IEEE CIS

AMD Newsletter

Robotics
Psychology
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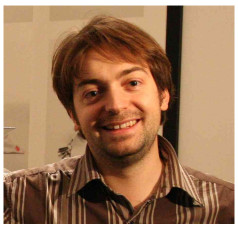
The Newsletter of the Autonomous Mental Development Technical Committee

VOLUME 8, NUMBER 2 ISSN 1550-1914 October 2011

Editorial



As reported by Minoru Asada as well as by Angelo Cangelosi and Jochen Triesch, the first edition of the joint IEEE ICDL-Epirob in Frankfurt was a real success, gathering many of the usual attendees, as well as newcomers, of the two conferences. It was unanimously decided that the organization of such a joint event should be reproduced next year. Zhengyou Zhang, editor in chief of IEEE TAMD, also just announced that IEEE TAMD was selected for coverage in Thomson Reuter's products and services, beginning with V.1 (1) 2009 (the very first issue). This includes Science Citation Index Expanded, Journal Citation Reports/Science Edition and Neuroscience Citation Index.

This month, the newsletter presents a stimulating dialog exploring the frontiers of developmental and evolutionary robotics, within the so-called evo-devo approach which might become more and more central in our research in the future. Yaochu Jin and Yan Meng asked a question about the interaction between phylogeny, ontogeny and epigenesis, as well as about the interaction between morphological and mental development: "Evolutionary Developmental Robotics – The Next Step to Go?". Answers by Josh Bongard, Daniel Polani, Stéphane Doncieux, Fumiya Iida, Nicolas Bredeche, Jean-Marc Montanier, Simon Carrignon, and Gunnar Tufte show that we are just at the beginning of novel far-reaching conceptual and technological projects, exploring questions such as how development can be the articulation between evolution and learning or how new materials can allow us to explore growing bodies and their impact on cognitive development.

Then, a new dialog is proposed by Katharina Rohlfing and Britta Wrede, about the mutual influence that research on developmental robotics and human-robot interaction should have on each other: "What novel scientific and technological questions developmental robotics bring to HRI? – Are we ready for a loop?". Those of you interested in reacting are welcome to submit a response (contact pierre-yves.oudeyer@inria.fr) by March 1st, 2012. The length of each response must be between 300 and 500 words (including references).

— Pierre-Yves Oudeyer, INRIA, Editor

Message from the Chair of IEEE AMD Technical Committee

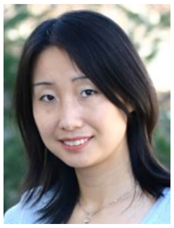
First of all, I am happy to inform you that the First Joint IEEE International Conference on Development and Learning and on Epigenetic Robotics held on August 24^{th}-27th, Frankfurt, Germany, was extremely successful. Congratulations to both Angelo Cangelosi and Jochen Triesch who contributed to the conference as co-general chairs, and to all other committee members who worked very hard. I appreciated all participants as well as all invited speakers for their stimulating talks. The second edition of the Joint IEEE ICDL-Epirob conference will be held in San Diego, US on Nov 7-9 2012. I encourage all committee members and any volunteers to propose activities such as workshops and tutorials in conjunction with this conference in 2012 and after.

Secondly, thank you for your heart-warming messages from all around the world to Japan after the earthquake. Many people including scientists and researchers have been working very hard to settle Fukushima nuclear plants accidents, and also to restore Tohoku area. I believe Japan will recover in a couple of years, and personally hope to have our third ICDL-Epirob conference in Osaka in 2013 as a symbol of the restoration. Thank you in advance for your cooperation.

— Minoru Asada, Chair of the AMD TC

Dialog Column

Evolutionary Developmental Robotics – The Next Step to Go?

Yaochu Jin, Department of Computing, University of Surrey, UK
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Developmental robotics, commonly known as *epigenetic robotics* (Metta & Berthouze, 2006) is mainly concerned with modelling the postnatal development of cognitive behaviors in living systems, such as language, emotion, curiosity, anticipation, and social skills. Over the past decade, epigenetic robotics has enjoyed great success and achieved significant progress in understanding mental development.

Despite its significant success, the current approaches to developmental robotics can be challenged both from ontogenetic and phylogenetic point of views. First, development of biological organisms consists of both physical and mental development. Thus, developmental robotics that concentrates on mental development is incomplete. Ontogenetically, mental development is based on and closely coupled with physical development of an organism, including development of both the body plan and the nervous systems. For example, new findings in neuroscience reveal that early development of nervous systems are also considerably driven by neural activity (Spitzer, 2006), suggesting that activity-dependent and activity-independent development of neural networks cannot be separated. *Morphogenetic robotics* (Jin & Meng, 2011), inspired from biological morphogenesis, has recently been proposed as a new research area that deals with the physical development of robotic systems, thus complementing epigenetic robotics to provide a full picture of developmental robotics.

Second, biological evidence suggests that autonomous mental development is driven by intrinsic motivational systems (Deci & Ryan, 1985), among others. Such findings have triggered one key research area in epigenetic robotics that studies the role of intrinsic motivation systems in mental development (Oudeyer et al., 2007). Typically, an intrinsic motivation system is pre-defined in the robotic system. However, autonomous mental development in living system was not *hard-wired* from scratch, rather has gradually shaped by a brain-body co-evolution embedded in a changing environment.

The introduction of morphogenetic robotics addresses the first challenge in developmental robotics to a certain extent by integrating mental and physical development. Nevertheless, the evolutionary origin that accounts for both physical and mental development is still missing. In addition, in morphogenetic robotics, the gene regulatory network that governs the neural and morphological development cannot be designed manually. Thus, the role of *evolution* becomes increasingly important in studying physical and mental development in robotics systems.

Evolutionary robotics (Nolfi & Floreano, 2006) applies evolutionary algorithms to the automatic design of neural controllers for autonomous robots. Unfortunately, the role of development has largely been neglected. We argue that integrating research on developmental (including epigenetic and morphogenetic) robotics and evolutionary robotics is indispensable. Developmental plasticity can not only bias evolution, but also enhance evolvability by maintaining genetic diversity in changing environments and resolving the robustness-variability trade-off. For example, it has been shown most recently that an evolutionary perspective on autonomous learning might bring about new insight into understanding the driving force behind mental development (Singh et al., 2010).

The past decade has witnessed rapid technical and theoretical advances in evolutionary developmental biology (Müller, 2007) (often known as evo-devo) understanding molecular and cellular mechanisms that control the biological morphogenesis. Evolutionary developmental biology has also helped us gain deep insight into human cognitive development, resulting in a new discipline known as evolutionary developmental psychology (Griffiths, 2007). As the role of genes is too important to be neglected in cognitive development (Ramus, 2006), we believe that it is high time to bring together evolutionary robotics and developmental robotics to form a new discipline *evolutionary developmental robotics* (evo-devo-robo).

Going from epigenetic robotics to evolutionary developmental robotics is not straightforward. A few important questions remain to be answered. For example, how to realize physical development in robotic systems? Must we use hardware (real robotic system) for research in evo-devo-robo? Many researchers in evolutionary robotics are convinced that a real robotic system must be used, which, unfortunately might have been the biggest hurdle that has prevented this area from further progressing. Another question is, given two different time scales in evolution and development, how much resources should be

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devoted to evolution and how much to development? How to provide an environment, real or simulated, that is complex enough to enable the system to evolve behaviors of cognitive significance? Thus, our proposal to move from epigenetic robotics towards evo-devo-robo may have raised more questions than answers in the study of autonomous mental development.

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Morphogenetic Robotics Recapitulates Artificial Ontogeny

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Jin and Meng state that "Morphogenetic robotics (Jin & Meng, 2011), inspired from biological morphogenesis, has recently been proposed as a new research area that deals with the physical development of robotic systems...". I applaud the spirit of the authors' aim, but take issue with the statement that this is a 'new research area'. As early as 2001 (Bongard & Pfeifer, 2001; Bongard, 2002; Bongard & Pfeifer, 2003), my colleagues and I introduced a methodology by which robots are grown from simulated genetic regulatory networks (GRNs) and artificial evolution acts on these GRNs to evolve increasingly capable robots, an approach we termed Artificial Ontogeny. This work led to the evolution of GRNs that guided the 'physical development of robotic systems', thus realizing the concept of 'evo-devo-robo' as proposed by Jin & Meng.

Of course, all of us in academia stand on the shoulders of those who came before us. My own work was inspired by that of Eggenberger (Eggenerger, 1996; Eggenberger, 1997) who demonstrated the evolution of GRNs that direct the growth of three-dimensional shapes. Eggenberger demonstrated evolved shapes with increasingly interesting topologies, so one might term his approach 'evo-devo-topo'.

Jin and Meng argue that by incorporating evo-devo into robotics, we may be able to harness the awesome creative potential of the evolution of development. Recently I have shown why this is so. In (Bongard, 2011) I demonstrated that by evolving populations of robots that develop from an infant legless form into an adult legged form — and if, during evolution, this infant form is gradually lost — we can evolve legged locomotion much more rapidly compared to a similar approach that only acts on robots that maintain the fixed legged form.

In this spirit, I encourage the authors to pursue their concept of morphogenetic robotics and endeavor to show not only that it is possible to incorporate evo-devo into robotics, but also why we might wish to do so.

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Development: The Missing Link between Evolution and Learning

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The difficulty in creating intelligent robots contrasts with the comparative "ease" with which biological evolution produces intelligent organisms: one feels that something important is being overlooked in robotics. A core assumption used is to adopt the platonic view that intelligent behaviour is anchored in abstract concepts which act top-down onto the world over which they (p)reside. However, this perspective has increasingly given way to the *embodiment*-based perspective (Brooks, 1991; Pfeifer & Bongard, 2007).

The latter considers brain and environment as tightly linked via the agent's sensorimotor interface with subtle structural matches between the physical world and the agent's internal stimuli which are not merely a naive translation of brain signals into bodily action. The right sensorimotor dynamics can significantly offload cognitive burden onto the environment (Paul, 2006), and this can be quantified using information theory (Berger, 2003; Polani, 2011), suggesting an advantage for organisms with a well-adapted embodiment, since the cognitive burden is metabolically expensive (Laughlin, 2001).

However, an evolutionary process driven by variation and selection only is bound to be very slow. Furthermore, the capacity of the DNA is not sufficient to encode all necessary fine-tunings that a grown organism requires. Thus, part of the information necessary to structure and to adjust the grown organism's body and behaviour must be provided by physics and the environment during the lifetime of the organism.

Conventional learning does this to some degree. However, the importance of translation of physical stimuli into optimally matched neural signals highlights the importance of an intermediary level between slow evolution and fast learning: *development*. For instance, development can take advantage of structural knowledge depending on the agent's body layout, ahead of any additional knowledge of the precise spatiotemporal structure of sensory stimuli (Philipona et al., 2004; Olsson et al., 2006; Modayil, 2010). It also suggests that an intermediate developmental level is instrumental to bridge the gap between long-term evolution and short-term learning, both in biology and robotics.

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It's time for the Development of Evolutionary Robotics and the Evolution of Developmental Robotics

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While Evolutionary Robotics remained for a long time limited to the design of simple reactive behaviors, new methods, like the novelty search (Lehman & Stanley, 2010) or the behavioral diversity (Mouret & Doncieux, 2011) allowed to solve more complex problems without the recourse to fitness shaping or any kind of decomposition. Such work has proved, for instance, that even a direct encoding, i.e. with no development at all, can generate quite complex sequential behaviors with a straightforward fitness function (Mouret & Doncieux, 2011). These methods open new perspectives to an evo-devo-robo approach: by limiting the risks of premature convergence towards too simple creatures, the behavioral diversity approach may facilitate the evolution of a developmental scheme, and the exploration ability of a novelty search approach may help, for instance, identifying the most salient organisms morphologies that a particular development scheme could generate.

The successes of an encoding without development does not allow to conclude that development is not useful, just that it was probably not the cause of current ER limitations, or at least not the most important one. The advantages of defining encodings that allow the evolution of structures with regularities like symmetries, repetitions, and patterns in connection schemes (Stanley et al., 2009; Mouret et al., 2010) have recently shown the potential gains of such developmental schemes in terms of scalability or generalization ability. Likewise, the importance of both phylogenetic and ontogenetic body plan changes for ER has also been recently highlighted (Bongard, 2011). More generally, the importance of development in the context of the evolution of complex systems appears in the increasing audience of the GDS track (Generative and Developmental Systems) at the GECCO conference, which is now one of the most active community to which ER is related.

Recent discoveries in the ER field opens then new perspectives that may benefit the developmental robotics field. Likewise, the increasing importance of development within the ER community shows that it seems to be time to create or renew the dialog between the fields of Evolutionary Robotics and Developmental Robotics, and create an Evo-Devo-Robo community.

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Towards Autonomous Robotic Growth

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Self-organization is one of the most important design principles of biological systems, which created cells, muscles, bones, blood, neural circuitry, sensors, other organs, families, communities, and the entire eco-system on the planet. For our systematic analysis and comprehensive understanding of the dynamics in such a large-scale complex system over an extended period of time, it is necessary to articulate the dynamics into different time scales. Obviously one of the most representative examples of this kind is the evolutionary, developmental, and here-and-now time scales if we talk about human (or animal) intelligence (Pfeifer et al., 2007).

A key concept that bridges over these three timescales is "growth processes" that play important roles in biological systems: animals are born small and adaptively enlarge body structures, strengthen and heal vulnerable body components (e.g. reinforcement of muscles and bones), and extend and replace old structures such as nails, hairs, skin, and teeth, for example (Vogel, 2003; Iida & Laschi, 2011). Sensory motor apparatus as well as associated "computational units" are simultaneously growing along with the body structures, in which a number of important scientific questions remain unexplored.

To make our robots autonomously grow, the plastic changes of morphology is, among others, one of the most significant challenges in robotics research, which has been previously investigated in the context of reconfigurable robots. Typically a reconfigurable robot consists of a number of smaller modules, and each module is capable of autonomously connecting to and disconnecting from each other (Hara & Pfeifer, 2003; Yim et al., 2007). The connection mechanisms generally employ mechanical grippers or electromagnetic adhesion, and with these mechanisms, a reconfigurable robot is able to change its shape from a snake-like locomotion robot to a legged robot, for example. The main lesson that we learned from the studies of reconfigurable robots is that modularity and connectivity are the key components for autonomous plastic changes of robot morphologies: when a robot consists of small-sized modules which are capable of flexibly connecting and disconnecting to each other, it is able to perform considerably more variations of tasks.

Biological systems take advantage of similar mechanisms for their growth processes: animals' body structures consist of many cells and they are able to flexibly connect to each other. Compared to biological cells, however, our reconfigurable robots have only very basic capabilities of autonomous morphing, and there are many questions to be tackled. For example, we still do not know how we can build more flexible connection mechanisms in a module such that each cell could connect to many other modules. How can these modules vary their mechanical properties (more elastic, more stiff, or softer)? How can they self-repair? How can they replicate themselves for physical growth?

From this perspective, recent technical progress suggested a few novel approaches that could potentially contribute to these challenges in the reconfigurable robot research. For example, the exploration of unconventional materials has led to several adhesion mechanisms such as a universal gripper based on granular materials, electro adhesives, and chemical adhesives (Brown et al., 2010; Iida et al., 2012). The use of Hot Melt Adhesive materials, in particular, has shown its capability to attach to many different materials while maintaining very strong connection forces (Oswald & Iida, 2011). We expect that these investigations on new connectivity and adhesion mechanisms would eventually scale up the reconfigurable robot research to more general solutions for autonomous robotic morphing and growth.

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Evolution of Development - The Next Step to Go?

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I would like to draw attention toward two issues: a co-evolution issue and comments related to the possibility of plasticity and growth of complexity (McMullin, 2001).

Jin and Meng state "autonomous mental development in living system was not hard-wired from scratch, rather has gradually shaped by a brain-body co-evolution embedded in a changing environment". I would like to comment on the co-evolutionary aspect. As argued by Jin and Meng, the resulting organism is at any point in evolutionary time a product of brain-body-environment co-evolution. However, if development is included, i.e. Evo-Devo, there is another candidate that co-evolves. The evolution of the developmental processes itself. As such, one of the key missing elements in artificial developmental systems is the lack of "evolution of development". That is, the developmental process, i.e. genotype-phenotype mapping, is a product of evolutionary history in a changing environment instead of a predefined developmental model (mapping). For EvoDevo-robotics this implies that the developmental process can change and adapt to the environment and thereby govern the development of brain and body. Such an approach would move the system further away from a hard-wired mental and body constrained model.

My second comment relates to the problem of how to realize physical development in robotic systems as pointed out by Jin and Meng. If one assumes that real robotic systems (hardware) must be used, I see two problems for the brain-body evo-devo approach: a simpler (brain) and a more complex (body) problem. Brain development can be approached by computational structures that are capable of expressing computation from the first cell. Such computational structures include Cellular Automata and Artificial Neural Networks. That is, the developing "brain" is capable of showing activities as it "grows" and "change". This is rather straightforward to achieve in a simulator or real hardware. For the body, the difficulty is much more complicated. There is a need for a truly developing body that can grow and change. As artifacts do not have the possibility to create extra mass out of environmental substances I would guess that developmental bodies fits best within simulators.

Furthermore, a question that is related to both development of brain, body and the previous addressed issue of evolution of development is the emergence of sensors and actuators (Cariani, 1993). In an Evo-Devo system, the body and the brain grow in complexity. Growth in complexity may here refer to an increased number of inputs and/or outputs as well as to the brain's handling of the increased information flow, and naturally the influence of the interacting body.

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Evolutionary Adaptation of a Population of Robots: Benefits and Issues of the Evo-Devo Approach

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Within twenty years, Evolutionary Robotics as a field has changed in many ways. Recent publications advocate from already existing connections, even if limited, with issues addressed in the field of Developmental Robotics. These works may be broadly considered at the cellular level (e.g. compact and evolvable representations undergoing an artificial ontogenic process (Tyrrell & Jin, 2011; GECCO, 2007)) and organism level (e.g. adding an incentive for behaviour novelty and curiosity in the selection pressure (Lehman & Stanley, 2011; Delarboulas et al., 2010)). Current interest is both motivated by the promises it may hold regarding addressing scientific deadlocks (scalability and robustness issues) as well as recent advances in the field (Doncieux et al., 2011). Therefore, we do agree with Yaochu Jin and Yan Meng's proposal to strengthen the link between the evolutionary and developmental robotics communities, would it be at existing conferences (GECCO, Epirob, etc.) or through dedicated workshops.

Our own motivation comes from our current work on evolutionary adaptation of a population of robotic agents (Bredeche et al., 2011): we focus on the design of environment-driven self-adaptive distributed algorithms to enable survival at the level of a population of independent robotic units. The population is limited in size, and hardware implementation within real robots is targeted. In this scope, we focus on various aspects of evolutionary dynamics such as emergence of consensus, evolution of cooperative and/or altruistic behaviours, group specialisation and speciation, etc. Thus, we share the core motivation regarding the design of autonomous self-adaptive robots with at least part of the Developmental Robotics community, even though we focus on the population level rather than the individual level.

In this context, an evo-devo approach may both bring benefits and raise new questions. Firstly, the equilibrium between what can be captured at the level of the evolution and what can (or must) be left to development may lead to more compact genotypic representations, developing into more robust and scalable phenotypes, possibly endowed with life-long plastic properties. Then, the interaction between phenotypic plasticity and evolutionary adaptation is expected to raise many questions: How does this interaction impact the fitness landscape? What is the effect of the evolutionary path on the structure of the ontogenetic process? What can be canalised into the evolutionary process? What is the nature of environmental feedback? As a matter of fact, each of these questions requires a two-step answer as we should not only understand the underlying mechanisms, but also be able to transfer and integrate this knowledge into the design process, which is not a concern in other related domains such as Evolutionary Biology or Artificial Life.

To end this short reply, we would like to address the concern about methodology raised by Yaochu Jin and Yan Meng. There is indeed a true challenge of simultaneously ensuring that the working technical hypotheses are respected (which is easier with real robots) and performing an extensive experimental study (possible only with simplified setups due to the computational cost of evolutionary algorithms). Our own experience has driven us to consider a kind of multi-level experimental approach, ranging from full-fledged hardware robotic experiments to realistic robotic simulation and over-simplified agent-based modelling simulation. We advocate for switching from one level of implementation to the other on a relatively short-term basis, and considering real-world implementation only to challenge results obtained in simulation. From our own experience in large-scale robotic projects (e.g. Symbrion), such a trade-off proved to be efficient so far in order to get significant results in a reasonable amount of time, validating only the most relevant results on real robots. Thus, we expect to retain both the benefits of real world validation and in-depth scientific understanding while paying a lower price with regards to the hardware implementation effort.

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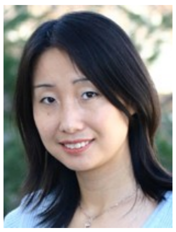
Reply and Summary:
Evolutionary Developmental Robotics – The Next Step to Go?

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We are grateful to all the authors for their in-depth and valuable comments on evolutionary developmental robotics (evo-devo-robo). We are pleased that Mr Bongard encouraged us to conduct further research on morphogenetic robotics (Jin & Meng, 2011) and appreciated our efforts to promote the evo-devo approach to robotics. We feel extremely excited that the hypothesis we put forward in our dialog that "… developmental plasticity can not only bias evolution, but also enhance evolvability …" has been verified to a certain degree in Bongard's recent work (Bongard, 2011), where it was shown that development in morphology can accelerate the evolution of robust locomotive behavior. Bongard's work clearly indicates that introducing evo-devo into robotics could provide us a new key to understanding natural intelligence in robotic systems. On the other hand, we would also like to clarify that we are not claiming that we were the first to study physical development of robotic systems under the governance of a gene regulatory network (GRN). As Bongard stated, research on artificial development in computational system (also known as artificial ontogeny) has been started almost a decade ago, mainly in the research area of artificial life. Despite this, morphological development has largely been neglected in developmental robotics (Lungarella et al., 2003). The main motivation of (Jin & Meng, 2011) was to promote the idea of studying morphological development in robotics together with cognitive development, realizing a complete picture of developmental robotics. As a consequence, morphogenetic robotics can include morphogenetic self-organization of swarm robots (Guo et al., 2011), morphogenetic self-reconfiguration of modular robots (Meng et al., 2011c), neural development (Meng et al., 2011) as well as the coupling of morphological and neural development (Jin et al., 2009, Schramm et al., 2009).

We are happy that Bredeche and his colleagues agreed that it is high time that evolutionary robotics and developmental robotics be closely integrated. Meanwhile, they indicated that the evo-devo approach to robotics may rely on both hardware and simulation, to be more specific, a multi-level experimental approach. Whereas Bredeche et al. agree that evo-devo is potentially a beneficial approach, they also raised a few very intriguing questions, mainly on how to allocate efforts devoted to evolution, learning and development and how these issues can be related to robotics. We do not have an answer to all these questions, but some of our work may have provided insight into these issues. For example, findings in (Paenke et al., 2009) suggest that evolutionary adaptation and phenotypic plasticity together can offer unique advantages in dynamic environments, and that for given dynamics of a changing environment, evolution is able to find the optimal distribution between evolutionary adaptation and lifetime plasticity. In (Schramm et al., 2009) it has been found that given a developmental plasticity in body plan, the evolved controller is optimized for the resulting morphology. On the other hand, it has been shown that evolution is able to find an optimal distribution of workload between body and controller (Jones et al., 2010). Needless to say, interaction between evolution, learning and development and its influence on cognitive and morphological development are a very interesting topic in evo-devo-robo.

We appreciate that Doncieux endorsed our idea of fostering an evo-devo-robo community by strengthening the dialog between evolutionary robotics and developmental robotics researchers. It is very interesting to notice that by introducing diversity in selection (Lehman & Stanley, 2010) and behaviors (Mouret & Doncieux, 2011), complex behaviors can be evolved without development. We fully agree, however, that success in evolution without development can by no means lead to the conclusion that development can be left out in understanding the evolutionary shaping of highly intelligent systems such as human beings.

Dialog Column

Most recent findings in brain science (Lebel & Beaulieu, 2011) have revealed that curiosity and other behavioral diversities may be most likely the result of brain rewiring that continues from childhood into adulthood. In other words, novelty search and diverse behaviors are essentially an abstraction of development.

Iida argues that self-organization of a large-scale complex system (e.g., self-reconfigurable robots) over an extended period of time requires articulating the dynamics into different timescales, such as evolutionary, developmental, and here-and-now timescales, on which we fully agree and consider it a major challenge in evo-devo-robo. Iida also notes the analogy between self-organization of biological cells and reconfigurable robots, and raised a few questions on how to apply the biological principles to robotic systems. We have developed two different reconfiguration robots, called Cross-Cube (Meng et al, 2011c) and Cross-Ball (Meng et al., 2011b), where robot modules can self-organize the morphology of robots to adapt to dynamic environments using a hierarchical GRN. We also agree that the modularity and connectivity are the key components for self-organization of reconfigurable robots, which may be resolved by exploiting unconventional materials. We believe that such soft robots with novel materials will definitely provide us with robotic platforms for future "evo-devo-robo" systems.

Although Polani did not directly comment on our proposal of creating an evo-devo-robo research field, his remarks on the important role of development, which is considered to be an intermediary level of adaptation between evolution, a long-time scale adaptation mechanism, and learning, a short time-scale adaptation, clearly confirm the need to adopt the evo-devo approach for understanding intelligence. But most importantly, Polani pointed out a trick used by nature in evolving complex systems: many environmental influences, physical or chemical, can be used for free and need not to be encoded in the DNA. The key question is how nature can canalize and thus reuse such environmental constraints without explicitly encoding them in the DNA. This is exactly where developmental plasticity can play its role. His recent work (Polani, 2011) showed that cognitive burden can be offloaded to the environment. Our recent work (Meng et al., 2011) also demonstrates that developmental plasticity in neural networks can offer an efficient representation of temporal information without explicitly encoding it.

We agree on Tufte's two valuable comments on evo-devo-robo. His first comment reiterates that the developmental process (i.e., genotype-phenotype mapping) results from the co-evolution of brain, body and environment, instead of resulting from a predefined mapping. His second comment relates to the physical realization of brain and body development in robotic systems. Tufte suggests that brain development might be relatively straightforward using computational models such as cellular automata, which can be implemented physically. This is true in a sense, but hardware implementation might become nontrivial too when embedded in morphological development, as what happens in nature.

To summarize, we are very much delighted that all authors agree with us that development is a key element in understanding natural intelligence in robotic systems, thereby explicitly or implicitly confirming our suggestion that evo-devo-robo would be the next step to go for researchers in the evolutionary and developmental robotics communities. We may start by organizing dedicated workshops at established conferences such as CEC, GECCO, ICDL/Epirob, or ICRA. We look forward to working with colleagues interested in further promoting evo-devo-robo, a new and exciting research area in robotics and cognitive science.

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Dialog Initiation

What Novel Scientific and Technological Questions Developmental Robotics Bring to HRI? Are we Ready for a Loop?


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The notion of embodied systems that enable multi-modal interaction and thus facilitate learning grounded in sensorimotor experience is a current overarching paradigm in robotics. However, we argue that taking a developmental stance should take us beyond active but self-directed cognition (Gelman, 2009); developmental robotics should provide us with insights into the advantages of social learning. Thus, it should be questioned how systems can take advantages of the input and incremental interaction with the social and physical environment. Only then we will find new dimensions enabling learning processes on robots that help to overcome current limitations of generalization. However, we suspect that our current methods – accessing children's development as well as designing learning systems – hinder us asking the right questions.

In human developmental research, the view of active cognition (Gelman, 2009) is supplemented by a view focusing on specifically designed input and the fact that children's minds allow taking advantage of it (Frith & Frith, 2011). Research (Zukow-Goldring, 1996; Gogate et al., 2000; Brand & Tapscott, 2007, Rohlfing et al., 2006) persuasively shows that cognition is not only self-directed but also distributed "over a system of people and objects within an environment" (Rohlfing et al., 2006, p. 97). In this system, crucial learning information is ostensive (Csibra & Gergely, 2009) and reduced; we argue that robotic systems that are sensitive towards such input benefit from this specifically placed reduced information. We have implemented a first approach towards such a tutor spotter suggesting that it can induce tutoring behavior by users (Lohan, 2011).

However, research on human infants has shown that effective learning requires more than just providing social input. The social information has to be flexible as it should be co-constructed (Colins & Marková, 1999) online and contingent with the child's feedback (e.g. Markova & Legerstee, 2006). Our own research contributes to the argument that it is not only the input but rather the interplay between the input and the feedback of the participants that enables the learner to take advantage of tutoring: in (Pitsch et al., 2009; Vollmer et al., 2010), we showed that learners provide feedback in the form of e.g. their eye-gaze (signaling their attention or anticipating subsequent actions) which shapes the way input is provided (e.g. Smith & Trainor, 2008; Pitsch et al., 2009) and it is crucial for robotic systems to elicit multimodal tutoring input (Fischer et al., 2011). This, however, is only the first step towards understanding the power of interaction and how, within this exchange, the specifically tailored input influences what is learned.

Dialog Initiation

Based on research results pointing to the loop, we question the capability of current robotics approaches to learn and generalize actions as well as language in embodied systems. Specifically we see shortcomings with respect to the following:

(1) Current representations consider knowledge as a static entity, where incrementality is interpreted as adding new data points (e.g. Rodrigues et al., 2010) or (sometimes) new classes (e.g. Gnadt & Grossberg, 2008; Allyon et al., 2010). However, when we take the fact more seriously that learning takes place in an interaction loop (Pitsch et al., 2009; Wrede et al., 2010), we have to design representations that are inherently dynamic and store knowledge not as a binary but a dynamic state to which the environment and experiences contribute. First solutions for emerging hierarchical structures have been presented by e.g. Tani and colleagues (Yamashita & Tani, 2008) but in these approaches, structure emerges at different levels of a hierarchy with higher levels serving as sequencing concepts over lower level motor primitives rather than from vague to concrete.

(2) Learning systems support short-term memory. However, learning systems need to be equipped with long-term memory that facilitates knowledge assimilation and consolidation processes (cf. (Gläser & Joublin, 2010) for a memory-based language learning approach).

(3) Current systems are restrictive with respect to the pragmatic frame of interaction. For example, either the tutor's input or self-exploration are the sources of learning. However, a learning system needs to be able to switch roles, thus becoming a tutor as well as mixing different sources of its learning in order to allow for self-reflexive processes consolidating accumulated knowledge further.

(4) Supervised learning algorithms are not able to take qualitative feedback of a tutor into account. However, we need to consider feedback that goes beyond binary reinforcement signals but rather emphasizes specific parts of the learner's behavior, such as the manner how an object is grasped or the goal where it has to be put.

The complementary, methodical monopoly in developmental research let the studies focus only on one side of the learning process (either the learner or the tutor) and falls short of accessing the interplay between the tutor's behavior and the learner's feedback. Exceptions to the monopoly are studies that manage to encompass the loop in interaction in a systematic way (Koterba & Iverson, 2009; Hofer et al., 2008) and thus provide a comprehensive view on children's learning. We think that a bridge between qualitative and quantitative methods of analysis offers a solution to advance current approaches: Qualitative methods like Conversational Analysis can aid us in identifying the means that the participants use to signal feedback (Vollmer et al., 2010); quantitative methods give us evidence about the significance of different types of feedback on the shape of the interaction loop (Koterba & Iverson, 2009). Using multiple and new methods (Yu et al. 2009) will foster insights into how inter- and intra-personal coordination are related to each other (De Jaegher et al., 2010) as the interaction unfolds and how it drives long-termed learning processes.

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Summary Report on IEEE ICDL-Epirob 2011 Conference

From Infant Brains to Robots

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It was an experiment. For around 10 years, two major conference series have provided a forum for researchers interested in the fundamental mechanisms of development and autonomous learning in biological and artificial systems. On the one hand, there is the International Conference on Development and Learning (ICDL) series, which grew out of a workshop held in East Lansing, Michigan, USA in 2000. On the other hand there is the International Conference on Epigenetic Robotics (EpiRob) series, which had its first meeting in Lund, Sweden, in 2001. This year, during August 24-27, these conferences held a first joint meeting in Frankfurt am Main, Germany.

Participants from across the globe registered for this first joint meeting, which took place at the new Science City Frankfurt-Riedberg in the North of Frankfurt am Main, featuring magnificent views of the Frankfurt skyline and the nearby Taunus mountains. Program Chairs Katharina Rohlfing (Univ. of Bielefeld) and Ian Fasel (Univ. of Arizona, Tucson) did an excellent job in organizing the review process and putting together a representative, high-quality program from the 120 submissions. As for previous ICDL conferences, we allowed for two submission formats: 6-page papers and 2-page extended abstracts, with the latter only being eligible for poster presentations. After one day of tutorials and special sessions in a dual track format, the participants enjoyed a high-quality single track program of talks combined with two poster sessions. A major theme throughout the conference were mechanisms of curiosity and intrinsic motivation, a topic that had already featured prominently at last year's ICDL conference in Ann Arbor, Michigan. Highlights of the program were the four invited plenary lectures by Erin Schuman (Max-Planck Institute for Brain Research, Frankfurt am Main), Michael Tomasello (Max-Planck Institute for Evolutionary Anthropology, Leipzig), Andrew Barto (Univ. of Massachusetts, Amherst), and Lisa Oakes (Univ. of California, Davis).

Summary Report on IEEE ICDL-Epirob 2011 Conference

Several awards were given out: the overall best paper award sponsored by CITEC (http://www.cit-ec.de/) was given to Kenta Kawamoto et al. from Sony Corporation for their paper "Development of object manipulation through self-exploratory visuomotor experience". The best student paper award also sponsored by CITEC went to Matthias Rolf et al. from Bielefeld University for their paper "Online goal babbling for rapid bootstrapping of inverse models in high dimensions". Furthermore, Pedro Sequeira et al. from the Instituto Superior Técnico / INESC-ID received the best student poster award sponsored by the Cognitive Science Society for their work "Emerging social awareness: exploring intrinsic motivation in multiagent learning". In addition, a number of student travel grants were sponsored by Microsoft Research and by the IEEE Computational Intelligence Society, while Springer sponsored free access to one of their online journals for the winners of the best paper and best student paper awards.

When asked at the end of the conference, if such a joint ICDL-EpiRob meeting should be held again, all participants agreed. The experiment was a success. And it will be replicated!

This conference report will appear in IEEE TAMD, Vol. 3. , No. 4.

IEEE TRANSACTIONS ON AUTONOMOUS MENTAL DEVELOPMENT

Volume 3, Issue 2, June 2011 **Link:** http://ieeexplore.ieee.org/xpl/tocresult.jsp?isnumber=5873552

Grounding Language in Action

Rohlfing, K.J., Tani, J. Page(s): 109-112 (pdf)

Abstract: The topic of this Special Issue is that action and lan guage are interwoven. Driven by traditional approaches that prevail in our education, we might be surprised about the connection between language and action, since we are inclined to view language as a symbolic system as it connects entities in the world with the corresponding conceptions that a perceiver has in mind. Action, on the other hand, was considered to be an event in the world that has to be perceived first. Only then, could it also be labeled by a perceiver, so a particular conception of it could be represented in the mind. The research from perspective on how cognition develops, however, contributed to findings suggesting that what we know about action, language and interaction emerge in parallel and have an impact on each other. This parallel development seems to provide a ground for further mental growth. For a system to develop, it requires different processes to interact not only with each other, but also with the physical world. This coupling is also a valuable source of intelligence as it provides knowledge that shapes the system's performance without actually being part of the system.

Language Does Something: Body Action and Language in Maternal Input to Three-Month-Olds

Nomikou, I., Rohlfing, K.J. Page(s): 113-128 (pdf)

Abstract: We conducted a naturalistic study in which German mothers interacted with their three-month-old infants during diaper changing as an everyday activity. Following the idea that "acoustic packaging" educates infants' attention, we explored whether the verbal input to the infants in natural interactions simultaneously contains action information. Applying a microanalysis method, we first analyzed the data qualitatively by identifying classes of body movement and vocal activities (that we called vocal types). We used these categories to observe the multimodal interaction practices of mothers and to describe the interaction ecology of everyday activity. Second, we analyzed the co-occurrence of language (in the form of different vocal activities) and action (in the form of body movements) quantitatively. We found that during early interaction with infants, German mothers vocalize in a tight temporal relationship with action over a considerable part of the overall interaction time, thereby making the vocal signal both perceivable and tangible to the infants.

Temporal, Environmental, and Social Constraints of Word-Referent Learning in Young Infants: A Neurorobotic Model of Multimodal Habituation

Veale, R., Schermerhorn, P., Scheutz, M. Page(s): 129-145 (pdf)

Abstract: Infants are able to adaptively associate auditory stimuli with visual stimuli even in their first year of life, as demonstrated by multimodal habituation studies. Different from language acquisition during later developmental stages, this adaptive learning in young infants is temporary and still very much stimulus-driven. Hence, temporal aspects of environmental and social factors figure crucially in the formation of prelexical multimodal associations. Study of these associations can offer important clues regarding how semantics are bootstrapped in real-world embodied infants. In this paper, we present a neuroanatomically based embodied computational model of multimodal habituation to explore the temporal and social constraints on the learning observed in very young infants. In particular, the model is able to explain empirical results showing that auditory word stimuli must be presented synchronously with visual stimulus movement for the two to be associated.

Emergence of Protosentences in Artificial Communicating Systems

Uno, R., Marocco, D., Nolfi, S., Ikegami, T. Page(s): 146-153 (pdf)

Abstract: This paper investigates the relationship between embodied interaction and symbolic communication. We report about an experiment in which simulated autonomous robotic agents, whose control systems were evolved through an artificial evolutionary process, use abstract communication signals to coordinate their behavior in a context independent way. This use of signals includes some fundamental aspects of sentences in natural languages which are discussed by using the concept of joint attention in relation to the grammatical structure of sentences.

Acoustic Packaging: Maternal Speech and Action Synchrony

Meyer, M., Hard, B., Brand, R.J., McGarvey, M., Baldwin, D.A. Page(s): 154-162 (pdf)

Abstract: The current study addressed the degree to which maternal speech and action are synchronous in interactions with infants. English-speaking mothers demonstrated the function of two toys, stacking rings and nesting cups to younger infants (6-9.5 months) and older infants (9.5-13 months). Action and speech units were identified, and speech units were coded as being ongoing action descriptions or nonaction descriptions (examples of nonaction descriptions include attention-getting utterances such as "Look!" or statements of action completion such as "Yay, we did it!"). Descriptions of ongoing actions were found to be more synchronous with the actions themselves in comparison to other types of utterances, suggesting that: 1) mothers align speech and action to provide synchronous "acoustic packaging" during action demonstrations; and 2) mothers selectively pair utterances directly related to actions with the action units themselves rather than simply aligning speech in general with actions. Our results complement past studies of acoustic packaging in two ways. First, we provide a quantitative temporal measure of the degree to which speech and action onsets and offsets are aligned. Second, we offer a semantically based analysis of the phenomenon, which we argue may be meaningful to infants known to process global semantic messages in infant-directed speech. In support of this possibility, we determined that adults were capable of classifying low-pass filtered action- and nonaction-describing utterances at rates above chance.

Are We There Yet? Grounding Temporal Concepts in Shared Journeys

Schulz, R., Wyeth, G., Wiles, J. Page(s): 163-175 (pdf)

Abstract: An understanding of time and temporal concepts is critical for interacting with the world and with other agents in the world. What does a robot need to know to refer to the temporal aspects of events-could a robot gain a grounded understanding of "a long journey," or "soon?" Cognitive maps constructed by individual agents from their own journey experiences have been used for grounding spatial concepts in robot languages. In this paper, we test whether a similar methodology can be applied to learning temporal concepts and an associated lexicon to answer the question "how long" did it take to complete a journey. Using evolutionary language games for specific and generic journeys, successful communication was established for concepts based on representations of time, distance, and amount of change. The studies demonstrate that a lexicon for journey duration can be grounded using a variety of concepts. Spatial and temporal terms are not identical, but the studies show that both can be learned using similar language evolution methods, and that time, distance, and change can serve as proxies for each other under noisy conditions. Effective concepts and names for duration provide a first step towards a grounded lexicon for temporal interval logic.

An Experiment on Behavior Generalization and the Emergence of Linguistic Compositionality in Evolving Robots

Tuci, E., Ferrauto, T., Zeschel, A., Massera, G., Nolfi, S. Page(s): 176-189 (pdf)

Abstract: Populations of simulated agents controlled by dynamical neural networks are trained by artificial evolution to access linguistic instructions and to execute them by indicating, touching, or moving specific target objects. During training the agent experiences only a subset of all object/action pairs. During postevaluation, some of the successful agents proved to be able to access and execute also linguistic instructions not experienced during training. This owes to the development of a semantic space, grounded in the sensory motor capability of the agent and organized in a systematized way in order to facilitate linguistic compositionality and behavioral generalization. Compositionality seems to be underpinned by a capability of the agents to access and execute the instructions by temporally decomposing their linguistic and behavioral aspects into their constituent parts (i.e., finding the target object and executing the required action). The comparison between two experimental conditions, in one of which the agents are required to ignore rather than to indicate objects, shows that the composition of the behavioral set significantly influences the development of compositional semantic structures.

Volume 3, Issue 3, September 2011 — Link: http://ieeexplore.ieee.org/xpl/tocresult.jsp?isnumber=6016499

Noise and the Emergence of Rules in Category Learning: A Connectionist Model

Cowell, R.A., French, R.M. Page(s): 194-206 (pdf)

Abstract: We present a neural network model of category learning that addresses the question of how rules for category membership are acquired. The architecture of the model comprises a set of statistical learning synapses and a set of rule-learning synapses, whose weights, crucially, emerge from the statistical network. The network is implemented with a neurobiologically plausible Hebbian learning mechanism. The statistical weights form category representations on the basis of perceptual similarity, whereas the rule weights gradually extract rules from the information contained in the statistical weights. These rules are weightings of individual features; weights are stronger for features that convey more information about category membership. The most significant contribution of this model is that it relies on a novel mechanism involving feeding noise through the system to generate these rules. We demonstrate that the model predicts a cognitive advantage in classifying perceptually ambiguous stimuli over a system that relies only on perceptual similarity. In addition, we simulate reaction times from an experiment by (Thibaut et al. Proc. 20th Annu. Conf. Cong. Sci. Soc., pg. 1055-1060, 1998) in which both perceptual (i.e., statistical) and rule based information are available for the classification of perceptual stimuli.

Using Object Affordances to Improve Object Recognition

Castellini, C., Tommasi, T., Noceti, N., Odone, F., Caputo, B. Page(s): 207-215 (pdf)

Abstract: The problem of object recognition has not yet been solved in its general form. The most successful approach to it so far relies on object models obtained by training a statistical method on visual features obtained from camera images. The images must necessarily come from huge visual datasets, in order to circumvent all problems related to changing illumination, point of view, etc. We hereby propose to also consider, in an object model, a simple model of how a human being would grasp that object (its affordance). This knowledge is represented as a function mapping visual features of an object to the kinematic features of a hand while grasping it. The function is practically enforced via regression on a human grasping database. After describing the database (which is publicly available) and the proposed method, we experimentally evaluate it, showing that a standard object classifier working on both sets of features (visual and motor) has a significantly better recognition rate than that of a visual-only classifier.

Learning Generalizable Control Programs

Hart, S., Grupen, R. Page(s): 216-231 (pdf)

Abstract: In this paper, we present a framework for guiding autonomous learning in robot systems. The paradigm we introduce allows a robot to acquire new skills according to an intrinsic motivation function that finds behavioral affordances. Affordances — in the sense of (Gibson, Toward and Ecological Psychology, Hillsdale, NJ, 1977) — describe the latent possibilities for action in the environment and provide a direct means of organizing functional knowledge in embodied systems. We begin by showing how a robot can assemble closed-loop action primitives from its sensory and motor resources, and then show how these primitives can be sequenced into multi-objective policies. We then show how these policies can be assembled hierarchically to support incremental and cumulative learning. The main contribution of this paper demonstrates how the proposed intrinsic motivator for affordance discovery can cause a robot to both acquire such hierarchical policies using reinforcement learning and then to generalize these policies to new contexts. As the framework is described, its effectiveness and applicability is demonstrated through a longitudinal learning experiment on a bimanual robot.

A Biologically Inspired Architecture for an Autonomous and Social Robot

Malfaz, M., Castro-Gonzalez, A., Barber, R., Salichs, M.A. Page(s): 232-246 (pdf)

Abstract: Lately, lots of effort has been put into the construction of robots able to live among humans. This fact has favored the development of personal or social robots, which are expected to behave in a natural way. This implies that these robots could meet certain requirements, for example, to be able to decide their own actions (autonomy), to be able to make deliberative plans (reasoning), or to be able to have an emotional behavior in order to facilitate human-robot interaction. In this paper, the authors present a bioinspired control architecture for an autonomous and social robot, which tries to accomplish some of these features. In order to develop this new architecture, authors have used as a base a prior hybrid control architecture (AD) that is also biologically inspired. Nevertheless, in the later, the task to be accomplished at each moment is determined by a fix sequence processed by the Main Sequencer. Therefore, the main sequencer of the architecture coordinates the previously programmed sequence of skills that must be executed. In the new architecture, the main sequencer is substituted by a decision making system based on drives, motivations, emotions, and self-learning, which decides the proper action at every moment according to robot's state. Consequently, the robot improves its autonomy since the added decision making system will determine the goal and consequently the skills to be executed. A basic version of this new architecture has been implemented on a real robotic platform. Some experiments are shown at the end of the paper.

Improved Binocular Vergence Control via a Neural Network That Maximizes an Internally Defined Reward

Yiwen Wang Shi, B.E. Page(s): 247-256 (pdf)

Abstract: We describe the autonomous development of binocular vergence control in an active robotic vision system through attention-gated reinforcement learning (AGREL). The control policy is implemented by a neural network, which maps the outputs from a population of disparity energy neurons to a set of vergence commands. The network learns to maximize a reward signal that is based on an internal representation of the visual input: the total activation in the population of disparity energy neurons. This system extends previous work using Q learning by increasing the complexity of the policy in two ways. First, the input state space is continuous, rather than discrete, and is based upon a larger diversity of neurons. Second, we increase the number of possible actions. We evaluate the network learning and performance on natural images and with real objects in a cluttered environment. The policies learned by the network outperform policies by Q learning in two ways: the mean squared errors are smaller and the closed loop frequency response has larger bandwidth.

Emergence of Memory in Reactive Agents Equipped With Environmental Markers

Ryang Chung, J., Yoonsuck, C. Page(s): 257-271(pdf)

Abstract: In the neuronal circuits of natural and artificial agents, memory is usually implemented with recurrent connections, since recurrence allows past agent state to affect the present, on-going behavior. Here, an interesting question arises in the context of evolution: how reactive agents could have evolved into cognitive ones with internalized memory? Our idea is that reactive agents with simple feedforward circuits could have achieved behavior comparable to internal memory if they can drop and detect external markers (e.g., pheromones or excretions) in the environment. We tested this idea in two tasks (ball-catching and food-foraging task) where agents needed memory to be successful. We evolved feedforward neural network controllers with a dropper and a detector, and compared their performance with recurrent neural network controllers. The results show that feedforward controllers with external material interaction show adequate performance compared to recurrent controllers in both tasks. This means that even memoryless feedforward networks can evolve behavior that can solve tasks requiring memory, when material interaction is allowed. These results are expected to help us better understand the possible evolutionary route from reactive to cognitive agents.