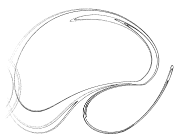
SPATIO-TEMPORAL PATTERNS

AND

ACTIVE WAVE COMPUTING

Theses of the Ph.D. Dissertation



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2004

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INTRODUCTION

PATTERNS and waves are so "natural" that we do not pay particular attention to them in our life normally. We do not even notice most of them. Yet, they are inherent phenomena of our world. A wave is created when the state or position of a substance locally changes spatially and temporally synchronized in such a way that this local change propagates. In a broad sense the pattern is a distribution of a property of the medium. A kind of mixture of waves and patterns is also possible: a traveling pattern can form a wave, or from the other point of view a wave can have texture (see Fig. 1).

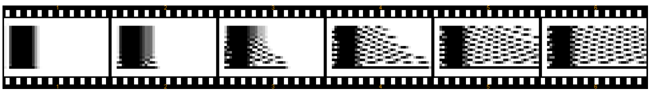

Figure 1: Novel type of traveling pattern. Consecutive snapshots of the active medium.

When we are talking about waves man usually thinks of the classical waves that spread in conservative systems. An example for this well known by everybody is the surface waves of water. This case, the energy pumped into the system is conserved.

Nonlinear waves spreading in excitable (non-conservative) medium differs from the "classical" waves. Waves in the classical sense (e.g. electromagnetic waves spreading in vacuum) mostly constitute physically closed system in themselves, i.e. they do not interact with other systems e.g. with a media. It is enough to integrate the state variables of the closed system into the energy balance of such waves and the energy computed taking them into account remains constant during the process. In the case of the excitable waves the conservation of energy is hold only when one considers the state of the wave and the media and the interaction between them. However it seems not to be hold if we consider the wave as a subsystem. Nonlinear waves spread at the expense of energy stored in the media such a way that an activated point activates the neighboring points of the medium. From this comes the name *autowaves* coined by R.V. Khorlov, as an abbreviation for autonomous waves. The name expresses well the property that the propagation is self–sustaining. The dispersion and decay properties of a spreading autowave are characteristically different from that of the classical ones: the wave does not decay nor the waveform is distorted during the propagation. Autowaves cannot be reflected from the boundaries, nor can they interfere. When colliding, autowaves annihilate each other. Diffraction is the only property classical and autowaves have in common. Up to now, several types of active waves were described and studied. Depending on the nature of the observed phenomena different names have been used in the literature, such as autowaves, traveling waves or trigger/triggered waves, target waves or concentric waves and spiral waves.

We know several well-described phenomena of active wave propagation. Flame propagation in combustion system is a typical example. Chemical reaction–diffusion systems can also produce autowaves. Many autowave processes were found in biology. Perhaps the most obvious is the nerve impulse propagation. An important autowave process can be found in the cardiac muscle. The contraction of the muscle follows traveling wave patterns due to the propagation of electrical impulses in the hart tissue.

Another rather surprising example of autowaves is the communication method of the cellular slime mold amoeba species. Interestingly, the members of a colony of amoeba communicate with spiral and target waves. When no more food (bacteria) is left and they are starving some of them sends out spiral and target waves and attract the neighboring amoebas. Then they transform to spores until food becomes available.

Alan Turing in his paper in 1952 proposed a model to explain mechanism of pattern formation in a reaction–diffusion system. He suggested that chemicals could react in such a way that the steady state of the reaction is a heterogeneous spatial pattern of chemical concentration and that this can be the chemical basis of morphogenesis. Since the fundamental work of Turing hundreds of papers and several books dealt with the possible explanations of the complexity of forms found in Nature and their corresponding mathematical models.

As a result of efforts of many researchers in the field several methodologies and mathematical tools have been developed. A natural “classical” approach for modeling is to use PDEs. However, recently, it became apparent that not all phenomena could be reproduced with the continuous PDE models.

Systems of discretely coupled cells with some kind of transfer process between the cells are often used to model the above mentioned phenomena that occur in living cells, tissues, nervous system, ecosystems, reaction–diffusion systems describing chemical processes. Such discrete modeling framework among others (e.g. cellular automata, nonlinear lattice, etc.) is the cellular nonlinear/neural network (CNN).

CNN is a locally connected array of nonlinear dynamical systems called cells. It is discrete in space but continuous in time. Its connections or couplings determine the dynamics of the system. CNN provides a well-defined mathematical and a hardware feasible physical framework to study the emergence of patterns encoded by the local interactions of identical cells. The easy VLSI implementation of the cell array is the most important advantage compared to other modeling frameworks.

In spatially discrete systems, such as the CNN, traveling pattern is the assembly of synchronized oscillations of individual cells. Thus it is straightforward that the trajectory of the system in the state space is characteristic to the pattern. If the attractor that the trajectory moves around is a chaotic one, a rather complicated pattern can be formed. This suggests that coupled oscillations can serve as the generator of forms and patterns. The first and second thesis in Chapter 3 and 4 of this dissertation deals with this.

Besides the modeling and studying of complex phenomena, CNN makes it possible to conceive novel inherently fast computation principles. Such parallel computation method is presented in the third thesis and chapter 5 of this dissertation.

Although in the state–of–the–art microprocessors more or less parallelization can be found, algorithms are executed sequentially since the computing principle is based on an abstract mathematical construct called Turing machine that has a fundamentally sequential operation. On the contrary, in active media things happen parallel. This is also true for the CNN. It is organized typically into a regular grid like array. Due to implementation issues the cells are mostly connected to the nearest neighbors. These connections for a cell are described by the same matrix. This connection matrix is called *template*. Electrical circuit implementation can be optimum choice since circuits can be well controlled compared to e.g. chemical solutions and current VLSI technology enables the easy mass production of large arrays. The elementary cells of the arrays are identical circuits that operate parallel. If we want to make use of this for computation we must think different, compared to the usual way that man got used to at digital computers. One should take into account that the computation goes parallel and the task should be expressed in the form of the available parameters. These are the initial state of the system, couplings and boundary conditions. The result of the computation is established as the steady state or any intermediate state of the system developed by the collective behavior of the array.

The receptive field is a basic structure found everywhere in the neural pathway. It can be found in the tactile system, retina and in the cortex. The receptive field is the set of neurons from where a neuron receives input. This usually means the local neighborhood of the neuron. With the aid of the CNN several type of artificial receptive filed can be built.

MAIN RESULTS

In the following theses the CNN is applied as active medium. Within this framework I investigate the nonlinear dynamics of pattern formation and the behavior of a specific active wave.

In the first thesis I present novel 2D traveling patterns exhibiting rich nonlinear dynamics including spatio-temporal chaos. I study the corresponding dynamical system and determine the parameters that control the character and the dynamics of the pattern. I show that the 2D pattern is composed of coupled 1D rows of coupled oscillators. For this I used both simulation and CNN-UM VLSI chip.

In the second thesis I focus the analysis to one row. I show that even the different boundary conditions, initial states and the dimensions of the system can change the dynamic behavior e.g. from periodic to chaotic. For this I computed Lyapunov exponents based on simulations.

In the third thesis I present the mathematical analysis of local curvature controlled trigger wave. I show how it can be used for practical image processing purposes.

First Thesis

Spatio-temporal signatures in CNN

I discovered a linear, space invariant 2D template class with few nonzero elements that can produce complex, chaotic spatio-temporal behavior depending on the template parameters and the input of the array. It generates spatially bounded or unbounded traveling patterns according to the parameters. I introduced the "Spatio-temporal Signature" – a still image that is the snapshot of the output – as a descriptor for the dynamic state of the array. This image reflects the temporal history of the dynamics in space due to the propagating effect.

I gave principles for the template design. I gave a 1D template of which corresponding CNN exhibit complex, chaotic behavior depending on the input.

Second Thesis

Chaotic dynamics, coexistence of attractors in 1D CNN

I uncovered novel complex dynamics in 1D CNNs with a sign-antisymmetric template class. I investigated the effect of the boundary condition, dimension of the system and the initial state. I found that boundary condition behaves as bifurcation parameter. I found coexistence of attractors depending on the initial state.

II/a. Effect of boundary conditions in 1D CNN

I showed that the dynamic behavior of a 1D CNN with a sign-antisymmetric template class depends on the boundary conditions. I presented examples that demonstrate the rich dynamics of the CNN system such as stable, periodic, quasi-periodic and chaotic dynamics.

II/b. Effect of dimension and initial sate, coexistence of attractors

I found that the steady state dynamics depends on the initial state: attractors coexist simultaneously in the same system. I showed that hyperchaotic behavior can occur in a CNN that consist of more than five cells. I demonstrated that the parity of the size of the 1D system drastically changes the dynamics.

Third Thesis

Curvature controlled trigger wave

I showed that the CNN with a nonlinear diffusion type template class computes the approximation of the so–called "Curve Shortening Flow" of shapes. Indeed, the process can be described as local curvature controlled trigger wave propagation in the CNN array. In this framework the curve is represented as the boundary region of a solid black shape against white background. As a result of the diffusion–like evolution of the CNN array, a smooth 2D transition zone called *boundary region* is formed between black and white regions. The width of the region is controlled by the template parameters. The evolution of the shape of this region corresponds to the evolution of the curve. To show this, at first I analyzed the characteristics of the boundary region of the evolving shape than I studied the dynamics of this transition region.

III/a. Stability of the boundary

I proved that the boundary region is stationary provided that the region is horizontal or vertical. I gave relation on the number of linear cells in a horizontal or vertical boundary region. I gave approximation on the minimal number of linear cells of arbitrary oriented straight boundaries.

III/b. Dynamics of the boundary region

I showed that the temporal derivative of the state variable of a linear cell being in the boundary region is the quasi-linear function of the local curvature of the isointensity line to which the cell belongs provided that the state variable of the cell is close to zero. This is fulfilled in the centerline of the boundary region. The boundary region changes so that its local curvature is zero. In other words the shape contours get smoothed provided that spatial constraints make this possible. I gave method to compute the convex hull of a shape in one transient. Moreover, I gave method to separate two-dimensional clusters of points.

POSSIBLE APPLICATIONS AREAS

First Thesis

Spatio-temporal signatures mentioned above may be used to easily identify the system dynamics.

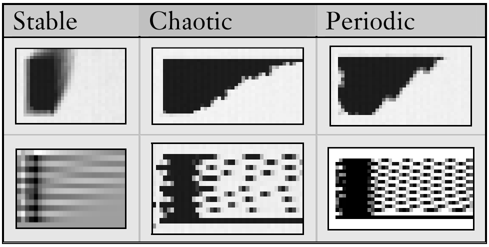

Table 1: Spatio-temporal signatures for different values of r and p.

The template class presented can be a suitable spatial and/or temporal pattern generator or clock that controls e.g. locomotion (see Fig. 1). The system in the chaotic operation mode can be used as colored-noise source.

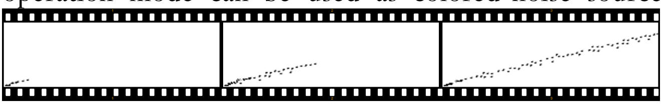

Fig. 2: Three snapshots of the propagation of the "bird" pattern.

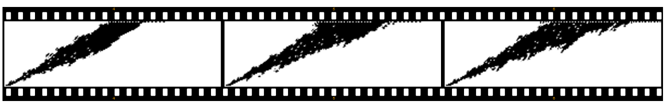

Fig. 3: Three snapshots of the propagation of the "eruption" pattern.

Moreover, templates with more nonzero elements may be used for complex pattern generation (Fig. 2 and 3).

Second Thesis

The results suggest that the different dynamical states of the system in the form of coexisting attractors (Fig. 4) may be exploited in information storage after further research.

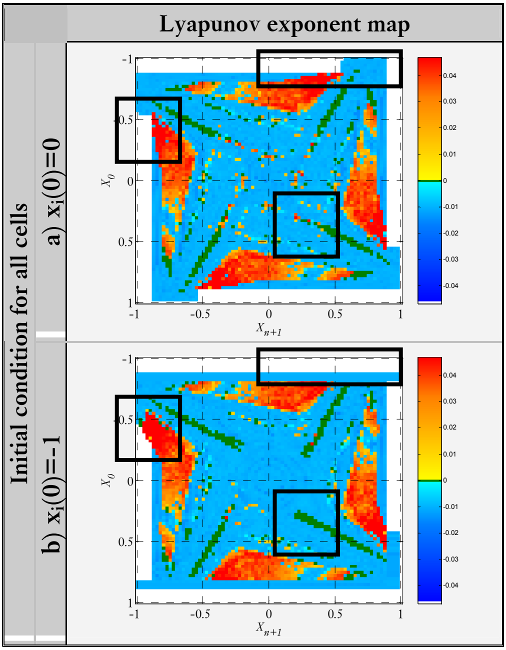

Figure 4. Coexistence of attarctors in 4×1 CNN with a) $x_i(0)=0$, b) $x_i(0)=-1$, i=1..4 (all cells have the same initial state). Observe the coexistence of chaotic attractor↔ limit cycle, chaotic attractor↔ torus and torus ↔ limit cycle. Color code. Yellow-red: chaotic attractor; green: torus (quasi-periodic); blue: limit cycle (periodic); white: equilibrium point.

Although it has not been investigated in this thesis, it can be conjectured that similarly to the effect of boundary condition (Fig. 5) the input can also change the dynamics of the system, thus it may be used for pattern recognition and information storage too. Similarly to the *first thesis* this system can also be used as colored-noise generator.

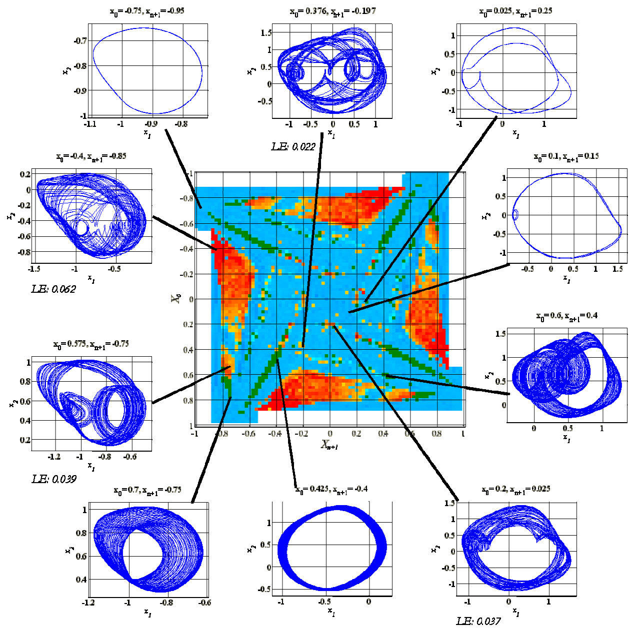

Figure 5. Lyapunov map. Some observed attractors are shown. Color code. Yellow-red: chaotic attractor; green: torus (quasi-periodic); blue: limit cycle (periodic); white: equilibrium point.

Third Thesis

Results of this thesis are more directly connected to image processing. The local curvature is a rather characteristic, rotation and scale invariant feature of shapes. This can be efficiently computed parallel by the CNN. (See Fig. 6 and 8)

Smoothing of shapes can also play important role in pattern recognition (Fig. 6 and 8).

Clustering of points or patches is another possible application (Fig. 7).

The form and area of convex hull of shapes is another important feature. This also can be effectively calculated by the CNN in parallel fashion (See Fig. 9).

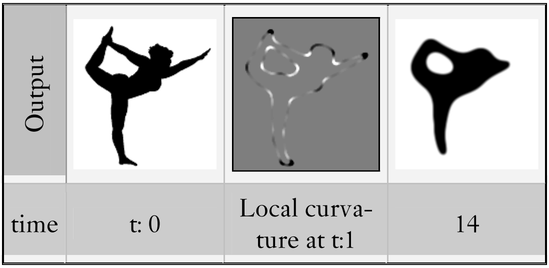

Figure 6 Smoothing of shapes and the local curvature. Black color means positive, white color means negative curvature.

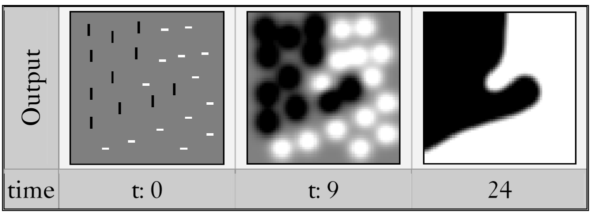

Figure 7 Clustering of patches

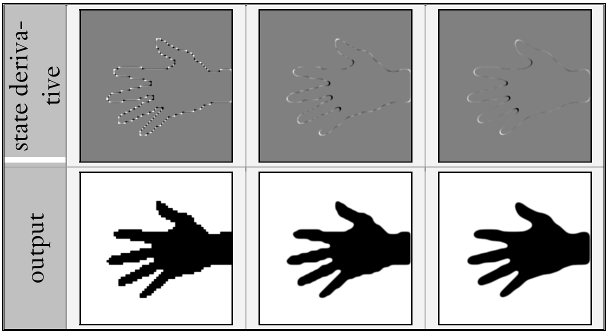

Figure 8 Curvature smoothing. Upper row shows the snapshots of the state derivative. The bottom row shows the output of the CNN.

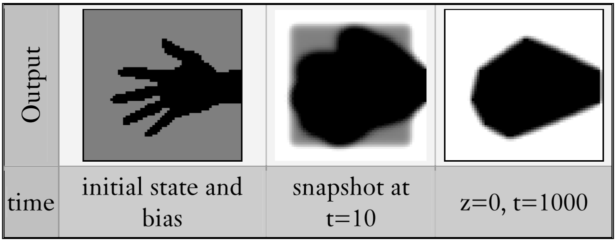

Figure 9 Calculation of the convex hull of a shape.

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Appendix

CNN–UM in mobile robot

The aim was to design and produce a mobile platform based system that is able to identify objects or events by simple features (shape, texture, motion, etc.) and to approach or navigate to them. Moreover it is able to gather information and transmit information about them to the base station. The mobile unit communicates with the base station through wireless channel. The base station monitors the mobile unit of which control can be taken over at any time.

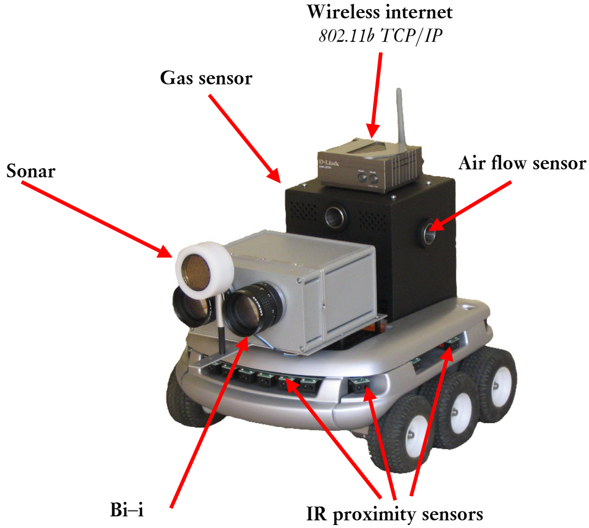

Figure 10: Mobile unit overview.

The robotic system is equipped with several sensors, operates on battery and controlled by the Bi-i smart camera system introduced in chapter 3 of the dissertation. The robot itself is an off-the-shelf mobile platform fabricated by K-Team from Switzerland.

The hardware of the system is the result of collaboration of several partners of the project. The Bi-i system was designed and produced the Analogic Computers Ltd. The airflow and gas sensors were produced by MTA-KFKI-MFA research institute (see Fig. 10). The high-level algorithm frame for controlling the mobile unit was designed at MTA-SZTAKI in which I took part.

Main components of the system are the base station that consists of a PC with a wireless bridge and the mobile unit. The mobile unit is built up from a mobile platform (Koala), the Bi-i smart camera system that hosts the

CNN–UM and the sensory platform. The Koala is a processor controlled mobile platform equipped with IR proximity sensors and sonar that controls the low level navigation of the car. The Sensory platform hosts the gas and airflow sensors.

The Bi-i system is responsible for the high-level control. It contains three dedicated processors (CNN-UM, DSP -digital signal processor, Communication processor). The processor of the robot car is the responsible for the control of the motors. It computes a low-level obstacle avoidance algorithm that is modulated by the Bi-i system. The car receives direction and speed commands from the Bi-i that computes the most part of the so-called hybrid strategy based mobile robot control algorithm. The main emphasis is put on the visual processing that is the most computationally intensive part of the control architecture (Fig. 11).

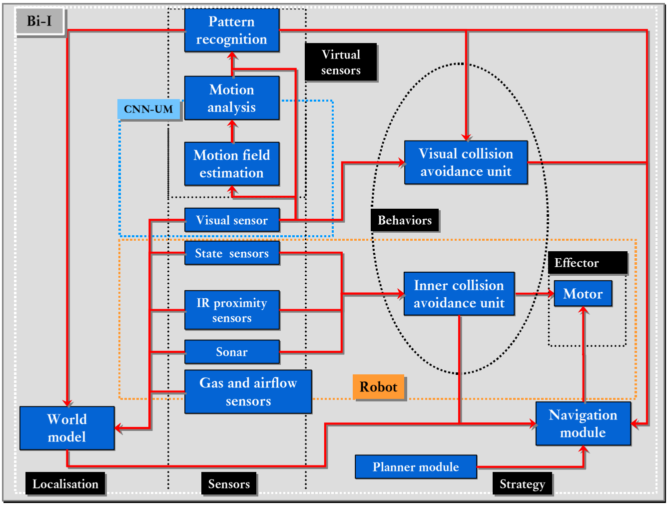

Figure 11: Mobile robot control architecture.

The computationally intensive parts of the image processing algorithms run on the CNN-UM. This includes the topographic preprocessing of images (feature and motion extraction and the fusion of them). The DSP controls the CNN-UM, gathers measurements both from the sensory platform and from the robot car. The car provides – if necessary – IR, sonar measurements and homeostatic sensory information. The DSP computes some part of motion analysis and performs post processing necessary for the categorization of information. The other modules that run on DSP updates the *world model* – a global memory of the space discovered –, determine the goal to be reached *(planner module)* and performs the integration of the different sensory modalities so as to make a suitable input to the *navigation module*, that select the appropriate behavior (movement) to reach the goal.

Figure 12: Mobile robot in the test labyrinth.

The mobile unit is tested in a closed test-world (Fig. 12) in which different object or places should be recognized/found by the fused infrared, ultrasound, gas and visual sensory information.