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Cognitive Computational Models for Intelligent Engineering Systems

Ph.D. Thesis Booklet

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1 Introduction

1.1 Cognitive informatics and its directions

The new results of cognitive sciences together with the emergence of modern tools of high computational capacities lead to the appearance of cognitive informatics (CI), as described on a webpage of the University of California *"a cutting-edge and multidisciplinary research area that tackles the fundamental problems shared by modern informatics, computation, software engineering, AI, cybernetics, cognitive science, neuropsychology and medical science. CI is the transdisciplinary study of cognitive and information sciences, which investigates into the internal information processing mechanisms and processes of the natural intelligence - human brains and minds - and their engineering applications in computing and Information and Communication Technology (ICT) industries"*.

This dissertation does not intend to achieve any results in the research field of classical medical biology, but by considering their approach, it tries to propose models in technical applications of cognitive informatics that are capable of solving complex practical problems.

Concerning the national relevance of the methods of cognitive science, the names of Béla Julesz and Csaba Pléh definitely have to be mentioned. There are also different technical approaches in Hungary such as those dealing with the dynamical behavior[4] and cellular level modeling [13] of neurons, information theoretical questions [1], building on the approach of methods of cognitive sciences. An outstanding example in Hungary, Tamás Roska and his research group should be mentioned. They have achieved excellent results in implementing the retina like CNN analogic computer, with which they have successfully solved several technical problems.

Moore's law has well predicted the exponential growth of computational capacity of silicon based computational tools in the last decades, which inspired the emergence of classical AI. The level of intelligence of such AI systems however did not follow the exponential development of the hardware they were deployed to. By now it should be obvious that even if the complexity of computers is comparable to that of the human brain (at least from the aspect of the number of basic computational units, i.e. transistors and neurons) a computer can not solve many of the problems that are easily solved by basic human intelligence. This difference is even more apparent if we compare the speed of a transistor (range of nanoseconds) and a neuron (range of milliseconds), used as basic computational units. The key of computational capacity of the brain besides the large number of computational units (neurons), lies in the broad interneuronal connections, working simultaneously in a very complex and yet uncovered parallel and recurrent structure. This explains why the efforts of conceiving artificial intelligent systems beyond the limits of transistors have turned towards the approach of neurobiology and cognitive sciences for seeking new directions.

The technical approach to cognitive and biological methods is not a novelty, their relation is in fact characterized by three main directions.

The direction of biology inspired intelligent methods covers the algorithms techniques in the field of artificial intelligence, mathematics and numerical modeling that are based on the neurobiological and cognitive aspects of brain functions [6, 37, 20]. These methods typically use higher order mathematics and perform exhaustive algorithmic calculations, and were designed to suit the underlying mathematical toolbox and run on a Von Neumann type processor.

The direction of biological modeling aggregates the models of informatics, mathematics, information theory and other technical fields, which were conceived with the goal of a deeper understanding of the biological structure or "hardware", and functions of the cerebral cortex [41, 42, 43]. The biological models are made to support or confute theories in biology and cognitive sciences. The field of neurocomputation is closely related to this direction, where the informatical models of neurobiology that are often used to solve problems of distant areas. The goal of this direction could be grasped as the design of the "cognitive hardware".

The direction of cognitive informatical modeling includes models that aim to provide solutions to problems in technical informatics as well as in information and communication technology industries, by considering the approaches and methods of cognitive science. It is not the goal of these models to perfectly copy the structure and characteristics of biological systems, but to resemble in functionality to the cognitive processes according to which they were designed. Cognitive informatics is the methodology of artificial or imitated real cognitive process implemented on tools of informatics. The goal of this area could be summarized as the design of the "cognitive software". It is important to note that according to the potential application of such models their efficient parallel implementation is a basic requirement.

The border between the above fields is quite ambiguous, with many overlapping. The main difference between them is in their goals and their approach to cognitive sciences. My research work presents new results in the field of cognitive informatics, and as such it builds on both neural-networks-like numerical, and other parallel computational tools on the implementation level.

It is well known that medical, biological and brain research areas of the cognitive science mainly deal with anatomical, cellular-, and neurobiological and physiological modeling based on different paradigms of the cerebral cortex. In my research work I consider the above models with the effort of using their approach in cognitive informatical modeling of particular technical problems.

1.2 Cognitive informatical approach to vision

An intelligent system is composed of three main units, responsible for perception of the environment, processing the acquired information and actuation into the environment. There are no sharp borders between the three units, the intelligent behavior can not be limited to the processing unit only. This is why the methods of cognitive science are relevant not only to processing, but also to perception and actuation.

Many brain researchers consider the *"eye as a window to the brain"*, which explains why neurobiological and cognitive research efforts targeting natural intelligence have turned towards vision. Visual information processing is the most important perceptual modality, since the largest amount of information about the environment is gained through our eyes [29].

Consequently a wide range of vision related cognitive research has already been inspired from the aspects of neurobiology [5, 27, 32, 30, 17, 44, 12, 10, 18], cognition [9, 34, 19] and neurocomputation [15, 21]. David Hubel was the first to unveil the structure and functionalities of the primary visual cortex [23] and describe the orientation selectivity. It was later showed by Shevelev that the primary visual cortex is responsible for encoding the seen corners and crossings [38, 39, 40]. Based on the results of cognitive and biological research, many started to deal with the modeling of vision from biological [24] and cognitive aspects [25, 26, 47, 14]. Based on their approach, new vision-models of cognitive informatics have emerged, but their goal was not to imitate the visual cortex on the cellular level, but to apply cognitive functions in solving complicated problems from the field of technical informatics [22, 21, 31, 8, 7, 11, 46, 45, 16, 28, 36, 35]. Most of these models consider the orientation selectivity described by Hubel, but on the implementation level they are very diverse and incompatible.

Beyond the models of cognitive informatics, parallel computational hardware tools have appeared on the analogy of the neural structure of the visual cortex. These tools allowed the fast and parallel execution of simple cognitive models of visual processing. Such tools were the pixel-wise processing units integrated in image sensors [3][2][13] and FPGA based implementations [33].

2 General description of the technical problem

The research areas covered by the methods of cognitive science have significantly broadened and have received more attention in the last few years. Fields in engineering science dealing with high complexity intelligent systems tend to build more often on the results of cognitive science. An example can be the cognitive informatical tools of modern image processing, object recognition and machine vision, designed with the motivation of cognitive science. Consequently, it is an important task to model the processes described by cognitive science, using leading edge computational tools, and to provide a toolbox of cognitive informatics for solving complex engineering problems. The scientific problem in the focus of this dissertation is to provide vision based cognitive informatical models.

3 Goals of the dissertation

Goal 1: Cognitive informatical model of the primary visual cortex

It is well known that many cognitive informatical models are applied in aim of solving problems too hard for a computer, but easy for a human.

The goal of such models besides solving specific tasks is to have similar functional properties to the brain. In constructing such models it seems obvious to consider a functional similarity with the brain also on the level of basic components.

The first step of visual information processing in the primary visual cortex is the simultaneous, parallel extraction of features, which is of great importance from the point of higher level visual information processing, such as object recognition. The cognitive informatical models known from the literature deal with the modeling of this function, but on the conceptual and implementation level they are very different and incompatible.

Based on the scientific literature one can conclude that there is no generally accepted uniform cognitive informatical model for the feature detecting functionality of the primary visual cortex. Also, the known cognitive informatical models do not define operations on the data structures of V1-like models.

Based on the above described, the specific goals of the dissertation were:

- To propose a concept that provides a uniform and general framework for the informatical modeling of cognitive functions.
- To work out a cognitive informatical model within the proposed concept, which implements the major low level feature detection functionalities of the primary visual cortex. It is a further goal of the model to be directly compatible with informatical models implementing higher order cognitive functions, and as such be applicable in solving a wide range of technical problems.
- To achieve a maximal cognitive plausibility according to the scientific literature in neurobiology and cognitive sciences, while keeping its efficiency

in solving technical problems.

- The model should be directly implementable on modern parallel computational tools.

Goal 2: Opto-mechatronical implementation

The functions of the primary visual cortex are of high computational complexity, which explains why high speed computability of related informatical models is a basic requirement for their efficient implementation. The primary visual cortex can perform the modeled functions at very high speeds by virtue of its parallel computational structure and high information connectivity. Such a high connectivity is not available by modern silicon based integrated circuit manufacturing technologies.

In this respect, the goals of the dissertation was to design and implement an opto-mechatronical device that performs the major, computationally complex functions of the primary visual cortex. A basic requirement towards the device was to perform the cognitive functions in a quality comparable to that of the original model, but at a computational cost several orders of magnitudes lower.

Goal 3: Informatical role of optical aberrations

The non-overlapped arrangement of ganglion receptive fields discovered by Packer and Dacey in 2002 is in a conceptual conflict with classical, convolution based linear filtering methods.

Based on this I proposed to solve the following particular problems:

- To investigate the above mentioned conflict and to propose a cognitive informatical model for its solution.
- In the design of the cognitive informatical model I intend to consider the effect of optical aberrations, fluctuations of accommodation and the disjunctive arrangement of ganglion receptive fields.
- My further goal is to implement the model in the form of an experimental hardware-software system, and to prove the solution of the conflict by the means of laboratory experiments.

Goal 4: Application of the proposed model

The proposed cognitive informatical model performs the first step of visual information processing using tools of technical informatics. Based on Goal 1 the model has to be compatible with informatical models implementing higher order cognitive processes with the purpose of solving technical problems, such as image categorization and robot localization.

Based on this I considered the following goals:

- To attach the model to a modern object recognition engine, such that the image primitives describing the objects and necessary for the engine are provided by the proposed model. The so obtained system has to be applicable in solving categorization and recognition tasks.
- Categorization of abstract (hand drawn, wire-line) images using the object recognition system.
- To support the localization system of a mobile robot at the Laboratory of the NTNU by the recognition of surrounding key-objects using the proposed object recognition system.

4 Theses

The results achieved in the dissertation are summarized in four thesis groups. The author's publications where the actual theses groups were published are indicated in square brackets. Other publications of the author related to the dissertation are [P22–39].

Thesis 1: The Visual Feature Array concept [P1–2, 6–15, 19]

I proposed the Visual Feature Array (VFA) concept which provides a uniform framework for informatical models of cognitive functions and the representation of low level perceptual modalities, with a special respect on vision.

Embedded in the VFA concept I conceived the VFA-model, in which I defined and developed simple and complex operations of filtering, lateral and projective cognitive functions of the primary visual cortex, using a finite element orthogonal hyper-grid and SIMD (Single Instruction Multiple Data) operators. as a model of the primary visual cortex. The model builds on modern modeling tools of informatics and transforms cognitive functions into systematical finite element orthogonal grids and Single Instruction Multiple Data operations. The proposed model also uniformly integrates well known methods of the wide range of earlier cognitive solutions.

I validated the efficiency and quality of the proposed cognitive informatical models using the Heath method, and compared the results with those of classical operators (Sobel, Laplace, Canny), according to which I proved that the proposed *cognitive operations are applicable in a broad field of problems of technical informatics.*

Thesis 1.1 *I defined end stopping, Gabor-function based and foveated filtering operations in the VFA model. I showed that these operations implement the monocular functions of Hubel's Ice Cube model, and they map their results in an n-dimensional data array representing simple functional units of the primary visual cortex.*

Thesis 1.2 *I integrated two cognitive processes – contour integration and lateral inhibition – of the primary visual cortex into the VFA model in the form of iterative lateral operations. I determined the parameters for lateral operations at which both the contour integration and the lateral inhibition are implemented by the VFA model in a comparable way and efficiency to human perception. In case of lateral inhibition I showed that the winner-take-all functionality of cognitive functional units is fulfilled, consequently the overlap between layers along the orientation dimension of the VFA model is eliminated.*

Thesis 1.3 *I defined basic and complex projective operations in the VFA model, which represent the information processing between simple and complex cognitive units. I showed that the defined projective operations are efficiently applicable to detect complex image features (crossings and corners).*

Thesis 2: Opto-mechatronical implementation of cognitive informatical operations [P3,4,20]

I designed and implemented an opto-mechatronical hardware device in the form of a laboratory prototype, which performs the Gabor function based filtering and contour integration operations elaborated in Thesis 1.

Thesis 2.1 *I implemented an oriented motion blur filtering operation by an opto-mechatronical system, based on the characteristics of a vibrating mirror and the Sobel operator. Using the subjective techniques of the Heath comparison method I showed that the so obtained filtering operation is equivalent with the union of the Gabor function based filtering and contour integration operations described in Thesis 1.*

Thesis 2.2 *I proved that the computational complexity of the implemented opto-mechatronical system is* $O(x_{max} \times y_{max} \times h(\theta))$*, while that of the Gabor function* *based filtering and contour integration operation is* $O(x_{max} \times y_{max} \times p \times q \times h(\theta))$ *and* $O(x_{max} \times y_{max} \times p \times q \times i \times h(\theta))$ *respectively.*

Thesis 3: Role of optical aberrations and fluctuations of accommodation, and their effect on cognitive informatical operations [P5,17-18,21]

I investigated into the contradiction between the non-overlapped arrangement of ganglion receptive fields published by Packer and Dacey in 2002, and the classical convolution based linear filtering operations widely adapted in informatical solutions.

Thesis 3.1 *I showed that if conventional filtering operators are used on the analogy of the recent discovery, then the information loss exceeds the acceptable level for such problems. With this I pointed out that linear filtering methods have a poor biological relevance.*

Thesis 3.2 *I proved that the information loss can be compensated by optical aberrations and fluctuations of accommodation. Based on the optical model of the eye and the size of foveal receptive fields I showed that the amount of aberrations and fluctuations in the eye is in the magnitude which is necessary for the compensation of such information loss.*

Thesis 3.3 *Based on the above results I elaborated a cognitive informatical model to solve to contradiction while keeping the analogy of the discovery of Packer and Dacey, and including the effect of optical aberrations and the fluctuations of accommodation. This new cognitive informatical model can provide an answer to the question with a cognitive relevance about why the information loss on ganglion receptive fields is undetectable for the brain.*

Comment *Besides the above theses, I also postulated three hypotheses concerning the new discovery, and supported them by laboratory experiments. Concerning these results, we have done studies together with David Hubel's* [1] *research group dealing with cognitive vision.*

The first hypothesis says that the role of eye accommodation during fixation has information theoretical implications.

[1] David H. Hubel along with Roger W. Sperry and Torsten N. Wiesel have been awarded the 1981 Nobel prize in medicine and physiology.

The second hypothesis says that fluctuations of eye accommodation may be responsible for the compensation of information losses caused by the non-overlapped receptive field architecture.

The third hypothesis says that the spot size on the retina is tuned to cause an optimal logical link between retinal receptive fields.

Thesis 4: Application of the VFA concept in intelligent engineering systems [P16]

I used the VFA model to amend the object recognition engine of Alex Berg developed at Berkeley University and published in 2005. I used the VFA model to populate the object epitome library of the engine and to detect characteristic image features necessary for object classification. I applied the obtained system to solve two problems of technical informatics.

Thesis 4.1 *I applied the amended object recognition engine to classify images of abstract (hand-drawn simple wire-line schematic) objects. I showed that this technique is able to classify abstract objects of three categories at success rates of 75-85%, depending on the abstractness of the information. Based on test results I showed that the amended object recognition engine reaches its highest success rate when according to the real cognitive process, the orientation dimensionality is close to the value measured by Hubel, and the Gabor function based filtering operation is applied.*

Thesis 4.2 *I applied the amended object recognition engine to the localization necessary for the navigation of an NTNU-laboratory-based mobile robot seeing four segments of the panoramic view. I showed that the object recognition engine using the VFA-model-based representations of the images recorded by the on-board cameras is able to recognize key objects of the surrounding structured environment at a success rate of 80%, which exceeds the necessary 75% for a successful localization.*

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