelligent functions. Multilayer composite materials and systems have been suggested [2] to develop sensing and actuating members working as biomimetic *"bones"*, *"blood vessels"*, *"muscles"*, *"nerves"*. Such macroscale physics which is based metaphors of life structures and functions is developing into a field aiming at biomimetic intelligent robots, in which *"intelligence"* means the capability of collecting the data related to changes in the robot's environment or in the robot's evolution, or related to damage, of processing such collected data and of reacting autonomously through actuators in order to reduce or remove according to preprogrammed instructions any *"danger"* or any drawback in attaining a prefixed objective. This continuously expanding activity is now tackling the most ambitious problem of designing and building automata featuring the biological evolutionary and/or self-reproducing behavior [3].

Biomimetic robotics [4] with the support of logic circuitry from ***AI*** and of sensors, actuators and power supplies from microengineering, aims at designing robots featuring animal-like sensing, actuating and power: robots with the sense of touch, robots of low-level intelligence, with sensorimotor coordination capable of locomoting, avoiding obstacles and manipulating objects as a result of their capabilities of processing incoming information from the environment, along with information belonging to their internal states; high-level intelligence robots featuring biomimetic cognitive and psychological aspects. for instance attention, emotion, motivation, decision making, learning, in addition to the low-level intelligent capabilities such as perception and sensorimotor functionality.

It is argued here that metaphors of low- and high-level intelligent biological functions much closer to reality can be attained by working with the recent and the envisageable advances in nanotechnology together with the physical principles by which at the present time we tentatively approach the description and research of biological intelligence and of life itself. This is the reason why it is preferred here to speak of *metaphors* instead of *models*. *Noncommutative geometry*, *fiber bundle topology* and *harmonic analysis* on the Weyl-Heisenberg group (cf. Sect. **5**) are powerful tools for analysing the nature of the results from the emerging science of *Quantum Holography* (**QH**) [5] and its extension into *Generalized Quantum Holography* (**GQH**) in case of interactions other than photonic, and for application of **QH** and **GQH** to Bionanotechnology on approaching the problem of physical embodiment of the two fundamental features of biosystems: the solidarity of structure and function into just one and the same thing, dubbed *structure-function*, and the ability to compute beyond the Bremermann limit to information processing so as to overcome the *"cybernetic crisis"* stemming from the so-called non-computability in practice [6], and thus attaining the condition for their own existence, evolution and learning.

2 *AI* BIOINSPIRED AUTOMATA

While the focus here is on the possibility of stretching quantum coherence information from the microphysical up to the thermodynamic, dissipative level, where the physical condition for self-organization and for learning as a not pre-programmed activity is reached, reference is to be made in short to the physics underlying biosystems for a comparison with its representation in the logical space, in order to describe and understand the ***AI*** and *hard-wired* (**HW**) connectionistic approach to bioinspired automata, as opposed to the present approach, based on the energy and information (symbolic) dynamics in the physical phase space [6] of nano-scale and nano-to-micro integrated systems.

3 SYMBOLS, DEFINITIONS AND ACRONYMS

All terms are listed in the order of their introduction:

∇ ≡ the nabla; • ≡ dot product; **f** ≡ the flow of information; *R* ≡ redundancy of system degrees of freedom; *S(t)* ≡ the sum of entropy associated with the matter-energy exchange with the environment and of entropy produced inside the system; *t* ≡ time; S_{max} ≡ entropy corresponding to the maximum number of complexions at equilibrium; Lie(**G**) ≡ Heisenberg Lie algebra; **G** ≡ the Weyl-Heisenberg group; $H_\nu(\psi, \varphi, x, y)$ and $\bar{H}_\nu(\psi, \varphi, x, y)$ ≡ complex-valued Liouville densities; x, y ≡ variables in the automaton phase space; q ≡ coordinates; p ≡ momenta; $\mathbb{R}$ ≡ the whole real line; ν ≡ optical frequency; Ω ≡ the symplectic form given by the edge product containing the optical frequency ν, $\Omega = \nu \bullet dx \wedge dy$; ∈ ≡ ... is a member of; ⊗ ≡ product of spaces; Lie diffeomorphism ≡ differentiable mapping with a differentiable inverse; → ≡ a mapping procedure;

time series: Markovian strings of symbols taken to represent environmental stimuli, as objects and functions, and the automaton inside interlevel **f**; ***syntactic automata***: those working by pre-programmed instructions based on formal logic; ***semantic automata***: those working on not *one-to-one* mappings among sets of outside stimuli as time series, by **f** compression with formation of collective representations featuring a smaller number of degrees of freedom than stimuli, with the emergence of meaning, where compression means the reduction of the number of degrees of freedom into a manageable amount (the *semantic ↔ pragmatic* closed chain), for example just like our way of describing fluid flow by macroscopic equations, e.g. Navier-Stokes equations at the hydrodynamic level, and the meaning attached to them for working in our macroscopic, phenomenological world, with respect to a kinetic level description of the fluid flow; ***cognitive system***: a system capable of describing itself.

fMRI: **f**unctional **M**agnetic **R**esonance **I**maging
bioNMEMS: biomimicking nano-**MEMS**.

4 THE AUTOMATON'S PHASE SPACE vs. ITS LOGICAL SPACE

The following points characterize biological intelligence, their embodiment being sought-after here through the mathematical interpretation of **QH** and **GQH** when applied to Nanotechnology.

1) Biosystems do not process information as a xerocopy machine (i.e. by *one-to-one mapping*); they compress information so as to *simulate* the environment by building increasing abstractions of the signal time series from it which impinge on them. This self-organization process can occur through their thermodynamic and mechanical far-from-equilibrium condition. From Theoretical Statistical Physics, this means that for **f** in the phase space it is $\nabla \bullet \mathbf{f} < 0$; i.e. Liouville's theorem $\nabla \bullet \mathbf{f} = 0$ is not true for actually *learning* systems. It would be true for any preprogrammed one-to-one mapping which in the logical space would be a tautological process, just as all mathematics are. In telecommunication systems, the volume of **f** can change shape, but its density keeps constant (i.e. $\nabla \bullet \mathbf{f} = 0$, like happens for incompressible fluid flow) so that the initial message can be received unchanged (i.e. not compressed) at the output.
2) Accordingly, Shannonian information, suitable for telecommunication systems, cannot be applied to biosystems on the basis of the *entropy ↔ negentropy* principle; actually it would be a stumbling block in understanding their very nature. It can be applied to physical systems just under mechanical and thermodynamic equilibrium conditions (where Maxwell-Boltzmann distribution holds good) i.e., not to dynamic, *open* and far-from-equilibrium nanobiological systems which ask for kissing Maxwell-Boltzmann distributions good bye.
3) The thermodynamics of the evolutionary/learning process gives the necessary condition

$$R = 1 - [S(t)/S_{max}] \rightarrow 1 \quad (1)$$

which means that new degrees of freedom are to be introduced into the system either by a continuous exchange of matter, or by making systems consisting of highly flexible, long nanoscale units (macromolecules, super- and supra-molecular structures) realizing nanomechanical and thermal far-from-equilibrium conditions. In the logical space of the **HW** connectionistic approach applied to nanosystems, the structure would hardly meet the need for a durable steady state condition.
4) *Structure-function* solidarity means that the process

sensing → information processing → actuating

is a closed chain where syntax, semantics and pragmatics form a closed chain in the indistinguishable unity of structure-function:

syntax ↔ semantics ↔ pragmatics

This ultimately (i.e. on the nanoscale) means the close, inseparable connection between mechanical and electronic degrees of freedom.

The following physical approach to the design of bio-inspired automata embodies such lines and can be applied to nanostructured and nano-to-micro integrated systems realizing ***semantic*** automata i.e. those working on ***extralogical*** (information compression) processes.

5 NONCOMMUTATIVE GEOMETRY TO PROCESS INFORMATION

Soon after W. Heisenberg introduced the canonical commutation relations in quantum physics, Hermann Weyl showed that they could be interpreted as the structure relations for the Lie(**G**). **G** is a noncommutative structure [7, 8] which can be shown to reveal the existence in Quantum Physics of some basic tools for *noise-robust* coherent information processing that makes it possible to develop bio-nanotechnological systems featuring the capabilities mentioned above and embodying the two physically contrasting processes through which biosystems *self-organize*, *learn* and *evolve*: the **unitary**, i.e. the symmetry-conserving processes, where quantum coherence can occur and live, and the **dissipative**, i.e. the symmetry-breaking events where decoherence holds the dominant sway [9].

5.1 The Weyl-Heisenberg Group as an Information Processor – *Stretching Information from Coherence to Dissipation*

QH is a two-step coherent imaging process that can be realized by ultrashort-pulse laser sources. In the first processing step, the three-dimensional image is spatio-temporally coherently encoded both in local amplitude and local phase difference information, e.g. for the nano-structured automata case, sensory information. The **G** approach to **QH** reveals the hidden symmetries and the symplectic spinorial organization form [5, 7, 8] inherent in **QH**, which can be described according to Wheeler-Feynman's transactional interpretation of Quantum Mechanics, connected to Feynman's quantum histories and path integrals, as an *emitter-absorber* transaction through the exchange of advanced and retarded waves, a kind of handshake between the emitter and the absorber participants in a quantum event. Keeping the general model in [10] to its very bone as a primer for Nanotechnology applications, the basic idea of the emitter-absorber transaction model is to consider both parts of the retarded and advanced complex wave decomposition

$$2\cos 2\pi\nu t = \exp 2\pi i\nu t - \exp(-2\pi i\nu t), \qquad t \in \mathbb{R} \tag{2}$$

as a physical reality. Similarly, in **QH** the decomposition of the interference pattern

$$\left\| U_\nu \left(\begin{vmatrix} 1 & x & 0 \\ 0 & 1 & y \\ 0 & 0 & 1 \end{vmatrix} \right) \psi + \varphi \right\|^2 = \|\psi\|^2 + \|\varphi\|^2 + H_\nu(\psi, \varphi, x, y) + \bar{H}_\nu(\psi, \varphi, x, y) \tag{3}$$

gives rise to $H_\nu(\psi, \varphi, x, y)$ and $\bar{H}_\nu(\psi, \varphi, x, y)$ with respect to Ω_ν and $\Omega_{-\nu}$ of the flow and counterflow of frequencies ν and $-\nu$ respectively. For instance, in the case of automata, to record the sensory information the symplectic hologram plane ($\mathbb{R} + \mathbb{R}$, Ω_ν) *could be made up of two-dimensional processing arrays of nanocomponents analogous to arrays of pixels.* So the *"holographic transform"* is defined by the mapping $\rightarrow$ of the spatiotemporally coherent two-mixing wavelet densities $\psi(t') \bullet \nu dt'$ and $\varphi(t) \bullet \nu dt$ of operating optical frequency ν and diffraction angle determined by Ω_ν:

$$\psi(t') \bullet \nu dt' \otimes \varphi(t) \bullet \nu dt \rightarrow H_\nu(\psi, \varphi, x, y) \bullet \nu dx \wedge dy \tag{4}$$

Now, the holographic transform describes the collective stationary interference distribution of wavelet packets in the symplectic hologram plane. The reconstruction procedure of **QH** as a spatiotemporal quantization or the *"geometrical quantization strategy"* [8] occurs from the hierarchical fibration of contiguously excited, adjacently decoupled energetica strata by an application of the symbolic calculus of pseudodifferential operators associated with the Weyl-Heisenberg group **G**. This group governs the cooperatively synchronized emitter-absorber transaction model of Quantum Dynamics on $\mathbb{R}$, i.e. the flow and counterflow of optical photons in a *photonic implementation of a nanoscale device*. So, the cooperatively synchronized model of **QH** is *combined* with the geometrical quantization approach through **G**.

The Weyl-Heisenberg group **G** in its application to the nanobiotechnology systems would be a *(2n +1)*-dimensional manifold; for simplifying the presentation, a three-dimensional version is briefly considered. It is the underlying group of the basic quantum commutation relations such as $[q^i, p_j] = i\hbar\delta^i_j$. As the *2-* and *2n*-dimensional cases are structurally identical, to simplify the notation it will simply be written *(q, p)* for (q^i, p_j). In the three-dimensional version, the group law is given by

$$q'' = q' + q; \;\; p'' = p' + p; \;\; \zeta'' = \zeta'\zeta \exp(i/2\hbar)(q'p - p'q) \tag{5}$$

With **G** as the simply connected Lie group of unipotent matrices, with algebra *g*, we have for the lowest dimensional Weyl-Heisenberg group **G**:

$$\mathbf{G} = \left\{ \begin{vmatrix} 1 & x & z \\ 0 & 1 & \zeta \\ 0 & 0 & 1 \end{vmatrix} \;\middle|\; x, \xi, z \in \mathbb{R} \right\} \tag{6}$$

which can be viewed as the additive Abelian group $\mathbb{R} + \mathbb{R}$. For Nanotechnology and Bionanotechnology, i.e. $n > 1$, a larger Z-graded complex Weyl-Heisenberg Lie algebra g_n made up of the subalgebras isomorphic to the complexification $g_n \otimes \mathbb{C}$, with $n \geq 1$, will be required. It can be shown thus that **G** is a two-step nilpotent Lie group, and an exponential map exp:$g \rightarrow$ **G** can be built, *which is the basic link between the real vector space structure of g and the multiplicative group structure of* **G**.

The physical picture stemming from the mathematical procedure consists in that the group **G** is the noncommutative group of symmetries to analyze and synthesize the convolution structure of the wavelets originating from a mother wavelet in the case of phase coherence under the action of the Fourier transform (i.e., just Huyghens' principle), and it implements the symmetries mentioned above and concerning quantum level adaptive resonance self-organization on the basis of phase conjugation for *any proper geometric scale*, from the microphysical, i.e. the quantum physical scale, to the macrophysical scale. Accordingly, as a response to the environmental time-series that impinge onto the system and provide wavelets coherent enough to form a stationary quantum interference pattern for holography in an

$\mathbb{R}\otimes\mathbb{R}$ plane where wavelet mixing takes place, *there are no algorithmic instructions, but just learning; no net hardware/software distinction, but just a physical morphological/dynamical solidarity*. *Coupling with the environment can go vertically from macro- to meso-levels,* and the so-called "*cybernetic crisis*" from *exponential complexity* [6] is overcome through the *Lie diffeomorphism* (differentiable mapping with a differentiable inverse). The basic relation: exp: $g \rightarrow$ **G**; log: **G** $\rightarrow g$ summarizes all that. Through the **G**'s noncommutative geometry supported by fiber bundle topology the structure-function (*hardware-software*) solidarity is realised as a result of such relationship between **G** and its algebra g, and of the basic features of any holographic process, which are recalled in the following. Through **QH**, like through nanoscale chaotic dynamics [6] a hierarchy of levels can be attained with the necessary solidarity to get a **cognitive**, self-organizing system.

QH mathematics, as applied to **fMRI** [5] for medical diagnoses through tomography, mainly concerning the neural system, is capable of stretching the quantum field information channel referring to the orientation of angular momentum of coherently precessing proton spins up to the macroscopic level where high precision images are generated inside a tomographic slice. As to **bioNMEMS**, coherent waves could be induced in highly nonlinear oscillator arrays of nanosensors on the basis of their (ubiquitous) tendency to *synchronization*, possibly involving quantum phenomena on the mesoscopic scale which underlie classical nanoscale behaviors as to information processes, e.g. in interaction of quantum physics with chaotic dynamics [6]. This interplay between information at the microphysical and the macroscopic level can be captured also in the case of **GQH**.

5.2 From QH to GQH

The various parts of any hologram are not correspondences of the various parts of the object. On the contrary, any single part conveys something of the whole: all parts of the output reflect all parts of the input. In **QH** *each photon bears information about the entire system*. Combination of **QH** with the powerful nonlinear information processing capabilities based on linear superposition (for coherence) due to Weyl-Heisenberg's group symmetries, and the nonlinear mapping through the noncommutative geometry of such group, is a novel promising technology for nanoscale devices and systems, not necessarily of photonic character. Indeed, like continuous wave holography, **QH** through its noncommutative geometry interpretation represents a principle that can be applied to wave phenomena of any kind. This **GQH** principle can be applied also to systems relying on chemical waves. The connection between microphysics, mesoscopic physics and macroscopic observables would be the connection between *chemical dynamics*, i.e. the breaking and formation of chemical bonds, and *chemical kinetics*, i.e reaction rates at the concentration level, where *"concentration"* is a macroscopic concept.

6 CONCLUSION AND OUTLOOK

The term *"geometric quantization"* [8] designates technically the coadjoint orbit method in the Lie group representation theory. This method is a way of organizing information on that group into a coherent pattern. It is just such organization capability that makes the nilpotent Lie group **G** a valid tool for constructing proper substrates for **QH**. Such approach to **bioNMEMS** would set forth a powerful nanoscale theory for a physical technology of biomimetic automata, i.e. for a *bionanoware* which, if so conceived and realized, would embody the new system of formal logic advocated by John von Neumann, i.e. a system moving *"closer to another discipline which has been little linked in the past with logic. This is thermodynamics, primarily in the form it was received by Boltzmann"* [11], but with the added possibility of dealing with noncomputable processes at the classical or quantum kinetic or detailed non-statistical level, depending on their kind and degree of coupling with the environment: a link between unitary, reversible logic processes, and dissipation.

REFERENCES

[1] Y. Bar-Cohen, "Electroactive Polymer Actuators and Devices", Proc. of SPIE **5051**, 2003.

[2] H. Asanuma, "Formation of Sensitive/Active Phases in Metal and Polymer Based Structural Materials for Health Monitoring and Other Functions", in "Structural Health Monitoring 2002 – Proc. First European Workshop", Cachan (Paris, France), Ed. Daniel Balageas, DEStech Publications, 46-44 , 2002.

[3] T. Higuchi, M. Iawata and W. Liu, Eds., "Evolvable Systems: From Biology to Hardware", Springer-Verlag, 1997; E. Sanchez and M. Tomassini, "Toward Evolvable Hardware", Springer-Verlag, 1996.

[4] Y. Bar-Cohen and C. Breazeal, "Biologically Inspired Intelligent Robots", SPIE Press, 2003.

[5] W. Schempp, "Magnetic Resonance Imaging – Mathematical Foundations and Applications", John Wiley & Sons, Inc., 1998.

[6] S. Santoli, "Nanochaos and Quantum Information for a Physical Theory of Evolvable Semantic Automata", American Institute of Physics Proc. **517**, 500-509, 2000; S. Santoli, "Mesophysical Anticipatory Cell Behavior – Enroute to Quantum and Classical Nanobiology", Intl. Jrnl. of Computing Anticipatory Systems **10**, 382-401, 2001.

[7] A. Connes, "Noncommutative Geometry", Academic Press, 1994.

[8] J.A. De Azcárraga and J.M. Izquierdo, "Lie Groups, Lie Algebras, Cohomology and Some Applications to Physics", Cambridge University Press, 1995; J. Madore, "An Introduction to Noncommutative Differential Geometry and Its Physical Applications", Cambridge University Press, 1999.

[9] S. Santoli, "What Kind of State is the Living State?", Lecture given at the Wayne State University, Dept. of Computer Sciences, Biocomputing Group, Detroit, USA, October 28, 1997.

[10] J.G. Cramer, "The Transactional Interpretation of Quantum Mechanics", Rev. Mod. Phys. **58**, 647-687, 1986.

[11] J. von Neumann, "On the Logical and Mathematical Theory of Automata", in "Collected Works of John von Neumann", V, 288-328, Pergamon Press, 1965.