Text recognition, event detection and some theoretical aspects of cellular wave computer architectures

Cellular wave algorithms with semantic embedding and a new graph representation of cellular binary dynamics to investigate invertibility

Ph.D. Theses

Kristóf Karacs

Scientific adviser:
Tamás Roska, D.Sc.
ordinary member of the Hungarian Academy of Sciences

Consultant:
Gábor Prószéky, D.Sc.

Doctoral School of Multidisciplinary Engineering Sciences,
Faculty of Information Technology,
Pázmány Péter Catholic University
(PPKE-ITK)

Analogical and Neural Computing Systems Laboratory,
Computer and Automation Research Institute,
Hungarian Academy of Sciences
(MTA-SZTAKI)

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"Ask, and it shall be given you; seek, and ye shall find; knock, and it shall be opened unto you."

Mt 7:7.

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Introduction and objectives

Every seeing human takes it for granted from early childhood to be able to recognize objects and patterns around us. It is so evident for us we rarely realize how complex the visual pattern matching process of our brain is. For some time, using the advances of technology, research of human vision is gaining increasing attention among biologists, but there is still a long way to go to fully understand the processes that take place in our mind when we see people and objects and we are able to recognize them. In parallel, computer scientists have been trying to create models for visual recognition tasks, but they faced enormous difficulties, and solutions could be made only for a very limited set of problems, typically with high power dissipation. There are two main difficulties in performing such pattern recognition tasks. Both are connected to the fact that even among the most common and simplest tasks it is hard to find one in which the human brain does not make use of its huge network of highly associative semantic knowledge. One of the problems is that there are no fully adequate models representing these networks within the realms of current technological boundaries. The other one is that there are several knowledge levels in these networks and the brain uses them in a deeply parallel way, indeed sensing and processing cannot even be really distinguished. This parallel model is very far from traditional sequential models, in which different levels of information are processed in sequential blocks, so that they can be handled independently, and some feedback is added to the system to handle problems arising from the base model and to provide stability.

When I started my research I was convinced that plasticity and parallel evaluation of background knowledge have to be built into our models. The amount of incoming data in recognition tasks is huge, and extracting relevant features is the only way to tackle with it. If background knowledge is used only after the feature extraction stage, then many details might be discarded too early that makes it impossible to correctly recognize the target. During my research I was challenged with two interesting and complex pattern matching problems: Offline recognition of handwritten cursive texts, and localization and recognition of route number signs on public transport vehicles. Both of these tasks are deeply embedded in a semantic context.

Handwriting recognition is the machine analogue of the human reading process. My goal was to design a system mimicking the human reading by letting the linguistic knowledge to act immediately on letter and word level features without their explicit recognition.

The algorithms for sign detection and recognition were motivated by a project aiming to create a portable device for blind and visually impaired people, called the "Bionic Eyeglass", to help them in everyday problems they face due to the lack of vision. Such applications require deep understanding of the environment where the observed events occur, similarly to how reading a sequence of letters is embedded in a linguistic environment.

The ability to identify a bus or a tram is one of the most important ones among the dozen crucial functions determined by the representatives of potential users. I developed a semantic framework for processing information coming from sensors of different modalities. I applied the semantic embedding principle to develop new algorithms by means of transforming semantic descriptions of typical signs, displays and vehicles into procedures for cellular wave computers.

I also dealt with the theory of binary cellular nonlinear networks, also known as cellular automata. I gave a method that allows analyzing all orbits of one dimensional cellular automata of neighborhood size one for the existence of points where trajectories merge and proved that the nonexistence of such points is equivalent to the nonexistence of Garden of Eden[1] states as well as all orbits being Isles of Eden[2]. This topic belongs to the theoretical side of the field of locally connected cellular architectures.

[1] A state of a CA is called Garden of Eden *iff* no other state is mapped to it, i.e. it has no predecessor under the global map.

[2] A state of a CA is called Isle of Eden *iff* it is uniquely mapped to itself under the n^{th} iterated global map.

Methods of Investigation

Most of my research is directly connected to the Cellular Nonlinear/Neural Network (CNN), the CNN Universal Machine (CNN-UM) and the Cellular Wave Computing paradigm. The CNN templates developed were designed using analytical methods published in the literature ([18],[19]). I relied on the concept of the CNN-UM being a Universal Machine on Flows (UMF) [20] for the design of cellular wave algorithms. Besides the templates designed by myself I utilized many standard template classes [12], including ones that implement morphological and other image processing operators.

A key method I have developed is semantic embedding. I applied it to in spatial and multimodal spatial-temporal detection tasks to find topographic features by giving semantic description of sample input images and video flows based on structural scene analysis. I validated the feature detection algorithms on standard and self made test sets.

I used standard document scanners to acquire handwritten texts. Experiments regarding pattern detection in 2D video flows were performed on a Blind Acquired Visual Flow Database containing recordings taken with commercial cell phones with built-in cameras and compact digital cameras by blind persons in real world situations.

For algorithm development I used the software package named Aladdin developed by Analogic Computers Ltd [21], the ACE-16k cellular visual microprocessor [22] and the Matlab software environment [23] with the MatCNN toolbox [53].

For expression level language modeling I used bigrams, as a simple, non-semantic model, and I relied on statistical methods for probability estimations.

In the field of cellular automata I relied on results in theory of nonlinear dynamics, graph theory, symbolic dynamics, and especially on new results of L. O. Chua in qualitative theory of binary Cellular Nonlinear Networks [50].

New Scientific Results

Thesis I. Analogic algorithms with spatial semantic embedding for handwritten text recognition

Great variety of handwriting styles makes it hard to recognize handwritten texts by machines in general. I created a handwritten text recognition system that mimics the human reading process by incorporating cellular wave algorithms as a model of perception and integrating the use of linguistic knowledge into the recognition process. The system realizes lexicon reduction with a very high reduction rate (>99.9%) and with a coverage over 80%, which is comparable to previous results in the literature.

I.1. I developed a method called shape coding to embed the recognition of 2D morphological shape features into a semantic environment.

Making use of linguistic information can greatly improve the performance of recognition systems, but in the traditional way of using it for post-processing satisfactory results could not be achieved. Shape coding enables embedding linguistic knowledge into the recognition process without actually recognizing the letters or the word.
Advantages of this approach are twofold. On one hand it overcomes the problem of the mutual dependence of segmentation and recognition of letters (Sayre paradox [31]). On the other hand linguistic knowledge can influence the relevancy and importance of geometric features.

I.2. I determined six holistic features detectable on cellular wave computers and implemented several feature extraction and feature classification analogic algorithms

Holistic features are primitives of letters and they are detected on the word image without the need to segment it into letters. The six features are as follows: holes, ascenders, descenders, junction points, hills and valleys. Some features are classified into several feature classes based on their size, shape and/or position. Some characteristic feature maps are shown in Figure 1.

(a) (b)

Figure 1. Different classes of (a) holes, (b) ascenders and descenders

I.3. I determined general parameters characteristic to the writing style and I gave methods to adaptively compute them

Identified parameters include distance of baselines of the writing, thresholds for minimum ascender and descender height, size intervals for classification of holes, and average letter width. The methods developed are based on my experiments and are realized using cellular wave algorithms.

I.4. I created a method to map topographic features detected at the word level to possible letter positions

A topographic feature detected can belong to multiple positions in a word, therefore the mapping is ambiguous. Figure 2 shows a simple mapping problem. The method gives all possible mappings obeying the following geometric constraints: slant of the writing, horizontal order of features and vertical coupling.

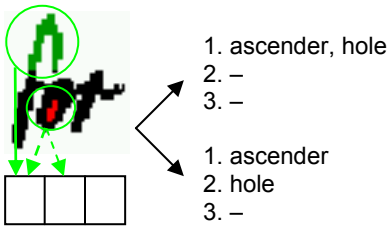

Figure 2. Mapping of topographic features is ambiguous, the hole in letter 'o' can belong to two distinct positions, doubling the number of possible mappings.

I.5. I created a method to estimate the number of characters in a handwritten word image using horizontal connected components as a quasi-independent measure

I experimentally proved that, considering a handwritten cursive word image, the number of horizontal connected components and the number of letters of the word has a strong correlation and their ratio is independent of the writing style. The new method can estimate the number of letters in a word more accurately than an estimation based on the pixel length of the word, meanwhile the input it relies on can be computed with a single cellular wave instruction, the **HCCD** template.

I.6. I developed a novel upper baseline detection algorithm that gives robust results even for words with a high number of ascenders

Detecting the upper baseline properly is very important to enable accurate feature detection. I gave a cellular wave algorithm for upper baseline detection that uses connected component detector to locate a horizontal baseline on a skew-corrected word image. Detection result is shown in Figure 3 for a sample word. I showed that restricting the upper baseline to be horizontal does not decrease the accuracy of feature detection, and that one free parameter can be determined more robustly than two.

Figure 3. Sample word image with computed horizontal upper baseline.

Thesis II. Detection of dynamic events and specific 2D patterns in saccadic and noisy visual flows recorded by a moving, blind platform

Extracting and reading signs from video flows recorded by a moving camera in real-world situations is a very complex task motivated by the way humans find and read signs and use it for orientation. I gave algorithms to perform sign detection in specific situations that can be described by pre-defined semantics and to recognize numbers in them. The algorithms have been tested and validated on recordings from the Blind Acquired Visual Flow Database, containing more than an hour of recordings and over 100 dynamic events.

II.1. I defined a general semantic framework for hierarchical processing of multimodal sensory information with embedded semantics

I created a framework for hierarchical processing of information coming from multimodal, topographic sensors and integrating semantics to control sensing-processing. I defined the following abstraction levels in the hierarchy: features, symptoms, events, situations. Events are recorded in an Event Register that, together with active situations and a priori goals, influences the attention mechanism. Attention Director controls actuators to interact with the environment and sensors to facilitate better sensing with regard to current situations and events.

II.2. I gave analogic cellular wave algorithms to detect and validate route number signs on public transport vehicles in a 2D visual flow

The video flows recorded by mobile devices are of low-quality and some control is needed to direct the camera towards the sign. The algorithm I created detects possible sign candidates and validates them by checking if they contain large figures. UMF diagram of the detection algorithm is shown in Figure 4. Detection is shown in Figure 5 for a sample frame. Valid signs are tracked through frames, and an enhanced image is produced by superposing sign images extracted from consecutive frames on one another to allow for better recognition results.

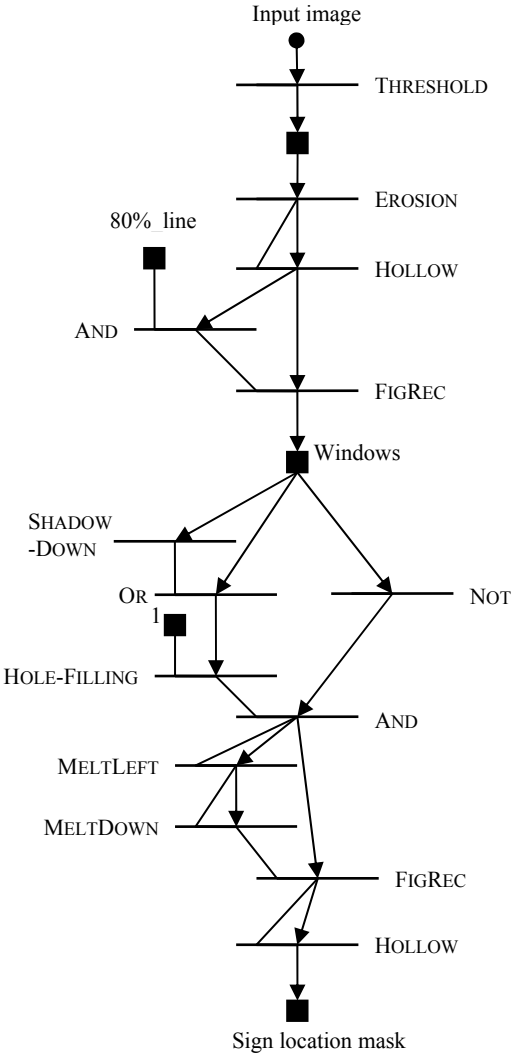

Figure 4. UMF diagram of the algorithm locating signs with a white background.

(a) (b)

Figure 5. Sign localization on a tram. (a) Original input frame (b) Sign location on binarized input

II.3. I gave a topographic feature detection based method to recognize numbers in signs extracted from 2D visual flows

Recognition is based on topographic feature detection by cellular wave algorithms. I use holes and straight lines as features and a box model is used in addition to allow the detection of open semi-holes in the shape of numbers. Sample topographic feature maps are shown in Figure 6.

Figure 6. Sample feature maps. Right open holes and their auxiliary lines are shown in cyan, middle vertical line is shown in blue, and upper round hole is shown in red.

Thesis III. Invertibility of one dimensional cellular wave computers

Analysis of invertibility of dynamical systems is of great importance. Based on the concept of isle of Eden, introduced by L. O. Chua, I developed a new construction for detecting merging points in binary cellular nonlinear networks (cellular automata) trajectories using a graph-theoretical approach. *Isles of Eden* are orbits with every state of it being the unique preimage of itself under the n^{th} iterated global map. I proved a general theorem connecting a well-defined set of cycles of the digraph to isles of Eden, and analyzed all 256 elementary cellular automata for non-trivial invertibility.

III.1. I defined a digraph for analyzing pairs of input patterns in elementary CAs, called the Isles of Eden digraph, and I gave an algorithm to construct it for any elementary CA. I proved a general theorem stating that there are no degenerate cycles of length L in the Isles of Eden digraph of a given CA if and only if all of its orbits are isles of Eden, which is equivalent to the invertibility of the CA.

The Isles of Eden digraph is a de Bruijn graph of pairs of two bit binary patterns, and its cycles of length L correspond to two binary strings of length L that are mapped to the same output. If the strings are equal the cycle is called degenerate. Non-degenerate cycles refer to different strings, referring to a merging point in the trajectory. To prove the theorem I proved through some auxiliary lemmas that for a given CA and a given pattern length the following statements are equivalent:

1. All cycles of this length are degenerate
2. Global mapping is surjective (there is no Garden of Eden)
3. Global mapping is injective (there is no merging point in the trajectory)
4. All orbits are isles of Eden
5. The cellular automaton is invertible

III.2. I determined all elementary cellular automata that are invertible for an infinite number of pattern lengths, and proved that non-invertible pattern lengths occur periodically.

I performed numerical simulations on the space of elementary cellular automata to analyze the surjectivity of the global map for all pattern lengths less than 20. Based on the results I determined candidates that might be invertible for infinitely many pattern lengths. I analyzed their Isles of Eden digraphs, and proved that non-invertible pattern lengths occur periodically for all of them (Table I). Figure 7 shows a sample Isles of Eden digraph for rule 45.

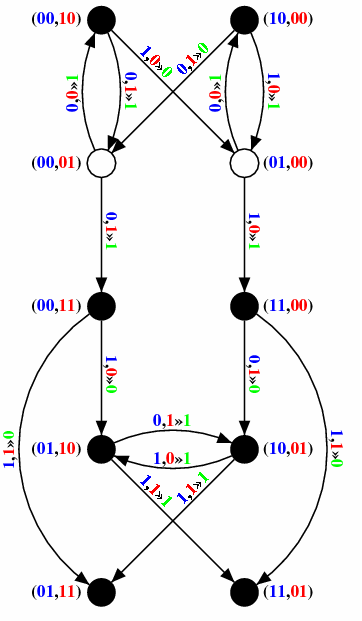

Figure 7. Isles of Eden digraph for local rule 45. All cycles in it are of even length, because their containing subgraphs are bipartite.

Table I. CA rules that are invertible for infinitely many pattern lengths.

Period of non-invertible states	Rule numbers
2	45, 75, 89, 101 154, 166, 180, 210
3	105 150
∞	15, 85 51 170, 240 204

Application areas of the results

Most of the research I did is directly motivated by applications. The advantage of the methods I developed for handwriting recognition is that they are general purpose algorithms, and they are not restricted to small dictionaries. Possible applications include processing of personal notes and official forms.

The semantic embedding framework can be used in a wide area, for any multimodal, multi-sensor information processing task. Of course, the general framework should be adapted and sophisticated according to specific aspects of the given problem.

Route number localization and recognition algorithms can be utilized in a portable device like the Bionic Eyeglass at bus and tram stops to provide help in finding the right vehicle for a visually impaired person. They can also serve as a basis for a more general Blind Mobile Navigation framework capable of high-level object detection and recognition. Such a framework can not only be used by a visually impaired person, but also in autonomous robots designed to operate in hazardous environments to facilitate their automatic navigation.

Results on the invertibility of elementary cellular automata can be used for further theoretical investigations in the field, and they can also serve as a basis of a more general research on new computational models using quantum computers and the relation of physics and computation. Moreover it can be used to investigate

methods for detecting real world patterns that are easy to generate but difficult to detect.

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[1] **K. Karacs**, G. Prószéky, and T. Roska, "CNN algorithms with spatial semantic embedding for handwritten text recognition," *International Journal of Circuit Theory and Applications*, to be published

[2] L. O. Chua, **K. Karacs**, V. I. Sbitnev, J. Guan, and J. Shin, "A Nonlinear Dynamics Perspective of Wolfram's New Kind Of Science. Part VIII: More Isles of Eden," *International Journal of Bifurcation and Chaos*, to be published

[3] G. Tímár, **K. Karacs**, and Cs. Rekeczky, "Analogic Preprocessing and Segmentation Algorithms for Off-line Handwriting Recognition," *Journal of Circuits, Systems and Computers*, vol. 12, no. 6, pp. 783–804, Dec. 2003.

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