Proposal for a Reinhart Koselleck-Project

on

"Building an Artificial Brain for an Autonomous Agent"

1. Personal Data

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2. Topic

An associative cortex model for the classification, evaluation and prediction of situations in an autonomous agent

3. Research Area

1. Computer Science
2. Brain Research, Cognitive Science

4. Intended Start of Project

01.01.2012

5. Summary

An associative memory based simplified cortex model that we have developed shall be improved and used as a "brain" of an autonomous agent that

i) generates a representation of the agent's situation by combining information from different sensory modalities and can thereby

ii) predict and evaluate future situations, depending on the agent's actions and

iii) generate actions and action sequences, i.e. appropriate behavior of the agent.

6. Research plan

We want to develop an artificial "brain" for behavioral control of an autonomous agent. The idea is to combine representations of several sensory modalities as well as motor actions and short action sequences in different "areas" or "modules" to generate a representation of the present situation, including the agent's body and its surrounding, that can be used to predict future development and the consequences of actions. These representations and their combination are developed in a neurobiologically plausible fashion based on a "simplified cortex model" (1), where the areas or modules consist of populations of spiking neurons and sparse activation patterns are used for representation and fixed by auto-associative synaptic connections (2); the areas interact by cortico-cortical connections (3) between these areas, which are formed by hetero-association (4). This framework takes up old ideas about neural representation in terms of cell assemblies (5) and more recent ideas about the more exact temporal relationships among spikes (action potentials) of the individual neurons (synchronicity, (6), temporal order, (7), etc.). There is a solid theoretical background concerning the representational and memory efficiency of such binary associative memories with sparse distributed representations (8), and some of these ideas have already been used in practical applications (9).

This particular approach is not only interesting as a model of the cerebral cortex, but also has a potential impact on a number of issues that are currently discussed in the technical oriented literature on autonomous or cognitive systems or robots in artificial intelligence or artificial neural networks. Some of these issues are listed below.

1. *Coordination and planning of actions and action sequences.* Here the extensive use of associative memories supports memory intensive methods (e.g.reinforcement learning, neural networks, in particular sparse associative memories) vs. computation intensive methods (e.g. inverse cinematics or planning), thereby fostering properties like learnability, flexibility and adaptivity. Perhaps the best-known learning paradigm in this context is reinforcement-learning or adaptive critic design (10). We have used quite similar ideas in the past based on sparse associative memories (11) and we have also worked on the combination of reinforcement learning and neural networks (12). In the more complex system to be built here we anticipate that a trade-off between different objectives (e.g. for food, drink, social contacts, but also new experiences and predictability or safety) becomes relevant. So our models may also contribute to the new developing field of multi-objective reinforcement learning (13).

2. *Information and sensor fusion.* In our architecture we use neural networks and neural associative memories for information fusion from different modalities (14) and recurrent connections for state transition modeling (15). This supports the representation and processing of uncertain information (16) and, in particular, the consideration of situation-dependent temporal variation in the certainty or reliability of different sensors or information sources. The combination of information fusion and sequence processing is a topic of active research in pattern recognition (17).

3. *Learning in recurrent neural networks.* Early work on this topic (18) created the impression that learning in feedforward architectures is practically much more useful than learning in feedback architectures. Some first spectacular results of echo-state networks or reservoir computing (19) showed that it can be useful (again for time-series processing) to combine a fixed recurrent "reservoir" network with a perceptron-like learning in the output neurons. More recently, the optimization or at least refinement of the reservoir by some kind of neural or synaptic plasticity becomes a topic of interest again (20). We have started to work on this topic (21) and want to use it for learning the appropriate sparse representations in higher (non-sensory, non-motor) cortical areas.

4. *Further development of a theory of cell assemblies.* Donald Hebb initiated the idea of a cortical representation of objects in terms of **cell assemblies**, i.e. groups of co-activated neurons that are strongly interconnected by excitatory synapses that had been strengthened by Hebbian synaptic plasticity (i.e. by coincident activation of the two neurons that are connected by the synapses). This classical idea (22) is at the basis of most modern theories of global brain function (e.g. 23). We have elaborated on this idea in terms of the theory of associative memory (24), in particular of auto-association in local recurrent networks (modules) and of bidirectional hetero-association (25) that may occur in cortico-cortical connections between areas or modules. This has led to some predictions concerning the size of assemblies (26) and to a first global cortex model (27). In this enterprise we also created a structured C++-framework for building up a useful inter-modular connectivity structure for very large networks of spiking neurons and running a simulation of this network (28).

5. *The potential functionality of emotions and empathy in autonomous agents.* This can be seen as a problem of human computer interaction, however, more fundamentally, this topic asks for the biological function of emotions and empathy and its behavioral realization in social animals (mammals) and humans. Clearly these properties can be useful for the species, but are they also useful for the individual? I have mentioned these issues and some related ideas in a recent paper (29). Biologically, emotions may be understood as specific sets of tuning parameters for the animal's sensory and motor systems for certain rare situations that are important for survival (fleeing, chasing, fighting, reproduction, etc.). A more psychological version of this idea is advocated by Dörner and his school (30). Socially, this tuning is accompanied by noticeable physiological signs like heavier breathing, higher blood pressure, enhanced locomotory activity, quick shifts of gaze, and the like. These signs can be interpreted as social signals and may even be independently produced in social interactions, perhaps leading to specific gestures and facial expressions in humans. Based on this kind of understanding of emotions, one can also develop a functional theory of empathy. In this context the concept of mirror-neurons (31) has to be mentioned, it is related to the idea that we may use our own emotional system to simulate and thereby predict the development of emotions in others (32). Of course there are also a lot of psychological accounts of emotions, mostly on a more phenomenological level, for example describing emotions in terms of basic emotion categories (33) or emotionally relevant dimensions like valence and arousal (34), or modeling emotions on a cognitive level (35). Mechanisms for emotions and empathy can be implemented by modeling the corresponding cortical areas (and some subcortical nuclei) following the abundant neurophysiological results and some recent modeling approaches (36). It will also be useful to integrate such areas into our cortex model in order to develop a biologically founded model for the (multiple) evaluation signals that are needed for reinforcement learning (37) and similar approaches to sequence generation and planning (see point 1).

6. *Language understanding*. We have demonstrated that our associative-memory-based cortex model can be used for language understanding from speech (38). It may also be useful in language (and speech) production due to the physiological principle called the motor theory of speech perception (39), by which it seems plausible that the same cortical areas can be used both for understanding and for production of language and speech. In connection with emotional understanding and empathy (point 5) this unified cortical approach to language understanding may eventually even be useful for human-computer dialogue systems in the development of companion technology as in our current collaborative research center, SFB-TR 62: "A companion technology for cognitive technical systems" at the universities of Ulm and Magdeburg. We have developed such a system for the understanding of simple command sentences (40) and exchanged our views with neuroscientists (e.g. V. Gallese, G. Rizzolatti, F. Pulvermüller) during and following up on our European project MirrorBot (41). There is again a close link between our approach to

language understanding and ideas on the relation between human language understanding, sign languages, monkey hand and arm movements and social interaction that came up in the discussion of mirror neurons (see point 5) and are probably best explained in the recent articles by Michael Arbib (see 42).

The concrete work we propose to do in order to contribute to all these topics of active research, is simply to extend our current cortex model which consists of a number of cortical modules locally interconnected by auto-associative synaptic connectivity and globally connected by (mostly) bidirectional hetero-associative long-range connections (43). This model has been developed in cooperation with my previous (Rebecca Fay, Zöhre Kara-Kayikci, Andreas Knoblauch, Heiner Markert) and current (David Bouchain, Florian Hauser, Iuliana Varvaruca) PhD students (44). For the extension we can use our own simulator framework and a reasonable spiking neuron model (for example as in 45). The extension essentially comprises the realization and integration of further cortical areas or modules as specified in the workpackages (WPs) below.

In order to imbed this model into an autonomous agent, it will not be necessary to use a physical robot as in our MirrorBot project or in our NeuroBotic laboratory (46), but it may be simpler, cheaper and more flexible to develop a simulation of the agent's environment at a higher level than a detailed physical simulation and of the agent's body that provides the interface to the cortical input (sensory) and output (motor) areas of the cortex model.

The functionality of the associative cortical model depends essentially on the pattern representations in the different areas or modules. For example, for a visual area we have to generate a reasonable visual representation in terms of a group of co-active neurons for each object. Visually similar objects should get similar, i.e. overlapping representations. This can be achieved by representing certain visual features in the activation of single neurons in the visual areas. Similar ideas can be used for other sensory modalities, but also for the higher areas where inputs from several sensory (or motor) areas are combined.

In our institute we have a lot of experience in generating such representations based on artificial neural networks, through our work on pattern recognition and sensor or information fusion (47). I have a particular long-standing interest in visual cortical representations (48) and keep following the experimental literature. In our group Prof. Neumann is active in modeling the visual system (49). We also did some physiologically motivated modeling in the auditory system (50), but we have not yet modeled emotional systems, although we recently did some work on the recognition of human emotions (51). This kind of work is also part of our current collaborative research center (SFB-TR 62).

In the following I give a brief description of the concrete implementation work to be done in terms of **workpackages** (WPs).

WP 1: *Conception, realization and implementation of one or two simulation scenarios for the agent's environment.*
Here we could start from an open-source game-playing environment like (52) or from a simple robot simulator like (53).

WP 2: *Construction of neural control systems (54) that realize basic senso-motoric loops to create a "simulated agent body" that interfaces the somatosensory and motor areas with the simulated environment.*
Recently we have gained some experience with this, both in simulations and with real robots (55). Although we are planning to use a rather high-level simulation of the environment we may need to consider a more fine-graned control for the generation of appropriate representations in the somatosensory and motor areas.

WP 3: *Modeling of the agent's sensory inputs (vision, audition) and design of the corresponding cortical representations (in terms of local assemblies).*
Here we can rely on previous experience in the MirrorBot project and in modeling of the visual and the auditory system including speech (56).

WP 4: *Improvement of the existing associative cortex model and extension by adding and integrating further modules.*
a) realization and integration of a somatosensory area (see WP 2),
b) further development of the existing motor and premotor areas,
c) further development of the existing speech and language areas (see point 6),
d) further development of areas for action planning and sequence learning based on the existing simple planning areas and on value-based actor-critic schemes.

WP 5: *Intrinsic plasticity in recurrent neural networks for the generation or improvement of neural assembly representations in higher cortical areas.*
Higher cortical areas are areas without direct sensory input or motor output. These areas get their input (mostly) from other cortical areas by hetero-associative connections. In our previous implementation we just used sparse random patterns (of co-activated neurons) to represent different items. Now we want to generate patterns which are similar for similar input activation. We can achieve this by activating the higher area by randomly initialized cortico-cortical connections from their input areas and stabilizing these patterns by auto-association (as well as bidirectional hetero-association in the cortico-cortical connections). For this stabilization by local synaptic plasticity we want to try more realistic spike-time dependent mechanisms (57) in addition to simple Hebbian correlation learning. Another interesting possibility is to use an additional "motivational" or "confirmational" signal (probably from the thalamic nucleus corresponding to the cortical area) to stabilize the learned synaptic changes (58). Similar mechanisms are also discussed in the context of reservoir computing (see point 3 above).

WP 6: *Realization of emotional mechanisms and corresponding modules.*
We want to integrate one module (at least) which represents emotional states of the agent (like, for example, the amygdala). There are two reasons for this: First such an area or module can be understood as part of the multi-objective value system in reinforcement learning (see point 1 above) and therefore be useful for learning motor sequences and more complex behaviors (59). Secondly, such an area can be useful or even necessary for an understanding of empathy in relation to the mirror neurons (see point 5 above). In this way our cortical model could be used for a simulation and better understanding of the mirror neuron idea not only with respect to communication and language, but also with respect to emotions and empathy.

WP 7: *Further development of the simulated environment to allow for multiple interacting agents and more complex planning problems.*
This will become necessary for investigating and testing the emotional mechanisms built in WP 6.

Of course, there is already a sufficient amount of work in the main core of the project, i.e. in WP 1 - 5, but once this model is working, it would provide an ideal opportunity to study the very demanding and speculative ideas of Rizzolatti, Arbib and others concerning emotions and empathy. Today it is very hard to predict, how far we will get with the two additional workpackages 6 and 7.

The core working group envisaged for this project consist of myself and two Ph.D. students.

i) One student should focus on the realization and simulation of the basic associative cortical structure, the development and simulation of intrinsic synaptic plasticity mechanisms in the higher areas and (thereby) the realization of state-based representations for behavioral learning in (at least) one of these areas.

ii) The other student should focus on the development of language, language learning, improvements of our current cortical language model and possibly modeling of emotional mechanisms, empathy and social interaction in small groups of autonomous agents.

After getting acquainted and familiarized with our current cortical model and the general state of the art in neural modeling, student (i) can start working on WP 1, 2, and 3. The main work will then be contained in WP 4 and 5. Student (ii) will probably need more time to get familiarized not only with our cortical model, but also with the neurophysiological, psychological, and neuro-linguistical background. This will involve visits to some of the leading experts, both on the experimental and the modeling side (e.g. G. Rizzolatti, P. Dayan, F. Pulvermüller, but also people that are more easily accessable through our SFB, like A. Brechmann, F. Ohl, H. Traue). After that, and of course partially in parallel, work on WP 4 (in cooperation with student (i)) and on WP 6 and 7 can be taken up.

For this kind of project application I am asked to point out the **special nature** of this proposal which may prevent it from being successful in the usual DFG Normalverfahren.

I believe this project is special in its very broad interdisciplinarity between computer science and neuroscience, with respect to both its goals and its methods. For typical reviewers from just one of these two disciplines it is usually hard to be convinced that such a project can achieve a clear direct publishable benefit within the estimated time.

Among computer scientists there is still a common prejudice that neuronal realizations may not be most efficient compared to more conventional approaches. This may indeed often be the case, but there are also many examples of efficient practical solutions that have been found by inspiration from neuroscience, e.g. our work on sparse associative memories (60). Among neuroscientists global brain or cortex models aiming at a large-scale functional or systemic understanding run against the usual scientific method of "downward explanation", i.e. going into the microscopic direction, from neurons down to synapses and from synapses down to channels and transmitter molecules. Another problem is that higher cognitive functions, in particular language, can hardly be studied in most animals. So this kind of work is regarded as extremely speculative, and it is indeed hard to make concrete detailed experimental predictions which follow from such a modeling approach in a reasonable way.

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7. Funds requested

The estimated total cost of the project is 750.000 Euro for 5 years, i.e. 150.000 Euro per year on average. This comprises 2 PhD students (or postdocs), wage level TV-L EG 13W, travel expenses, and means for additional processing power (e.g. cloud computing) if necessary. Of course, the necessary working space and desk-top computers (plus additional central computing opportunities) for the two persons will be provided by the Institute of Neural Information Processing. In addition, there will be costs for some student assistants (about 80.000 Euro for 5 years) and for printing and publication.

We expect relatively high travel expenses for the 3 persons involved, since individual lab visits to selected groups or experts will have to be organized in addition to the usual travel expenses for conferences.

8. Curriculum Vitae / Publications

Curriculum vitae

Date of Birth: June 6, 1949, Hamburg

Education

January 1969: High school diploma (Abitur), Hamburg

April 1974: Mathematics Diploma, University of Tübingen

July 1975: Ph.D. in Mathematics, University of Tübingen

January 1980: Teaching Qualification (Habilitation), University of Tübingen

Scientific Positions

October 1975 until April 1988:
Scientist at the Max Planck Institute of Biological Cybernetics, Tübingen

January 1981 until December 1986:
Heisenberg-fellow

October 1983 until September 1984:
Fellow at the Institute for Advanced Studies, Berlin

April 1987 until October 1987:
Research professor, Technical University of Darmstadt

May 1988 until September 1991:
Professor of theoretical brain research, Vogt-Institute for Brain Research, University of Düsseldorf

since October 1991:
Director of the Institute of Neural Information Processing, University of Ulm

January 1997 until June 2000:
Chairman of the Collaborative Research Center "Integration of Symbolic and Subsymbolic Information Processing in Adaptive Sensory Motor Systems" (SFB 527)

October 2000 until October 2002:
Dean of the Faculty of Computer Science, University of Ulm

Awards

November 1985:
"Forschungspreis Technische Kommunikation 1985" of the SEL-foundation for technical and commercial communication research

November 1998:
"Merckle-Forschungspreis 1998" of the University of Ulm

Various Commitments

- Member of the managing board of the Humboldt Studienzentrums of Ulm University
- Member of the scientific advisory board of the Zentrum für Kognitionswissenschaften (ZKW), Bremen University
- Referee for the Innovationskolleg Theoretische Biologie, Humboldt-University, Berlin
- Referee for several scientific foundations (e.g. DFG, BMBF, Volkswagenstiftung, Wissenschaftsrat, German Israeli Foundation, DAAD, Studienstiftung des Deutschen Volkes, The Israel Science Foundation, Boehringer Ingelheim Stiftung, Human Frontier Science Program, FWF Wissenschaftsfonds, Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung, Alexander-von Humboldt-Stiftung)
- Co-Editor of several journals (e.g. Neural Networks, Neurocomputing)
- Reviewer for several journals (e.g. Neural Computation, Biological Cybernetics, Neural Computing and Applications, Frontiers in Computational Neuroscience, Cognitive Processing, Physical Review E, Cerebral Cortex, IEEE Transactions on Systems Man and Cybernetics, PLoS Biology)
- Member of the program committee of several conferences (e.g. ICANN, IJCNN, ISNN)

Current Research Topics

Artificial neural networks, associative memory, biological brain modeling, Hebbian cell assemblies, information theory, pattern recognition.

Most important publications   (all a)

Palm, G., Poggio, T.: The Volterra Representation and the Wiener Expansion: Validity and Pitfalls. SIAM J. Appl. Math. 33, 195-216, 1977

Palm, G.: Computing with Neural Networks. Science 235, 1227-1228, 1987

Schwenker, F., Sommer, F.T., Palm, G.: Iterative Retrieval of Sparsely Coded Associative Memory Patterns. Neural Networks, 9(3), 445-455, 1996

Schwenker, F., Kestler, H.A., Palm, G.: Three Learning Phases for Radial-Basis-Function Networks. Neural Networks, 14(4-5), 439-458, 2001

Markert, H., Knoblauch, A., Palm, G.: Modelling of syntactical processing in the cortex. BioSystems 89, 300-315, 2007

Topic related publications   (all a)

G. Palm: On Associative Memory. Biol. Cybernetics 36, 19-31, 1980

Palm, G.: Neural Assemblies. An Alternative Approach to Artificial Intelligence. Springer, Berlin, Heidelberg, New York, 1982

Palm, G.: On the Information Storage Capacity of Local Learning Rules. Neural Computation 4, 703-711, 1992

Palm, G., Sommer, F,T.: Information Capacity in Recurrent McCulloch-Pitts Networks with Sparsely Coded Memory States. Network 3, 177-186, 1992

Knoblauch, A., Palm, G.: Pattern Separation and Synchronization in Spiking Associative Memories and Visual Areas. Neural Networks, 14, 763-780, 2001

Knoblauch, A., Palm, G.: Scene Segmentation by Spike Synchronization in Reciprocally Connected Visual Areas. I. Local Effects of Cortical Feedback. Biological Cybernetics, 87, 151-167, 2002

Markert, H., Kaufmann, U., Kara Kayikci, Z., Palm, G.: Neural associative memories for the integration of language, vision and action in an autonomous agent. Neural Networks, 22, 134-143, 2009

Wennekers, Th., Palm, G.: Syntactic sequencing in Hebbian cell assemblies. Cogn Neuodyn, 3, 4, 429-441, 2009. DOI 10.1007/s11571-009-9095-z

Abdel Hady, M., Schwenker, F., Palm, G.: Semi-supervised learning for tree-structured ensembles of RBF networks with Co-Training. Neural Networks 23(4), 497-509, 2010

Knoblauch, A., Palm, G., Sommer, F.T.: Memory Capacities for Synaptic and Structural Plasticity. Neural Computation 22, 2, 289-341, 2010

9. Sonstige Angaben

Untersuchungen an Menschen, Tierversuche, gentechnische Experimente oder ähnliches sind nicht vorgesehen.

Erklärungen

- Ich verpflichte mich, mit der Einreichung des Antrags auf Bewilligung eines Reinhart Koselleck-Projekts bei der DFG die Regeln guter wissenschaftlicher Praxis einzuhalten.
- Ich habe bei der Antragstellung die Regelungen zu den Publikationsverzeichnissen (III.8) und zum Literaturverzeichnis (III.6) beachtet.
- Ich werde den Vertrauensdozenten der Universität Ulm, Herrn Prof. Bossert, von der Antragsstellung unterrichten.

Ulm, 27.07.2011   Prof. Dr. Günther Palm