

THE CNN UNIVERSAL MACHINE: 10 YEARS LATER

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In 1992, a new spatial temporal computing idea had been proposed, the CNN Universal Machine. It turned out that a new paradigm in computing on image flows, a Universal Machine on Flows, has ignited the intellect of hundreds of researchers. Today, visual microprocessors based on this idea can perform about TeraOPS computing power and 10 000 frames per second. In this paper, after a brief description of the history of the invention, architectural advances, physical implementation, algorithmic developments, as well as the biology relevance, theoretical aspects, mission critical applications, and new directions are reviewed.

Keywords: CNN technology; CNN Universal Machine; visual microprocessors.

1. Introduction

Ten years ago, in 1992, a new computer architecture called the CNN Universal Machine (CNN-UM), which combines both analog spatial-temporal dynamics and logic had been invented.¹ The protagonist elementary instruction was a programmable version of a CNN dynamics (CNN: Cellular Nonlinear/neural Network²). This stored programmable, analog-and-logic (also called analogic) topographic sensor-computer architecture had been soon implemented on standard CMOS technology, with an accompanying new computational infrastructure, and a new world of spatial-temporal algorithmic thinking had emerged. For example, by using only two simple templates the acclaimed universal rule 110 of Wolfram³ can be easily implemented via a two-instruction program on a CNN-UM. The biological relevance had soon been recognized and programmable neuromorphic models have since been discovered. The first successful application case studies had been developed and more than a hundred active researchers had been working in this new field by 1995.

The Office of Naval Research (ONR) played a seminal role in developing this technology from the start, and later, via the Navy International Cooperative

research Program, gave a boost to this new technology. Many national projects have started all over the world supported by numerous agencies and programs. In Europe, among others, national funds from Hungary, Spain, Italy, Finland, Germany, etc., as well as joint programs of the European Union had contributed significantly. In Asia, Japan and Taiwan were among the firsts to recognize the immense potential of the CNN technology. With the recent launching of several start-up companies worldwide, the CNN technology is finally being exploited for commercial applications.

TeraOPS speed and several thousand frames per second was the benchmark in 1999 on a single-chip visual microprocessor and today we are heading towards 12 TeraOPS computing power on a sophisticated on-chip optical sensing CNN-UM capable of more than 50 000 frames per second. An experimental optical implementation with more than one million pixels and operating at one nanosecond per template processing step (with semiconductor laser arrays) seems to be the imminent next benchmark.

There are many mission critical applications where real-time dynamic interaction between sensing and processing is absolutely necessary. The separation between the analog sensing elements and the computer in current hardware can no longer be tolerated.

The many new developments and discoveries in laboratories all over the world cannot be reviewed here due to space limitation. For the latest results, the reader is referred to the latest Proceedings of the IEEE International Workshop on Cellular Neural Networks and Applications, held in Frankfurt in July, 2002 (published by World Scientific).

A new field of sensory-computing-actuating machines with a life-like array computer architecture is emerging, which integrates sensing, computing, and actuation in analogic programmable Cellular Machines.

We are foreseeing this next level of functional integration in analog-and-logic Cellular Machines, as well as new vistas of physical-biological “implementations” and the new fields of mission critical applications. We are convinced that we are at the threshold of a new wave of technological innovations in our emerging field. Moreover, in view of the third wave of innovation in the electronic industry, namely, the sensory revolution, this new sensing-computing-actuating machines might emerge also as the optimal computing paradigm for many new products and services. They rely on new sensor and actuator arrays (e.g., auditory, tactile, and other somatosensory devices), as well as sensory data fusion.

2. Architectural Extensions in the CNN Universal Machine: Ten Years Later

During the summer of 1992, ten years ago, in the framework of a focused workshop at Berkeley, which was proposed and supported by ONR and organized by Professors Leon Chua and Tamás Roska, a new computing paradigm based on the

CNN Universal Machine was first introduced to the research community. Several conferences and journal paper publications on the CNN Universal Machine followed soon after. The possibility of developing algorithms and programs based on CNN dynamics combined with local and global logic, was quickly exploited worldwide in the form of analog-and-logic (analogic) CNN algorithms and related software. The first successful physical implementation of a fully programmable CNN-UM (a 22×20 cell chip designed in Seville) provided the assurance to the research community that the concept is physically realizable. The key conceptual barrier at that time was to think about stored programmability in analog array systems based on the new concept of analogic software.

Following the various physical implementations as well as further studies in neuronal plasticity and activation mechanisms, three main extensions of the original CNN Universal Machine (CNN-UM) architecture, described next, have been developed:

- *Adaptive CNN-UM* architecture, endowed with constructs for local (i.e., cell by cell) potentiation and plasticity rules. This sensor-computer architecture allows a content and context-dependent adaptation. Early results on this architecture have already shown that image details can be extracted successfully under spatially different local lighting conditions and noise.
- *Integration of activation* to spatial-temporal CNN dynamics has led to a sensor-computer-actuator *analogic cellular machine*. Two interesting examples are the “walking” robot and the “swimming” robot developed in Catania.⁴ In the former, disabling some CNN cells did not stop the robot’s locomotion, only slows it down.
- *Integrating global algorithms* in the GACU (Global Analogic Control Unit) of the CNN-UM. When implemented in a DSP, this possibility provides for an ideal combination of both the digital and analogic array computing technologies.

It is important to mention that many innovations have been introduced at the circuit level that have resulted in many smaller but important architectural modifications.

3. Physical Implementation

After the first few design experiments on programmable CNN devices, a level of stored programmability and accompanied computational infrastructure had been incorporated in Seville into a 22×20 CNN-UM chip with optical input and binary output (using 0.8 micron CMOS technology).

The next breakthrough was the successful implementation of an ACE4k chip in Seville with full analog capability on a 64×64 array which showed an unprecedented computing power on a single chip. The equivalent digital computing power of this chip is in the order of a trillion operations per second (TeraOPS), depending on the template type, on an approximately 90 mm^2 silicon area using a 0.5 micron CMOS technology. The accompanying computational infrastructure with all the necessary

software tools enables the software designers, for the first time, to write algorithms without any knowledge of the chip details.

Other groups of designers in Helsinki, Leuven, Taiwan (BiCMOS), Hong Kong, Zurich, Italy (ST Microelectronics and several other places) and others proposed and designed many interesting chips and special design techniques for special applications. In addition, the many so-called smart sensor designs (special purpose nonstored programmable sensor devices) in laboratories and companies worldwide are supplying important design and technology expertise for stored programmable solutions as well.

Two emulated digital CNN-UM architectures and chips, called CASTLE I and CASTLE II, have been designed in Budapest recently. The first test chips of CASTLE I are working and two new designs are on the way. The CASTLE II chip is a 3×2 processor array with a variable bit length; it will be fabricated in 0.35 micron technology. The CASTLE III chip is an 8 bit digital processor array combined with analog sensors and an analog programmable diffusion array (in collaboration with the Seville group) and will be fabricated in 0.18 micron CMOS technology. These two chips will go to fabrication soon.

The *second generation of CNN-UM based CMOS visual microprocessors* are emerging right now. Two chips are representing this new generation: a complex-cell CACE1k chip, and an ACE16k chip, both designed in Seville and the accompanying computational infrastructure has been designed and manufactured in Budapest. The soon to be fabricated CASLTE III chip mentioned above will show another division of labor between the analog and digital implementation of CNN-UM devices.

The CACE1k chip is the first complex-cell CNN-UM chip which implements a second-order, or two-layer CNN core, where the intra-layer and inter-layer templates, as well as the layer cell time constants are all programmable. This chip will lead to new vistas, including the development of a realistic retinal model on a chip (in contrast to the over simplistic resistive-grid based silicon retinas). Complex nonlinear waves and pattern formation can be implemented in this chip with high accuracy.

The ACE16k chip has a cell processor configuration of 128×128 with several innovations, including a sophisticated photosensor complex in each cell, and it is fully digital from the outside. These visual microprocessors will change the way we think about visual computing, including its price/performance.

New directions include the integration of tactile sensors, as well as application-specific architectural additions. Some recent examples apply nontopographic sensory inputs to the CNN-UM computers, including the ones for epileptic seizure forecast.⁵

The *outlines of the third generation CMOS chips* are already emerging; they will be *system-on-a-chip* (SOC) devices, which incorporate all input interfaces and activation outputs, as well as the digital core in the GACU, as mentioned before. They will be truly analog-and-logic cellular machines on a single chip.

An *optoelectronic* implementation of a CNN Universal Machine has been completed recently in Budapest. The system consists of an optical architecture where

the B template operation is performed at the speed of light, and where the large neighborhood B template coefficients (up to 32×32) can be changed in a fraction of a microsecond when using a semiconductor laser array. The resulting picture resolution is approximately a million pixels.

The CNN *software technology* and accompanying development systems have reached a new level of reliability and availability. This is demonstrated by the recent internet access to a development system with ACE4k chips, reachable from all over the world for 24 hours a day at the Jedlik Laboratories of the Pázmány University, Budapest via: <http://lab.analogic.sztaki.hu>, “try the real hardware” section.

The first compact and *self contained CNN hardware-software units* are now entering the market.

4. Algorithms and Software Technology

The main developments of the last few years are as follows:

- The proliferation of the use of *nonequilibrium* templates. This has been motivated by the implementation of various Partial Differential Equations (PDEs), for example by the subsequent use of nonlinear dynamic waves for a finite time.
- The former CNN template library has evolved gradually to an *Analogic CNN Software Library*, where new subroutines and even small programs used in many different applications have been included. Instead of designing templates and subroutines for each new application, the re-use of templates and subroutines taken from this Library became a norm instead of being an exception. The free distribution of these Libraries (see the web site <http://lab.analogic.sztaki.hu>) has been a motivating force behind this fast evolving process.
- In algorithms, *multi-wave or multi-thread structures* are emerging with a higher level of sophistication. In addition, the integration of the use of subroutines on global variables (the algorithmic part of the Global Analogic Control Unit, GACU) represents an emerging area of algorithm developments.
- In the new version of the Development systems, including the analogic CNN *Algorithm Simulators* and the *Chip related Behavioral Models* of specific CNN-UM implementations, additional *programmability via switch configuration registers* has now been made possible.
- The *possibility of using complex cells*, that is second or third order cells, or a two- or three-layer first-order CNN cell array with different programmable time constants of the layers, is greatly extending the class of algorithms beyond what we can dream of. Indeed, it turned out that many retinal-like algorithms need this capability.
- One consequence of these developments is the emergence of a standard flow diagram for a *graphic representation of algorithms* on our Universal Machine on Flows — called *UMF diagrams*.

5. Biological Relevance

Right after the invention of the CNN paradigm, several CNN models for various neuronal structures were developed.⁶ The invention of the CNN Universal Machine has changed the scenario. The possibility to use analogic CNN algorithms and to make it stored programmable offered the capability to use the same visual or tactile microprocessor to run many different life-like perception systems. The first result was the CNN Bionic Eye,⁷ immediately following the invention of the CNN-UM (right after the Berkeley workshop where the CNN-UM principle was presented). Many receptive field combinations have now been translated into CNN models and reported in the Receptive Field ATLAS.⁸

During the last few years, several neuromorphic CNN algorithms have been developed. Three directions are particularly emphasized.

- The CNN modeling of the *mammalian retina* had been made possible by using the results of the discovery described in the recent Nature paper of Botond Roska and Frank Werblin,⁹ uncovering the multi-channel processing details in the inner mammalian retina. It is indeed fascinating that many sophisticated but simply “implemented” mechanisms and principles are manifested in the inner plexiform layer of the mammalian retina.⁹ The multi-channel processing and coding, the saccadic suppression, the prototype three-layer dynamics, and many others are almost “designed by nature” to be modeled naturally via multilayer CNN dynamics.
- One of the many new CNN processing principles,¹⁰ called the *twin-wave processing principle*, refers to the following way of recognizing objects: one wave or thread is used for recognizing a specific target object, and another for recognizing nontarget objects. Finally, the two waves (threads) are combined, where the first wave is exciting, while the second is inhibiting the neuron at the resulting output. The inhibitory part plays an important role in this principle.
- Another principle is the *adaptive dynamic content- (or context-) dependent sensing*. The sensors are locally tuned, pixel by pixel, depending on the results of the local or global processing outputs. Presently, the contrary is the norm. This means that, for example, in using a camera we have a spatially identical and prescribed sensor-tuning in the whole sensor array (practically all available cameras use this mode of operation), and the output is taken (e.g., by the usual A/D converter) for further processing by a computer. With this conventional approach, we can be quite sure that in sophisticated situations the target detection problem is unsolvable, even if we have computers capable of processing at infinite speed. Nature does it differently, using the dynamic content dependent sensing principle described above. We have started to mimic nature’s principle in some well-defined still image processing situations.¹¹
- *Learning and unlearning*. Based on recent discoveries in plasticity studies in the brain, Professor J. Hámori had suggested that we explore the single-neuron level learning and unlearning processes. One beauty of this process is the genuine

analog-and-logic nature of the processing, including the local genetic modification of the DNA code.

- Related to *tactile sensing*, we are now trying to uncover some multi-channel processing mechanisms, which also contains a combination of different receptive fields.

6. Mission Critical Applications

So far, most of our successful CNN application case studies were algorithm driven and curiosity driven. They include the mammogram diagnosis system, the early echocardiogram analysis, the fascinating walking and swimming robot controls, the bubble versus debris classification problem in high power helicopter engines, various motion picture coding techniques, epileptic seizure forecasting, etc.

With the emerging possibility of using commercially available fist-size self-contained programmable devices, real-life mission critical applications are becoming feasible. The technical and economic motivations are the very high frame rate, the very high computing power per dollar, the small size-and-power consumption. Some recent examples are as follows:

- Diagnosis of a spark plug (20 000 frame per second is needed, including sensing and detection).
- Material speed measurement in a web without mechanical parts for real-time web inspection.
- Multi-target tracking for navigation and security.
- Car safety.

7. Theory

The areas of theoretical studies are numerous. We select here only four major areas.

- Stability of templates and subroutines.

In spite of the many interesting and important results, there are still templates, which are stable, in all simulations, but we are unable to prove that they are completely stable. It is even more so with multilayer templates, as well as in the case where the layer time constants play an important role.

- Pattern classification in spatial-temporal waves.

Only recently we are in a position to conduct experiments with programmable complex cell chips with two layers (second-order cells). This is the first time, we can conduct experiments with nonlinear waves in a few seconds, using our complex cell CNN-UM chip testbeds. Our initial findings that are related to some new spatial-temporal wave classes are exciting. These classes can only be defined by considering dynamic motion fields.¹² No single two-dimensional pattern can characterize these “video-clip patterns”. Their use in recognizing complex “turbulent” events such as sudden blasts or the initiation of bursts of propagating flames are still to be explored.

- Algorithmic studies related to PDE-based techniques and multilayer templates. It is fascinating that simple templates can generate exotic wave patterns. It is far more difficult to use these spatial-temporal flows for detecting some really complex spatial-temporal phenomena. Recently, some truly constructive analogic CNN algorithms have been invented to use these PDE-based techniques for solving real-life tasks, such as detecting motion profiles in echocardiograms, or for detecting multiple moving targets.^{13,14} Many powerful new techniques in complex image processing, including level sets, etc. are PDE-based. However, they are hopelessly time-consuming on digital computers. The challenge is how to implement them on CNN-UM chips to downscale the time requirement from hours and minutes to seconds and milliseconds in a fist-size or single-chip device.
- Computational, algorithmic, and computer *complexity studies in analogic cellular wave computers* defined formally on Universal Machines on Flows.¹⁰ Digital stored-programmable computers are mathematically described by Universal Machines on Integers (UMZ), also called Turing Machines. If all parameters of a Machine are discrete (iterative in time, discrete in space but the data are real members (instead of integers), the Universal Machine on Reals (UMR) is the appropriate model.^{15,16} The Universal Machine on Flows (UMF) is a generalization and concise mathematical description of machines derived from the CNN Universal Machine. It acts on data defined by image flows and complex tasks and the instructions are completed in continuous time. Recently, a fundamental study on computational, algorithmic and computer complexity of Universal Machines on Flows was carried out.¹⁰ Some of the striking results show that, for example, some important complexity measures are independent of the problem size. Some simple hard search problems remain hard, but some other types of hardness comes into the picture, and some hard problems on UMR might be solved efficiently on UMF. In the case of nonasymptotic computer and computational complexity (i.e., the size of the problem remains within a finite range), the computing power might depend on some template parameters inducing phase transitions. This means that there are problem parameters that have certain values around which otherwise stable and well behaving problems suddenly need enormous computing power in digital machines, but only modest computing powers on UMF. We have also shown that the PDE is a less powerful operator than a canonically described CNN dynamics.¹⁷

8. New Directions

Finally, we suggest some (but not exhaustive) new research directions that might have major future impacts:

- Immunology-inspired analogic CNN algorithms.
- Twin-wave processing principles for difficult target tracking applications.
- Retinal Camera, including saccade-smoothing and programmable real-time display and target recognition. As proposed by B. Roska, this device will also serve

as a research tool for retinal researchers. The knobs and selectors will be the retinal model parameters.

- Nano-level technologies to implement specific sensor arrays and cellular wave computing principles, including nano-magneto-transistor arrays, chemical arrays, etc.
- Learning and unlearning implementations for modeling and implementing emerging and fading pictorial memories.
- Coding and measuring information content in analogic spatial-temporal flows and processing steps.
- Exploiting the principle of hyperacuity in both time (as in the barn owl¹⁸) and space (as in the electric fish¹⁹).
- Interactive tactile processing principles and demo systems for difficult tasks such as holding a fragile object, turning pages of books or journals, etc.
- Auditory scene dynamics detection for recognizing typical sudden auditory effects, such as blasts, break-ins, etc.
- Navigation over multiple target scenes and terrenes.
- Spatially distributed mobile sensor-actuator networks.²⁰
- Artificial Understanding via multi-modal sensing, for example handwriting recognition via morpho-language-patterns.

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References

Recent selected books:

- L. O. Chua, *CNN: A Paradigm for Complexity*, World Scientific, Singapore, 1998.
- G. Manganaro, P. Arena, and L. Fortuna, *Cellular Neural Networks — Chaos, Complexity and VLSI Processing*, Springer, Berlin, 1999.
- T. Roska and Á Rodríguez-Vázquez (eds.), *Towards the Visual Microprocessor — VLSI Design and the Use of Cellular Neural Network (CNN) Universal Machine Computers*, J. Wiley, Chichester, 2001.
- L. O. Chua and T. Roska, *Cellular Neural Networks and Visual Computing*, Cambridge University Press, Cambridge, UK, 2002.

Other selected references:

1. T. Roska and L. O. Chua, “The CNN Universal Machine: An analogic array computer”, *IEEE Trans. Circuits Syst. II* **40**, 3 (1993) 163–173.
2. L. O. Chua and L. Yang, “Cellular Neural Networks: Theory”, *IEEE Trans. Circuits Syst.* **35** (1988) 1257–1272.

3. S. Wolfram, *A New Kind of Science*, Wolfram Media Inc., Champaign, IL, 2002.
4. P. Arena, L. Fortuna, M. Frasca, and L. Patané, "CNN based central pattern generators with sensory feedback", *Proc. IEEE Int. Workshop on Cellular Neural Networks and Their Applications (CNNA'2002)*, 2002, pp. 275–282.
5. R. Kunz, C. Niederhöfer, and R. Tetzlaff, "Prediction of epileptic seizures by CNN with linear weight functions", *ibid.*, 2002, pp. 259–266.
6. T. Roska, J. Hámori, E. Lábos, K. Lotz, L. Orzo, J. Takács, P. Venetianer, Z. Vidnyánszky, and Á. Zarándy, "The use of CNN models in the subcortical visual pathway", *IEEE Trans. Circuits Syst. I: Fundamental Theory and Applications (CAS-I)* **40**, 3 (1993) 182–195.
7. F. S. Werblin, T. Roska, and L. O. Chua, "The analogic cellular neural network as a bionic eye", *Int. J. Circuit Theor. Appl.* **23** (1995) 541–569.
8. T. Roska and J. Hámori (eds.), "Receptive field atlas of the retinotopic visual pathway and some other sensory organs using dynamic cellular neural network models", *Report DNS-8-2000*, Comp. Aut. Inst., Hungarian Academy of Sciences, Budapest, 2000.
9. B. Roska and F. S. Werblin, "Vertical interactions across ten parallel, stacked representations in the mammalian retina", *Nature* **410** (2001) 583–587.
10. T. Roska, "Computational and computer complexity of analogic wave computers", *Proc. IEEE CNNA 02*, Frankfurt, 2002 (and the extended version in this issue).
11. M. Brendel and T. Roska, "Adaptive image sensing and enhancement using the cellular neural network universal machine", *ibid.*, 2002, pp. 287–312.
12. I. Petrás, T. Roska, and L. O. Chua, "Novel spatial-temporal chaotic patterns and a programmable, experimental, spatial-temporal bifurcation testbed", *Report DNS-6-2001*, Comp. Aut. Res. Inst, Budapest, 2001.
13. Cs. Rekeczky and L. O. Chua, "Computing with front propagation: Active contour and skeleton models in continuous-time CNN", *J. VLSI Signal Processing* **23**, 2/3 (1999) 373–402.
14. Cs. Rekeczky, Á. Tahy, Z. Végh, and T. Roska, "CNN based spatio-temporal nonlinear filtering and endocardial boundary detection in echocardiography", *Int. J. Circuit Theor. Appl.* **27** (1999) 171–207.
15. L. Blum, F. Cucker, M. Shub, and S. Smale, *Complexity and Real Computation*, Springer-Verlag, New York, 1988.
16. S. Smale, "Some remarks on the foundations of numerical analysis", *SIAM Rev.* **30** (1990) 211–220.
17. M. Gilli, T. Roska, P. P. Civalleri, and L. O. Chua, "CNN dynamics represents a broader class than PDEs", *Report DNS-4-2002*, Comp. Aut. Res. Inst, Budapest, 2001, (in print: *Int. J. Bifur. Chaos*, November 2002).
18. K. Lotz, L. Bölöni, T. Roska, and J. Hámori, "Hiper-acuity in time: A CNN model of a time-coding pathway of sound localization", *IEEE Trans. Circuits Syst. I* **46**, 8 (1999) 9994–1002.
19. P. Baldi and W. Heiligenberg, "How sensory maps could enhance resolution through ordered arrangements of broadly tuned receivers", *Biol. Cybern.* **59** (1988) 313–318.
20. M. Hanggi, "Mobile sensor-actuator networks: Opportunities and challenges", *Proc. IEEE Int. Workshop on Cellular Neural Networks and Their Applications (CNNA'2002)*, 2002, pp. 283–290.
21. L. O. Chua and T. Roska, "The CNN paradigm", *ibid.*, Part I, Vol. 40, 1993, pp. 147–156.
22. T. Roska, "Computer-sensors: Spatial-temporal computers for analog array signals, dynamically integrated with sensors", *J. VLSI Signal Processing* **23**, 2/3 (1999) 221–238.

23. T. Roska and Á Rodríguez-Vázquez, “Towards visual microprocessors”, *Proc. IEEE*, July 2002.
24. T. Roska, L. O. Chua, D. Wolf, T. Kozek, R. Tetzlaff, and F. Puffer, “Simulating non-linear waves and partial differential equations via CNN — Part I. Basic techniques”, *IEEE Trans. Circuits Syst. I: Fundamental Theory and Applications* **42**, 10 (1995) 807–815.
25. B. Roska and F. S. Werblin, “Saccadic inhibition is initiated in the retina”, *ARWO 2002 Abstract*, Fort Lauderdale, 2002.
26. F. S. Werblin, B. Roska, D. Bálya, Cs. Rekeczky, and T. Roska, “Implementing a retinal visual language in CNN: A neuromorphic case study”, *Proc. IEEE ISCAS 2001*, Sydney, 2001.
27. E. Csuhaj-Varju and Gy. Vaszil, “On the computational completeness of context-free parallel communicating grammar systems”, *Theor. Comput. Sci.* **215** (1999) 349–358.
28. G. Prószéky, “Syntax as meta-morphology”, *Proc. 16th Int. Conf. Computational Linguistics (COLING-96)*, Vol. 2, Copenhagen, 1996, pp. 1123–1126.
29. T. Roska, “Analogic wave computers”, *Proc. IEEE ISCAS 2001*, Sydney, 2001.
30. S. Espejo, R. Carmona, R. Domínguez-Castro, and Á. Rodríguez-Vázquez, “A CNN universal chip in CMOS technology”, *Int. J. Circuit Theor. Appl.* **24** (1996) 93–109.
31. G. Liñán, P. Földesy, S. Espejo, R. Domínguez-Castro, and Á. Rodríguez-Vázquez, “A 0.5 μm CMOS 10^6 transistors analog programmable array processor for real-time image processing”, *Proc. 1999 European Solid-State Circuits Conference*, September 1999, pp. 358–361.
32. Proc. IEEE ISCAS-2002: Many full sessions on CNN Technology related papers.
33. G. Chaitin, “Information theoretic computational complexity”, *IEEE Trans. Infor. Theor.* **IT**, 20 (1974) 10–15.
34. T. Roska, Á. Zarándy, S. Zöld, P. Földesy, and P. Szolgay, “The computational infrastructure of analogic CNN computing — Part I: The CNN-UM chip prototyping system”, *IEEE Trans. Circuits Syst. I* **46** (1999) 261–268.
35. L. O. Chua, T. Roska, and P. L. Venetianer, “The CNN is universal as the Turing machine”, *IEEE Trans. Circuits Syst. I: Fundamental Theory and Applications (CAS-I)* **40**, 4 (1993) 289–291.
36. T. Roska, “Analog events and a dual computing structure using analog and digital circuits and operators”, *Proc. Discrete Event Systems: Models and Applications*, eds. P. Varaiya and A. B. Kurzhanski, Springer-Verlag, New York, 1988, pp. 225–238.
37. W. Heiligenberg and T. Roska, “On biological sensory information processing principles relevant to cellular neural networks”, *Cellular Neural Networks*, eds. T. Roska and J. Vandewalle, J. Wiley & Sons, Chichester, 1993, pp. 201–211.
38. Sz. Tökés, L. Orzó, Cs. Rekeczky, T. Roska, and Á. Zarándy, “An optical CNN implementation with stored programmability”, *Proc. IEEE Int. Symp. Circuits Syst. (ISCAS’2000)*, Vol. 2, Geneva, 2000, pp. 136–139.
39. D. Bálya, B. Roska, T. Roska, and F. S. Werblin, “A CNN framework for modeling parallel processing in the mammalian retina”, *Int. J. Circuit Theor. Appl.* **30** (2002) 363–393.
40. I. Szatmári, “The implementation of a nonlinear wave metric for image analysis and classification on the 64×64 analog I/O CNN-UM chip”, *Proc. IEEE Int. Workshop on Cellular Neural Networks and Their Applications (CNNA’2000)*, 2000, pp. 395–400.
41. CNN Software Library (see on <http://lab.analogic.sztaki.hu>).
42. *Proc. IEEE Int. Solid State Circuits Conference*, San Francisco, February 2002.

43. Special Issue on CNN Technology, *Int. J. Circuit Theor. Appl.* **30**, 2/3, March–June, 2002.
44. C. Y. Wu and W. C. Yen, “A new compact neuron-bipolar junction transistor (ν BJT) cellular neural network (CNN) structure with programmable large neighborhood symmetric templates for image processing”, *IEEE Trans. Circuits Syst. I* **48** (2001) 12–27.
45. <http://lab.analogic.sztaki.hu>.
46. <http://www.ieee-cas.org/~cnnactc>.