

Liquid Cybernetic Systems: The Fourth-Order Cybernetics

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This paper is dedicated to those who struggle to see through reality.

Technological development in robotics, computing architectures and devices, and information storage systems, in one single word: cybernetic systems, has progressed according to a jeopardized connection scheme, difficult if not impossible to track and picture in all its streams. Aim of this progress report is to critically introduce the most relevant limits and present a promising paradigm that might bring new momentum, offering features that naturally and elegantly overcome current challenges and introduce several other advantages: liquid cybernetic systems. The topic describing the four orders of cybernetic systems identified so far is introduced, evidencing the features of the fourth order that includes liquid systems. Then, current limitations to the development of conventional, von Neumann-based cybernetic systems are briefly discussed: device integration, thermal design, data throughput, and energy consumption. In the following sections, liquid-state machines are introduced, providing a computational paradigm (free from *in materio* considerations) that goes into the direction of solving such issues. Two original *in materio* implementation schemes are proposed: the COLloidal demonsTraTOR (COgITOR) autonomous robot, and a soft holonomic processor that is also proposed to realize an autolographic system.


concept was brought by von Foerster in 1974 as the “second-order cybernetics,” describing the interaction rules and topology between subjects.^[2] Networks, organisms, and societies are, therefore, cybernetic systems, according to this definition. Lepskiy in 2015 introduced the “third-order cybernetics” as the study of interactions between a subject and a metasubject (which can be seen as the universe where the subject exists).^[3] Self-organized entities are an example of such cybernetic systems, and ecology is the science that describes the most important third-order cybernetic system: nature (see Figure 1). The natural evolution toward the “fourth-order cybernetics” has already entered a philosophical discussion phase but has not matured yet, from the physical, material, point of view. The “fourth-order cybernetics considers what happens when a system redefines itself. It focuses on the integration of a system within its larger, co-defining context. It also implies that a system will “immerge” into its environment,

1. Introduction

The word cybernetics has profound roots in our past, and it is certainly a proto-indoeuropean word that has to deal with *govern-ing*; its first documented occurrence goes back to Plato (Πλάτων, 346 b.C.), in ancient Greek: κυβερνητική τέχνη, literally *the art of the pilot*. It was first used by Wiener in 1961 to describe what nowadays is known as the “first-order cybernetics,” a system where a subject interacts with an object by action, reaction, and feedback.^[1] Industrial automation is the exploitation domain of the first-order cybernetics. The natural evolution of this

of which it is part. Immergence means “submergence” or “disappearance in, or as if in, a liquid.”^[5] This picture is not specific of liquids only, but also of gels and soft materials in general, glasses, solid-state solutions, and solid heterogeneous mixtures, and if a distinction has to be made, it is because of applications. The most important property that liquids possess over solids is their capability to reconfigure their internal structure over a short timescale, and this offers interesting applications in the information technology domain, where fast memorization and computation capabilities are demanded. Solid-state amorphous materials (glasses), often wrongly visualized as frozen liquids, also have the capability to reconfigure over a much longer timescale.^[6] Heterogeneous solid matter, solid solutions such as alloys are also able to explore a vast configurational space, having energy activation barriers that, in nature, can be overcome by high pressures and temperatures, as we see from the observation of rocks (for example, in the metamorphogenesis of sediments). But, again, the typical timescale is too broad for practical uses, with rare exceptions, such as shape memory alloys.^[7] Spinodal decomposition, martensitic transformations are fast, sometimes violent, reactions, making it difficult a technological approach.^[8] Our guess for a practical implementation of the fourth order requires to include in the picture fractal holograms: such systems that see an agent able to reconfigure

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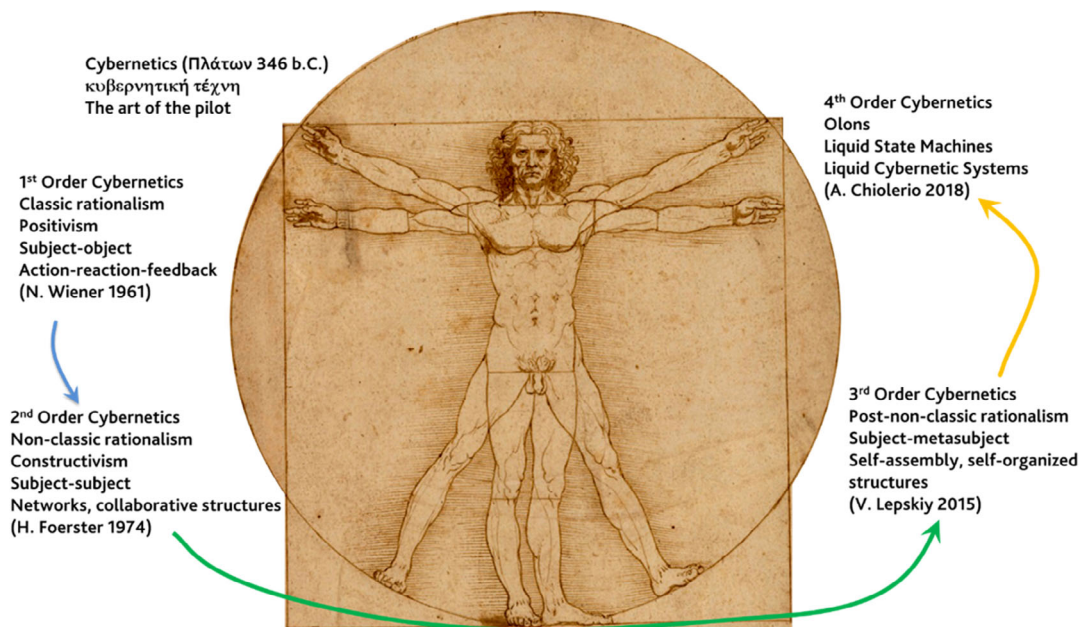


Figure 1. Sketch showing the consolidated three orders within cybernetic systems. Adapted under the terms of the Creative Commons CC-BY-SA 4.0 license.^[4] Copyright 2019, The Author, Published by Wikimedia Commons.

itself and rise to the level of multitude, implying that the rules of the whole multitude are mapped onto each agent (justifying fractal nature) and that the manifestation of a multi-dimensional configuration space derives from a low-dimensional information (justifying holographic nature).^[9] The reader will soon realize that liquid cybernetic systems introduced in Section 2 go into this direction. Before describing their features, we add a brief discussion about the most relevant limitations faced by current cybernetic systems, suggesting, without the intention of being exhaustive, some “conventional” approaches that are currently under development.

1.1. Device Integration

Processing information in commercial devices is done on the basis of Boolean logic operations carried out by the complementary metal-oxide-semiconductor (CMOS) technology. The well-known Moore’s law describing the doubling of transistors per die and similar scaling laws that have flourished to model the effects of miniaturization on reduction of energy per operation, on the increase of floating point operations per second (FLOPS), have left behind practical numbers. The impact of Internet of the Things (IoT) and the tremendous stream of data sensed around us, elaborated, and sent back to our portable devices in aggregated and interpretable form, realizing the fusion between the social (living) cybernetic system and the silicon/silica-based cybernetic system around us, pushes the demand for a more-than-Moore solution. Artificial intelligence (AI)-enabled tasks used for traffic monitoring, real-time translation of sensory information (i.e., images, audio and video streams, voices, etc.), autonomous vehicles, optimization of processes, etc. add another tremendous channel to this stream of information and computational requirements.

The natural solution of increasing the number of simple agents integrated on discrete components to multiply their workforce has brought technology to unprecedented heights, where light used in photolithographic processes has become extremely energetic (extreme UV [EUV]), where transistor channels are a few atoms wide, where quantization properties must be considered and can be exploited.^[10] The recent direction is to enable the so-called edge computing, in other words, exploiting the computational power of all devices available in a certain area, particularly during their idle time.^[11] Other solutions envisage the use of random access memories (RAM) for in-memory computing (IMC), suppressing the memory (or von Neumann) bottleneck of conventional computers.^[12] We will see how a holographic approach can offer a solution to the integration bottleneck, by addressing a multitude of coherence domains with the simple propagation of a spherical wave.

1.2. Thermal Design

High-performance commercial devices, i.e., central processing units (CPUs) and graphical processing units (GPUs), are already facing an impressive thermal energy density, higher than that of nuclear power reactors (200 W cm^{-2}) and rocket nozzles (1 kW cm^{-2}) and are approaching that of the Sun surface (10 kW cm^{-2}).^[13,14] Envisaged solutions go in the direction of using high heat capacity fluids such as ferrofluids (FFs) to dissipate heat and/or harvest energy, including both active and passive systems.^[15,16] Such approach can be seen from the point of view of the third-order cybernetics, as a form of self-organization of complex dissipative systems that behaves more efficiently, or, in other terms, as the urgency to reduce the forward action (emissions) that technology is producing toward its met subject (nature) to reduce the amplitude of feedback (climate change).

In a holographic approach, without the need to convey neither charge nor spin currents among coherence domains, the thermal dissipation requirements are close to zero, ultimately depending on the energy conveyed by the sounding wave.

1.3. Big Data Handling

Information handling has been estimated to burn $\approx 10\%$ of global energy production, whereas data volume increases by some 20% per year. The most relevant fraction is absorbed by processing activities depending on computational speed and volumes, whereas the communication link is interestingly almost an invariant of the communication scale! Of course, multiscale data are not easy to compare, and one must consider that the global network is seen as a cybernetic system with a single communication channel. At global range (we may take the global scale to be in the order of Earth circumference, 40 000 km), the internet provider (IP)-generated Internet traffic usage in 2020 was predicted to be more than 200 EB month⁻¹, equal to 77 TB s⁻¹.^[17] Moving down, over 10/100 m ranges, as in the case of the network connecting servers in a single data center, traffic capacity is in the order of 100 TB s⁻¹.^[12] Over extremely small scales, in the 1/10 mm range, we can take data of a commercial intelligence processing unit (IPU) of last generation, where volume between memory and computation can be as high as 45 TB s⁻¹.^[18] Interesting novel topological concepts are under study, originated from condensed-matter studies that have been recently implemented in photonics and phononics, where the emergence of dissipationless transport channels was proved.^[19,20] We expect great changes to occur, impacting also single chip architecture, with a greater integration of photon-mediated communication channels, instead of charge-based ones.

1.4. Energy Consumption

Unavoidably, the other aspect of dissipation in cybernetic systems is energy consumption. Modern electronics has been able to provide ultralow-power devices, scalable performances, more efficient systems, and all ranges of solutions that can be profitably applied to the bigger scale. If we focus at the human scale where personal (computing) devices are and will be localized increasingly more, a number of energy harvesting devices have been developed, working on the gradients available from our own metabolic and ordinary activity: running, walking, breathing, sweating, homeostatic functions, and resulting thermal gradient with respect to external environment. If we look into the micro-scale, we must admit that biological systems are still unsurpassed in terms of energy efficiency, and we can only guess the reasons. At the time of writing, the most powerful non-distributed computing system is Summit, property of the United States Department of Energy and hosted at the Oak Ridge National Laboratory. It features a maximum computational capability of 196.5 peta floating point operations per second (PFLOPS) and a peak power consumption of 13 MW, meaning that approximately each operation burns 66 pJ.^[21] One of the features of biological brains, including human one, is their particular architecture, where memory and computation are co-located.^[12] Another fundamental aspect is the massive

parallelism, where each information channel using around 10 fJ spike⁻¹ (spike trains are those sequences of action potentials that can be measured in neurons and that provide external inputs to cortical circuits) versus 100 aJ commutation⁻¹ for current transistors activates several circuits and, therefore, increases its processing footprint.^[22] Therefore, we can now see how one single floating point operation performed by the most powerful super-computer is equivalent to 660 k elementary CMOS commutations and to 6600 biological spikes. This claim holds only considering a biological brain as a Turing-like machine, disregarding other functionalities that might be concurrent to computation, which, in honesty, we personally think is extremely reasonable to happen.

2. Liquid Cybernetic Systems

Compared with the conventional silicon-steel-based robotic systems (i.e., predominantly featuring a rigid body and solid-state electronics), liquid cybernetic systems feature a shapeless functional body free to move and adapt, eventually encased by a soft skin, or kept together by surface tension (see **Figure 2**). The body provides all needed functions, including data storage, processing and relay, sensing to external stimuli, mobility, and energy storage and distribution, such as biological cells. The body can be a liquid such as a colloidal suspension or a gel. The skin can be a self-healing material, therefore providing fault-tolerant capabilities, in case a partial spill of functional liquid occurs. They offer enormous promises, in terms of versatility, adaptability, resiliency, distributed architecture, and autonomy.^[23] Furthermore, liquids represent essential components of living beings and offer fundamental homeostatic functions. The said artificial liquid-state cybernetic systems have also been identified as Intelligent Liquid Integrated Functional Entity (I-LIFE), and their development has been pointed out to require focusing on their exclusive methods and properties, rather than progressing through a mere modification of conventional cybernetic (solid state) systems.^[24] We totally embrace this remark, as the reader will understand from the following matter. From the perspective

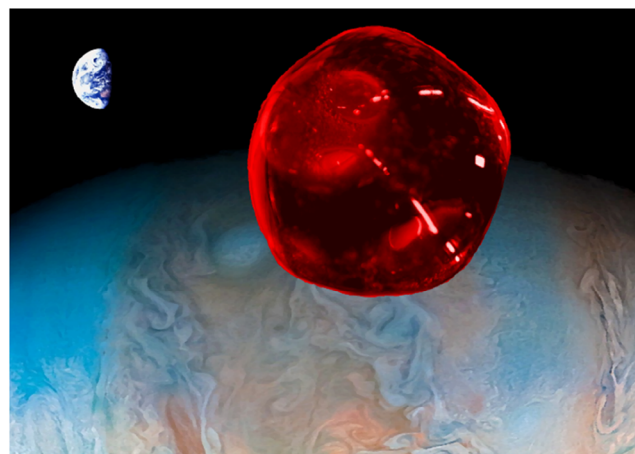


Figure 2. Pictorial representation of a liquid-state autonomous system (red blob in foreground) exploring the Jupiter clouds and sending data back to Earth (not in scale). Adapted with permission.^[23] Copyright 2017, The Authors. Published by Wiley-VCH.

of human-centric research, the purpose of developing cybernetic systems is that of expanding our own possibilities, using materials and devices that can allow surviving where our bare body is limited. Cybernetic extensions could be integrated with proper interfaces to pursue “cyborgs,” cybernetic organisms, enabling cognitive extensions, physical extensions, or even extensions to recover disabilities, such as active prostheses.^[25] One of the most intriguing directions of cybernetic research is leveraging liquid metal (LM) properties, combining intrinsic fluidity with good electrical conductivity and biocompatibility. LMs include gallium, bismuth, and their alloys, which are liquid close to room temperature.^[26] LM soft machines have already been described, as detailed in Section 2.2. Our focus here is the study of proper cybernetic systems, not yet biologically integrated.

Let us describe the computational aspect first, where “liquid” refers to a specific property of the neural network, and two different *in materio* implementation schemes, where “liquid” refers to the physical aggregation state, in the following.

2.1. Liquid-State Machines

In computer science, a liquid-state machine (LSM) is a computational model suitable for modeling biological circuits and more effective than other paradigms such as Turing machines or attractors that are better used to describe the dynamics of complex systems.^[27] The LSM picture allows modeling real-time computations on continuous streams of data and can be adapted to spiking. The LSM operates as a kernel projecting a low-dimensionality space (the Cartesian spatiotemporal universe of the physical input) onto a huge dimensionality space (the thermodynamic configurational space of the liquid), with the particular property of time conservation, i.e., keeping the time order of input (Figure 3). Regardless of the particular output, one is still able to distinguish the input states that caused that response. Another fundamental property that LSM must possess is called separation: the liquid states must be significantly different, feature that naturally reflects onto the separability of computed results.^[28] What is the typical aspect of a real LSM-based system? Here, “liquid” does not necessarily mean that the aggregation state of a “real” LSM is liquid. The term was chosen in computational neurosciences where LSM was developed to model

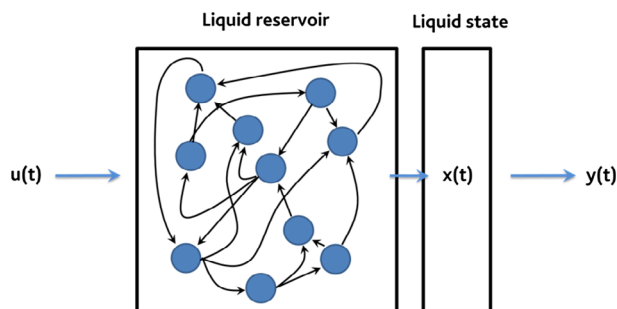


Figure 3. Sketch showing the concept of an LSM: a low-dimensional information as input is projected over the internal space of the liquid reservoir that features elements with a random and fluctuating connection diagram and a high dimensionality. The resulting liquid state is then extracted, again having a high dimensionality, and transformed to the proper output with the same dimensions as the input.

computation in biological spiking systems, to mean that the reservoir system is conceived as a liquid surface that exhibits perturbations caused by external inputs. LSM belongs to the field of reservoir computing (RC), a special case of artificial neural networks (ANNs) where instead of adapting all connections to minimize the training error, almost all connection weights are fixed, and only the output level is configurable.^[29] How would look like a “real” LSM might be quite different from any liquid we could immediately imagine. For example, a colony of ants can be described by the LSM model: composed by agents, with a collective behavior that cannot be anticipated by tracing the single agent. Each ant has unlimited freedom to move around, and the transfer of information takes place only with neighboring ants that can sense the chemical species emitted by each agent.^[30] Another example of “real” LSM is given by the immune system, whose patrolling capability relies on movement of proteins forced into a segregated geometry (body capillaries), nevertheless, able to orchestrate a collective response under certain conditions (Figure 4). The introduction of stochastic logics such as LSM in cybernetic systems implies certain constraints about precision, but fully compensates this featuring by an inherent noise immunity, which allows a massive, parallel, and reliable implementation.^[31] LSM is so stable that it was shown how to use the interference pattern of waves produced on the free surface of water to implement a perceptron model to perform the XOR Boolean operator and a speech recognition task.^[32]

2.2. The COgITOR Concept

The history of *in materio* liquid-state computers goes back as far as 1900s and has been masterfully summarized by Adamatzky, encompassing hydraulic algebraic machines, analog computers, fluidic logics, excitable Belousov–Zabotinski chemical media, fluid maze solvers, droplet logics, and liquid marbles.^[33] It would be rather difficult to imagine a cybernetic system not only able to perform computation (though the most difficult task) but also provide those means, which are fundamental for an autonomous robot, such as mobility, energy management, and sensing. The concept of a COLloidal demonsTratOR (COgITOR; from Latin passive tense of *cōgĭto*, meaning “I am conceived”) is presented in Figure 5. The COgITOR concept can achieve, at the same time, distributed sensing, massive-parallel information processing, energy harvesting, self-healing, and shape adaptation capabilities. It is very far from conventional solid/soft robotic systems.^[34] The COgITOR features a liquid portion segregated inside flexible casings: a sensing outer layer, a storage/computation inner layer, and an energy harvesting transverse construct. A distributed pressure sensor shell features deformable channels containing an electrically conductive liquid (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), ionic liquid, LMs, etc.), reacting to external stimuli by an impedance variation between its network nodes, as a consequence of liquid pumping.^[35] The channels are designed as random network, providing a sufficient yet economical (in terms of contacting elements) coverage of the curved surface: this choice allows for substantial savings in raw materials and energy while meeting demands of coverage and connectivity. Disordered structures show, in fact, a high degree of scale

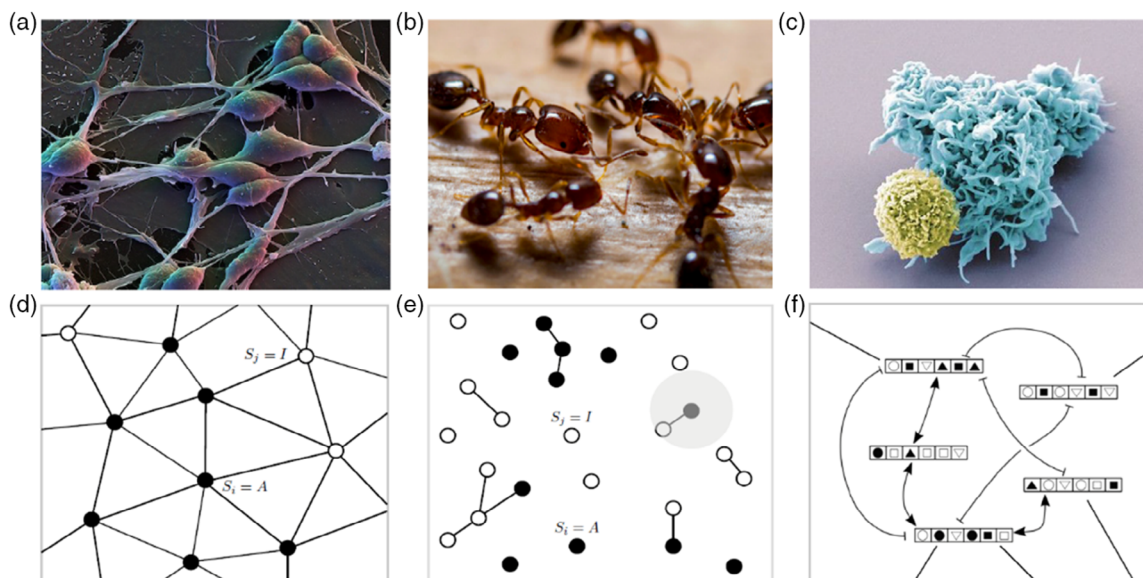


Figure 4. Examples of LSMS: a) neuronal cells with their d) connection scheme, b) ant colonies with their e) interaction scheme, and c) immunoglobulins and their f) interaction scheme. Reproduced with permission.^[30] Copyright 2017, the Royal Society.

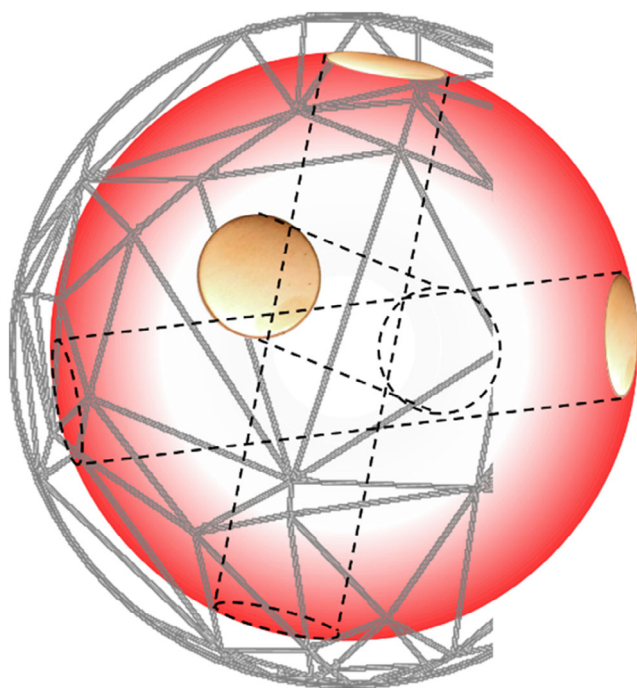


Figure 5. Layout of the COgITOR. Outer layer: random network for sensing, formed by a Delaunay triangulation of hollow channels hosting electrically (or ionically) conductive liquid; inner layer: spherical shell containing the functional liquid used for computation; transverse construct: three cylindrical containers hosting an FF used to generate a small amount of electric energy harvesting the thermal gradient to which the device is submitted.

invariance.^[36] A sensing layer in a standard robot is perfectly segregated, typically composed of a multitude of identical elements, connected to CPU where their exact location on the body is

reconstructed.^[37] A solution/suspension is obviously amorphous and homogeneous at a macroscopic scale, behaving as a single holonomic (=holographic in a topological sense, and dynamically fluctuating between microstates) component. It might even show resistive switching; in case, the colloid contains, for example, nanoparticles (NPs) that undergo a reversible redox on their surface.^[38] Resistive switching devices (RSDs) were shown to allow the implementation of any Boolean expression via “imply logic,” making it possible to realize a simple control system embedded in a liquid.^[39] It is possible to perform data processing in the COgITOR, as demonstrated in several experiments using excitation wave fronts in active non-linear media via the Belousov–Zhabotinsky reaction, and propagating lamellopodia in slime mould *Physarum Polycephalum*.^[40,41] We propose to enable liquid-state computing using “tectomers:” bi-, tri-, or tetra-antennary oligoglycine residues surrounding a central hydrocarbon chain, emerging new biomaterials potentially used as therapeutic agents.^[42,43] It is possible to measure a stable ferroelectric response reflecting the crystalline versus amorphous state, in a droplet of tectomers in solution.^[44] Activated by electric stimuli applied by a random network of electrodes, the ferroelectric state will affect electronic impedance, as well known for small molecule assemblies.^[45] Therefore, by means of microwave impedance spectroscopy (MIS), nowadays implemented in modern characterization tools to provide a broader range of materials properties, it could be possible to sense the aggregation status of tectomer molecules. The energy associated with this spectroscopy (in the μeV range) is small enough to not perturb even the smallest interaction forces between molecules (in the case of water, the hydrogen bond being >10 meV). Impedance spectroscopy is well known to be an accurate technique for studying polymer crystallization kinetics, through the real part of permittivity.^[46] Now imagine the inspection geometry we need to collect, with a reasonable signal-to-noise ratio (SNR), the impedance spectra of the computing layer over a spherical shell.

It is not difficult to end up with a spherical distribution of electromagnetic waves radiating from the center of the shell toward the external environment. The approach of placing a readout chip in situ has been already settled, for what concerns real-time in-tissue monitoring via a $100 \times 100 \times 50 \mu\text{m}^3$ ultralow-power ($6.18 \mu\text{W}$) CMOS radio.^[47] The same integrated circuit (IC) could also be able to generate electrical stimuli directed in a discrete amount of loci placed on the spherical shell, using either monopolar electrodes with a common ground placed at the center or along the circumference, or bipolar electrodes submitting to each locus the electric field without affecting the entire mass, either applying the electric field orthogonal to the shell or within the shell plane.

Notwithstanding the bistability of the functional molecules dispersed in the functional liquid, the COgITOR will represent a truly holonomic liquid processor, promoting a more general understanding of information processing, on the basis of suitable theoretical frameworks such as the Fourier logic or the holonomic brain theory.^[48] A complex set of states mapped on the spherical surface of our holonomic processor can be immediately accessed by an omnidirectional antenna onboard the IC to handle distributed information; through a synthetic biomimetic platform, new computing paradigms and logics could be implemented.^[49] Conventional cybernetic systems make use of the perfectly segregated CPUs we all know, where reconfiguration is possible typically at software level (such as in an adaptive neural network) or sometimes at hardware level, when programming is required (such as in field programmable gate array [FPGA]). Besides the electrical input and electromagnetic output of the computational shell, inter-molecular (or inter-particle) communication is possible, enabling a full spectrum of possibilities such as an interconnected brain involved in an external interaction. Viable molecular communication schemes involve smaller molecules and require necessarily some energy to be sustained, but much lower than standard electronics. Molecular communication is driving your thoughts while you read these lines, and several chemical species are used to fill the gap between neurons and continue the propagation of the signal.^[50] Also, biological molecules can be envisaged to enable computation, such as for example microtubules, that are protein (tubulin) polymers, which were shown to enable voltage oscillations at above 40 MHz in a solvated environment.^[51] The intrinsic softness of a COgITOR would naturally be compliant with biological components, if not cells, organs, and small living organisms.

To make fully autonomous the COgITOR, we should think how to store energy while keeping the liquid nature of the medium, how to harvest some potential fields available in the environment, and how to distribute this energy within the liquid mass.^[52] The technology called ThermOmagnetic hydRODYNAmic energy harvester (TORODYNA) uses a colloid, exploited to harvest energy from a tiny temperature gradient. The idea behind derives from the thermophysical potential of FFs that are suspensions of magnetic NPs dispersed in non-magnetic liquids whose flow and energy transport processes can be controlled by adjusting the external magnetic field B .^[53] By exploiting the thermomagnetic advection effect (thermal gradient parallel to external magnetic field) of an FF contained in a closed loop geometry, it was shown how to achieve direct electrical conversion of a thermal gradient as low as 1.25 K , up to $>10 \mu\text{W K}^{-1}$

with only 4 mL of FF.^[16] Coaxially segregated soft pipes could be used, permitting a closed loop circulation to the FF in each, using coils to extract energy by induction. A thermal gradient is normally established between the portion closest to light and the shaded opposite side of the pipe, providing a demo of energy generation even in the dark. There are other technologies available to achieve thermal gradient by means of liquid-state materials, to mention the most interesting one, thermoelectric effect in conductive polymers/ionic liquid blends, achieving up to $42 \mu\text{W m}^{-1} \text{ K}^{-2}$.^[54] In standard robotics, energy is harvested by means of solid-state devices, in a way similar to the one proposed here. The main difference is represented by a multi-effect harvesting capability, intrinsic of heterogeneous colloids featuring a complex composition that can, for example, show both pyroelectricity and triboelectricity, whereas conventional solid-state devices are less flexible in this regard.^[55]

The aesthetic appearance of the future cybernetic systems could be more diverse in amorphous shapes, as it could be endowed with transformable features, from one amorphous shape to another specific shape under stimulus or self-reconfiguration. The stiffness of the whole system could also be designed tunable from extreme hardness to perform tough tasks, to fluidic softness. However, the self-mobility would also be favorable, providing optional advantages for energy harvesting. Merging, self-rotation, and locomotion, for example, have been induced in a controlled way on an LM by means of an external electric field.^[56] Another property, fundamental for autonomous systems and, in particular, for exploration, is the ability to operate as a large size system or divide into smaller agents that can co-operate as a swarm, which was already demonstrated at the liquid state.^[57] Liquid-state motors, in the specific application of pumps, have also been observed.^[58] LM soft machines present unusual phenomena and are practically impossible to realize using standard hard components.^[59]

The COgITOR implementation scheme poses a new concept: liquid-state-enabled robotics with a new holistic approach, as extreme frontier of applied material science and nanotechnology, mimicking cells (adaptation, self-healing) and liquid neural networks (fault-tolerant). It will have profound impacts in holistic complex edge computing, enabling ultralow-power Zettascale computational volumes and timing. From the social point of view, this will turn into positive indirect impacts in the future, such as every field where big data and computational power are demanded: for example, autonomous drive and smart vehicles, future adaptive human machine interfaces (for example, integrated implants), and augmented reality.

2.3. Holonomic Soft Processors

Optical analog computing represents a high-risk high-gain route whose exploration has just started. One of the most remarkable results achieved so far is the observation of the interaction between laser beams and a hydrogel medium: the laser beam is able to modify the distribution of molecules in the hydrogel on the one hand, and to receive a focusing effect on the other hand, whereas normally the beam is broadened while travelling.^[60] The same hydrogel is able, furthermore, to act as distributed interaction facilitator, as two laser beams “feel” each

other even when their optical fields are not overlapped. Such interaction is tunable, which represents the fundamental ingredient to engineer practical computational paradigms (Figure 6). We remember, as clarified in Section 2.1, that “liquid” does not necessarily mean that the cybernetic system possesses a liquid aggregation state. This particular experiment suggests us to look for a more general form of nonlocality, as, for example, in quantum mechanics. Relativity and quantum theory both imply *undivided wholeness*, in which analysis into distinct and well-defined parts is no longer relevant. The hologram is a practical example that allows us to identify the meaning of this *undivided wholeness*, a radical concept often disregarded when dealing with quantum effects, in particular, in condensed matter. There is no direct bijective application connecting the real object and the hologram; rather, we can find a correspondence between each region of the interference pattern and reality, and a correspondence between

each region of reality and the whole interference pattern.^[61] Typical experiments, particularly those conceived in the condensed matter field, use characterization instruments that imply a correspondence similar to the case of holograms: there is no direct bijective application connecting the instrument and reality, but rather a correspondence between the image of reality (spectrum, projection, analysis of any sort) and reality itself. Breaking the implication chain and inserting multiple loops with complex devices unavoidably reduce the potential, computational in our case. Also, it is easy to imagine that brand new computational platforms can be conceived in non-segregated soft matrices. Massive parallelism, due to non-von Neumann (non-time sequential) architecture, is possible in a holographic medium, where the interference between two or more electromagnetic waves (coherent, monochromatic) is stored as physical modification of its status, and the simple operation of diffracting a

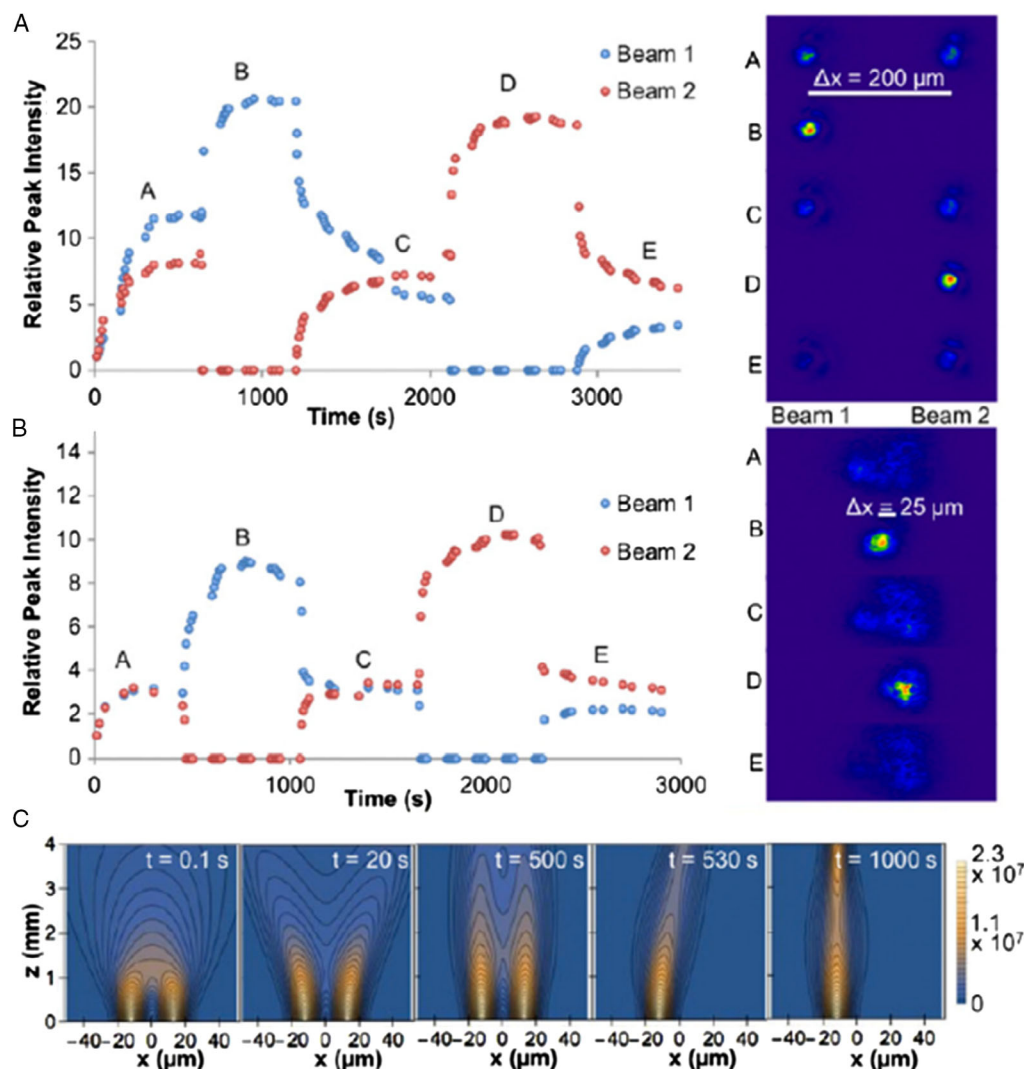


Figure 6. Hydrogel interaction with two parallel laser beams: memory and computational effects are demonstrated. A: temporal evolution of peak intensity of the two beams when the spatial separation between them is 200 μm , showing that switching off beam 2 is followed by an increase of beam 1 intensity. Similar results were observed in B, reducing beam separation to 25 μm . In C, numerical simulation of the beams is shown, for the B case. Reproduced with permission.^[59] Copyright 2020, National Academy of Sciences.

light pattern on the same medium corresponds to a huge number of binary operations. Quantum holography is, nowadays, a rapidly developing field, where technology has already enabled electron holography in materials science and to image electrostatic potentials and magnetic fields, X-rays, femtosecond pulse waveforms (spectral holography), and more generally where an aperiodic signal capable of undergoing interference is found, such as soundwaves.^[62] Quantum holography places its roots in two fundamental domains: quantum gravitation, seeking for black hole analogs that could be easily tested in laboratory, and biology, where some studies have highlighted the quantum holographic nature of our perception system (not only visual perception).^[63,64] We should point out that a quantum potential is there, and regardless of the nature of matter, we are locally affecting/interacting with, yet we will have a nonlocal perturbation of our states. The quantum potential is described in what is known as Bohmian mechanics or De Broglie–Bohm theory, a field in rapid expansion, including multiple extensions to relativity, magnetism, and hydrodynamic quantum analogs.^[65] To this end, a quantum holographic machine conceived to exploit the quantum potential will be incommensurably faster than any other classical machines, where such nonlocal effects can be perhaps seen as noise! Storing and computing information inherently push research toward extremely high packing densities, shifting from classical into quantum (particle, molecular) physics, chemistry, and materials science with the drawback of requiring very expensive equipment and exotic matter or matter states. The intrinsic parallelism of holographic systems, due to the presence of a number of elementary processing units (the molecules or monomers dispersed in a hydrogel or a solvent), suggests that a liquid-state logic device could be used with non-conventional architectures, such as Holonomic ones.^[66] Solutions for data storage and readout *in liquido* require a physical support able to change configuration under an external physical stimulus that could involve electric field, electromagnetic waves, light, acoustic vibrations, heat, and chemical stimuli. What sort of processes could be triggered by such stimuli? The spatial configuration of a molecule, for example, can reversibly switch among coiled, compact states, and extended ones, therefore influencing many optical and electronic properties.^[44] So, for example, the collective impedance state of a droplet depends on the average spatial configuration of the solvated molecules. Reversible chemical reactions can also be triggered, for example, under the effect of a particular light, resulting either in order–disorder transitions or in order–order transitions.^[67] Magnetization is another property that can be quite easily tuned, in response to temperature variations, pressure, and external fields.^[68]

Let us now define the physical scenario: a holonomic soft processor colloid whose volume is 1 L contains information whose physical size is limited by the convolution between the size of the material quanta (molecules, NPs, coherence domains, etc.) and the wavelength used to write/erase information. Current technology enables working with relatively inexpensive coherent light sources and powerful focusing elements-based, with the smallest volume affected by light could be around $500 \times 500 \times 500 \text{ nm}^3$. The total amount of information stored in the 1 L sphere could, therefore, exceed 10^{12} coherence domains. Now to give an estimate of the theoretical computing speed, we will combine the best results achieved so far in spatiotemporal modulation

of light beams and make the assumption of working with one single beam. The fastest optical modulator ever developed was demonstrated with sufficient SNR up to 1 GHz, meaning that it is possible to achieve 1 giga holographic operations per second (GHOPS).^[69] What is the effective equivalence between holographic operations and binary operations? A holographic logic ordinarily works over the continuous spectrum, rather than on a binary one. The dynamic range of typical optical experiments can be as high as 60 dB, accuracy that can be translated into a 20 bits of precision. This is not particularly competitive with binary logics, but we must recognize that precision could be increased operating in a digital mode (light and darkness) rather than continuous (all tones in between).^[70] Holographic algebra has distinctive features, such as filtering or cross correlation and association, as well as holographic (or Fourier) logic. Neither identity nor implication is relevant to holographic logic, as the only logic operation allowed is, given pattern A and pattern B, to what extent they both share a specific pattern C of commensurable size.^[48] A reasonable estimate of equivalence between binary logic and holographic logic is given by the number of elements that are interacting simultaneously; for every information injected into the system, all of the established information domains are interacting and concurring to the output; therefore, the answer depends on the system size.^[70] In our scenario, 1 L will be able to process 10^{21} operations per second, with an energy consumption close to 1 W. While typing, this machine is providing $\approx 5 \times 10^{10}$ FLOPS and can be compared with a holonomic soft processor having a volume of 5 pl, which is slightly higher than the volume of ejected droplets in commercial inkjet printers. Is there any shape constraint? Though the system is intrinsically shapeless, as previously said, it must be interfaced with the external world, to convey the information flow into a conventional channel such as fibers or electrical conductors, until more compatible means have been developed. As such, either a sphere or a torus are most suitable for maximizing the volume and minimizing the external surface, where coherence domains density is the figure of merit. Being incompressible, liquid processors would not respond to environmental pressure fluctuations, whereas temperature variations would affect the density and, therefore, produce an expansion (contraction) of the processor diameter that could be easily compensated by adaptive optics. On the opposite, if the figure of merit is not calculus-oriented but sensing-oriented, other shapes could be optimal: a thin liquid membrane, for example, would intercept perpendicularly propagating waves (sound, radio waves, light beams, etc.) and realize what is generally known with the term “morphological computation,” for the case of propagating mechanical vibrations.^[71] An interesting example of morphological computation is given by spider webs that, under certain circumstances, have been shown to be a dynamic system containing thread knots.^[72]

2.4. The Autolography Concept

In this last section, we will propose the autolography concept, representing the perfect scheme for the fourth-order cybernetic system: a fractal system able to reconfigure itself, where the information is processed on a low-dimensional space. **Figure 7**

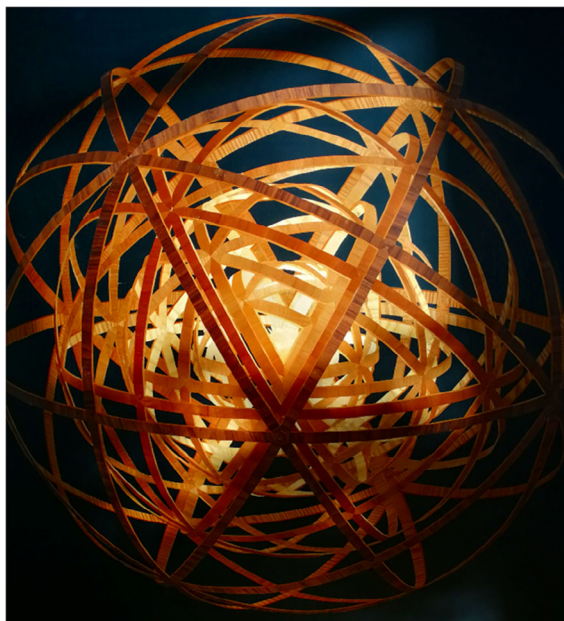


Figure 7. Fractal holographic universe. Reproduction of “Concentric Rinds,” May 1953, wood engraving by Maurits Cornelis Escher done by Magister Tudertinus Daniele Parasecolo, wood inlay 2020, picture by A. Chiolerio.

gives a symbolic view of such a concept, where the volume is divided into coherence domains (the circles of different diameters), and the information is processed from the center (where the star is located and radiates its light in different tones, depending on the distance from the light source) to the periphery, and from the periphery to the center (where shadows are casted in different tones, depending on the inverse of the distance from the light source). How to implement this picture? Producing an autolographic system could be done using the same ingredients described in the previous section for realizing the soft holonomic memory, adding a mechanism to enable the system to produce computation results (output) having the same physical nature of the input, so that the two can interfere and produce an active, instantaneous modification of the system structure. The input part requires an optical setup to focus on the surface of the autolographic system a tunable wavelength laser and geometrically pattern the light distribution with quite fast modulators (in the kHz range) that will represent the optical input. Writing the memory will require the use of photoactive materials, i.e., bacteriorhodopsin, azopolymers, tectomers, liquid crystals, or combinations of inorganic/organic elements, such as graphene quantum dots and ZnO NPs.^[73] The principle at the basis of writing is that the interference between the laser pattern projected onto the holonomic memory (carrying phase-coded information) and the active molecules will locally induce photocarriers and initiate a change of steric configuration in reason of a certain amount of energy transferred by the laser beam at a proper frequency. Another approach to volume holographic memories was developed using bacteriorhodopsin, a biological protein isolated from *Halobacterium salinarum*, that is responsible for photosynthetic activity and trans-membrane potential,

and features extreme ruggedness, making it suitable for real applications. Such molecule allows data being read and written in parallel, converting light energy into molecular conformational energy and vice versa.^[74,75] Once the memory is written, the same optical setup can be used to induce omnidirectional random lasing within the holonomic system toward the external environment, by focusing a sufficient amount of energy. Several materials, such as ZnO NPs, embedded in a polymer matrix or self-assembled fiber-like liquid crystals could be used as random lasing sources, that is typically recorded as a fluorescence spectrum.^[76–78] Also, Ag nanoflowers have been shown to greatly enhance the electromagnetic field because of their multi-branched structure and enable broadband plasmonic random lasing.^[79] Random laser emission with incoherent feedback, centered at 618 nm, was already observed, for example, from rhodamine B incorporated into a monolithic xerogel when excited by a 532 nm pulsed laser.^[80] The omnidirectional laser beam with spherical symmetry will expand from the focal point toward the outer part of the autolographic system, collecting information from travelling across the “written” liquid. To this aim, ZnO NPs are key to the successful operation, proving enhanced photocarrier generation on one side, and reversible conformational changes as a result of surface charges on the other side. The computational tasks (learning) of the autolographic system will be manifested in the associated reflection/attenuation response to optical stimuli. The inert, non-responsive and non-functionalized part of the sample will be ideally a mixture of solvents, such as water, ethanol, and ionic liquids, electrochemically stable with low vapor pressure, providing a suitable environment for supporting holonomic functionalities. Curable ionic liquids used as solvents might help in reducing the degrees of freedom, creating a soft material rather than a liquid.

3. Conclusion

We have seen how the logic evolution of cybernetic systems toward the fourth order of complexity is still incomplete, from the experimental point of view. The state of the art of contemporary von Neumann binary architectures has reached several limitations that prevent a further increase in computational elements density, and different approaches are under study to overcome those problems and offer brand new paradigms. LSMs, from the computational point of view, are one of such interesting models, whose equivalent in the experimental world is represented by *in materio* liquid cybernetic systems. The COGITOR concept provides an amorphous, liquid-state device able to adapt to extreme environment/shocks with limited loss of functionality (fault-tolerant); it features a holonomic approach to information storage/processing and readout, with an intrinsic massive parallelism enabled by the huge number of elementary processing units. Coherence domains can be locally programmed using electrical signals and addressed simultaneously by interfering with electromagnetic waves emitted by an embedded antenna, but inputs and outputs do not share the same physical nature. To complete the experimental framework, a last step is needed: the autolographic system, where functional optically responsive colloids are written by a laser coupled to a

high speed digital optical modulator and can produce random omnidirectional lasing for reading the collective state, whereas interference between forward and backward propagating waves is able to further modify the internal states of the system and enable computation, as both input and output share the same physical (electromagnetic) nature.

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Conflict of Interest

The author declares no conflict of interest.

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