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Human Brain inspired Artificial Intelligence & Developmental Robotics: A Review

Suresh Kumar
Aberystwyth University, UK
Sukkur Institute of Business Administration, Pakistan
suk9@aber.ac.uk

Patricia Sha
Aberystwyth University, UK
phs@aber.ac.uk

Abstract

Along with the developments in the field of the robotics, fascinating contributions and developments can be seen in the field of Artificial intelligence (AI). In this paper we will discuss about the developments is the field of artificial intelligence focusing learning algorithms inspired from the field of Biology, particularly large scale brain simulations, and developmental Psychology. We will focus on the emergence of the Developmental robotics and its significance in the field of AI.

Keywords: Artificial Intelligence, Development & Robotics

1. Introduction

Human kind has been trying to improve life make this world more useful for centuries. We have seen evidence where humans tried to make tools from the wood and rocks to use them for acquiring food and keeping safe themselves. In modern era, we can see researchers in the different fields are working to improve human life. Researchers in the field of medical science are trying extend and quality of life. On the other hand technologists are trying to make human life easier. In modern are we are still developing tools to keep human life safe and easier.

Humans invented mechanical tools to make their jobs easier. These tool used to be operated by the human or under the commands provided by humans directly. Robots are those kind of mechanical tools which were invented to help human in their jobs are work in such environments where it is dangerous or difficult for humans to work. In short, machines and tools were invented to make human life easier and work quicker. Moreover robots are not supposed to get bored with repetition of tasks and don't get tired like humans do.

We can see different kind of robots, from humanoid [1]–[3] to animal like [4], [5]. However, the word "Robot" was first introduced in the stage play in 1920 where a human played roll of a machine which looked and behaved like humans do [6]. This play can be assumed a human thought about future where humanoids machines to be seen acting, thinking, even look like humans. Almost 90 years later of that stage where term robot was

introduced initially, another play was staged in which a robot played roll of human [7]. The robot in this play was controlled manually by human which discards this machine, Geminoid, from the basic definition robot, an automated machine [8]. Even though robot in this play was not automatic yet it fulfils most of predictions made in the 1920's play. In 1950, Walter developed to mobile robots, which were automatic and moved at free will [9]. Today, many machines satisfies the definition for the term "Robot". However, humanoid seems to be most suitable machines for this term.

Initially, AI and robotics community focused on single purpose intelligence and robots. Rule based systems were the initial approach for AI systems. Now trends are being shifted toward general purpose intelligence and robotics [10]. Human body have more than 200 joints and about 244 degree of freedom (DoF), controlled by more than 600 muscles [11]. Such a large DoF helps human to manipulate different objects and perform different movements. The equipment, objects, tools, etc. in this world are designed in this world to be used by humans. To be helped by the machines, researchers design robots to manipulate objects as humans do. That is why trends in robotics design is shifting towards humanoid robots.

In this paper, we will discuss about the emergence of "Artificial Intelligence" inspired from developmental psychology and its implementation in robotics. In section II we will discuss about the early concepts of intelligence and artificial intelligence. In section III, some AI approaches inspired from the human brain will be discussed and in section IV we will present an introduction of developmental psychology in robotics and some related projects. Finally, in the section V we will make a conclusion about the two inspirations, biology (Human brain) & psychology, in the field of artificial intelligence.

2. Intelligence & Artificial Intelligence

We, modern human beings, were named as "Homo sapiens" which means "Wise man" [12]. Humans have capability of thinking, reasoning, recognition, acting, learning and behaviours. Neisser believes that "Intelligence" of one is a degree by which it can be compared to a typical intelligent subject [13]. Intelligence or intelligent can be defined in various ways depending upon the culture, status and language. The Word "Intelligence" originates from Latin word engender, which means generate [14]. This gives the idea that word intelligence means to generate information. Although word intelligence has no clear scientific definition but can be defined various ways. Honavar believes that intelligence is collection of various attributes such as perception, reasoning, adaption and learning, autonomy, creativity and organisation [15].

Focusing these aspects in robots, Asimov proposed three general laws for the robot [16], described as under:

- Robot should not harm human being and not allow them harm themselves.
- Robot should follow the instruction provided by human beings, except if the instruction conflicts with first law.
- Robot should protect itself, as long as it does not conflicts with first two laws.

A robot following the Asimov's laws must possess capability of acting automatically and ability to perceive human actions. To be acting automatically in this world and ability to perceive human actions, a robot must possess intelligence like humans do. Although many of the commercial machines, from home appliances to motor vehicles, are claimed to be intelligent, however those lack in very general intelligence. Field of "Artificial Intelligence" (AI) was emerged as a field of robotics to introduce intelligence in the robots. Nilsson relates terms such as perception, reasoning,

adaption and learning, autonomy, creativity and organisation, possessed by human beings with artificial intelligence as well [17]. He believe, an artificial system is said to be intelligent if it possess the capability of perception, reasoning, action, autonomy, organisation and adaption and learning. In broad sense, goal of AI is to develop machines which can think and act as humans do.

In 1956, first conference was held on artificial intelligence [18]. It was anticipated that soon machine may be replaced with human beings for different tasks which are dangerous or boring for the humans. Initially, focus of AI researcher was to develop machine to reason only rather than to reason and act. That is why initial focus was on top-down approach of intelligence machines, focusing reasoning and thoughts in machines [19]. This is why, initial theory about the artificial intelligence was that it is study of information processing for problems [20].

3. Human Brain Inspired Ai Models

Bio-inspired artificial learning systems are very popular in AI since the beginning of AI. AI researcher focusing on this approach, try to simulate human like processing in machines. In human psychology it was believed that heart is central part of thinking and reasoning. In 1664 a book on human brain, "Anatomy of the Brain", was published by English physician, which describes brain responsible for the mental functions [21]. Working of the human brain was studied by the biologists for further explanation about the human thinking. In 19th century biologists proposed two different theories about brain functions. One theory considers brain cells work all together for mental tasks, while other theory, Neuron theory, considers brains cells working independently for mental tasks. In later research it became clear that brain works in small networks of neurons and different parts of brain response to specific tasks [21]. A neuron consist of nucleus, cell body, axon and dendrites. Neurons receive signals from other neurons via dendrites and pass to other via axons and synapse. A typical neural structure is shown in figure 1.

In late 20th century, robotics started to replicate human brain process, particularly neural processes. Artificial neural networks

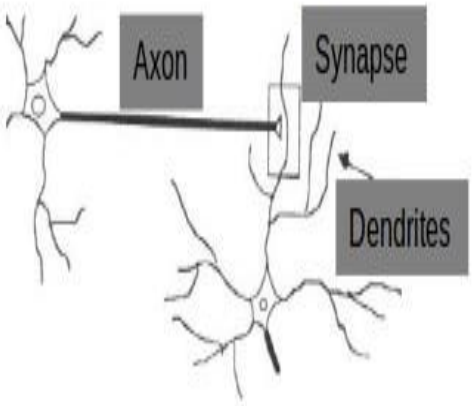

Figure. 1: Neuron Structure [22]

(ANN) are part of such efforts. ANN are structures of interconnected units, neurons, implemented mostly in software but are possible to implement in hardware as well. Each unit in the ANN emits a signal to all connected units when it is activated. Activation occurs when input signal to the unit is greater than the threshold. It is believed that ANN represent processing in biological system, human brain. A generic ANN architecture is shown figure 2. Learning in AI is adapted by changing network architecture and weights of the network connections [23]. There are three main learning paradigms; supervised, unsupervised and hybrid. But there are certain limitations in the ANN as well, like learning pattern should be defined, weights changed accordingly and information to be accessed by is to be defined.

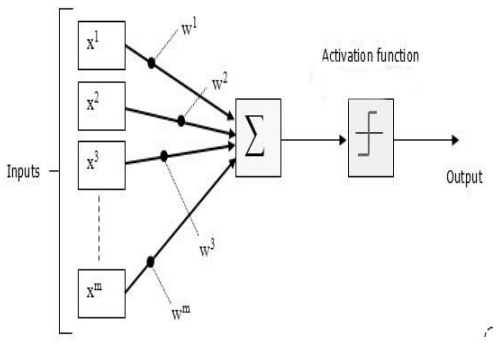

Figure. 2: A Typical ANN Architecture

ANNs are very popular among robotics and AI research community due to remarkable characteristics such as learning, noise tolerance and generalisation [24]. ANN are also provide parallel processing within the system. ANN consist of network(s) containing small processing units. Which resembles the networks of neurons in the brain, hence called artificial neural network.

ANN are now being used in wide range of robotic and other computational models. ANN are seems to be very useful when learning involves single task or a predefined environment. ANN systems are trained in the environment to perform the task provided and task is learned. ANN network are very fast due to parallel processes in the network, however the learning (training) takes longer and more computation. These network do not seems very reliable when environmental conditions are changed from the one it is trained.

Apart from ANN there are other efforts as well in the field of AI, some of them are still in progress. These are biologically inspired artificial brain architectures. Following the developments in neural science and considering "Brain as the seat of mid" researchers started to develop simulation of human brain processing for machines. Garis et al. in [18] describe these architectures as large scale brain simulations. Blue Brain project is the part of biologically inspired research, in which researcher are trying to simulate the neural processing in human brain. Supported by IBM, researcher are trying to develop simulation of cerebral cortex using super computer [18]. Project involves reconstruction of multilevel processing of neuron layers and synapse. This project, as assumed, will be able to simulate the processing of any part of the human brain if specific information provided.

Another project on reverse engineering was initiated in 2008 along with Blue brain project, system of Neuromorphic Adaptive Plastic Scalable Electronics SyNAPSE. The name of the project is taken from the inter neural conjunctions, synapse. Goal of this project is to produce brain like intelligent computer, however the intelligence will be comparable to small mammals, cats and mice. Neurogrid, project of Stanford researcher, is another approach to design the simulation of neural activity [25]. It is a hardware project which simulates neural activity of one million neurons having six billion synapse. Super computer using Neurogrid model is rival of the Blue brain project as this system consume very less power as compared to Blue brain computer.

Brain Based Devices (BBD) are another approach to neutrally control robotic devices. Fleischer use robotic devices not just to control using neural activity but also test the hypothesis about neural mechanism for the behaviours [26]. Their idea strongly supports the behavioural learning. BBD robots interact with the world autonomously without any prior instructions. BBD robots of this projects categorises signals received from the sensors attached, without prior information, and learns actions which produce such sensory information.

Even though Bio-inspired brain simulation projects are of great importance in the field of AI and have produced interesting results, however these projects still lacked in human like learning and not very cost effective [27]. However such projects seems

to be very useful to understand the neural processing of sensory information perception building.

4. Psychology & Robotics

We have seen significant developments in different domains of AI, such as pattern recognition, image processing, control systems and reasoning games. In some cases such machines can perform better than humans, however all of these developments in AI cannot be compared to general human intelligence as the main goal of the AI is to create human like intelligence in machines.

In bio-inspired robotics application, researchers mostly attempt(ed) to replicate neural processing in human brain. Whereas human brain is very complex and it is very difficult to understand and reconstruct neural activities of the human brain with our current and limited technology. In developmental psychology it is believed that intelligence is adapted from interaction with the environment in which human grows [28]. Research from psychology who believe this idea of intelligence in human consider humans as blank slate when born and knowledge is developed over the course of entire life.

Though the idea, about humans as blank slate at birth, is supported by a group of developmental psychologists but still widely used in developmental psychology and robotics. Another group of researchers believes that humans have innate knowledge to deal the world situations at birth [29]. This "Nature vs. Nurture" debate is classical and still researchers from both groups doing research to support their theory.

In this review we are focusing Nurture side of the "Nature vs. Nurture" debate and consider intelligence as hierarchical developed while acting in the environment rather than innate. Thus we will consider robotics models in which learning is hierarchical developed rather than built-in. As sensory information in our environment is contained in hierarchical architecture and most of the initial AI systems were not able deal to deal with this kind of sensory information hence were not able to create hierarchical learning [27]. To build a human like intelligent, artificial intelligent system need to be evolved like so, discussed in section 1. This is the main purpose of the field Developmental robotics. Although, the idea of such field, cognitive developmental robotics, was appeared long ago [30] but it was formally emerged in 2000 [31]. Developmental or cognitive robotics is branch of robotics in which agent learns its capabilities rather than hard-wired in it already. Thus learning is neither task-oriented not domain specific, unlike ANN.

Embodiment is very important in developmental robotics. The term "Embodiment" refers to the physical presence of the system not just a software or simulation. Such a system should be able to perceive the environment with the sensors provided and interact with the body, may be end effector(s).

Thus artificial intelligent system in developmental robotics develops intelligence with (artificial) brain and body. There are different researchers around the world, working on different projects on developmental robotics with different platforms, such as iCub, NAO, ASIMO, COG, CASPER etc. This community of research has shown interesting results using these platforms. A brief descriptions of some of those projects is given here.

- Schlesinger used reinforced learning, with the back-propagation and Qlearning, model to investigate the Baillargeons study [32] about causality perception [33]. In the experiment young infants were habituated to causal event, car moving behind an occluder. He found that infants, 6 months old, looked longer impossible events than possible events. In Schlesinger's model habituation stage was replaced with the training phase. Schlesingers finding concludes that the

eye tracking is disturbed by unusual event that may be the reason that infants look longer on impossible events.

- iTalk, another developmental approach for robotics, was aimed to achieve conceptualization, action development and social emergence with the cognition building. This project was more emphasising the social aspect of learning, imitation [34]. Implementing lingual learning capabilities in iCub, significant achievements were observed.

Research was also focused on how verbal communication in infants helps to learn constructive knowledge. Project has produced more than 100 papers.

- IM-CLeVeR project one of the recent projects on the developmental learning using humanoid platform, iCub. The objectives of this projects are; learning mechanism for abstracting sensorimotor information and learn new skill with the intrinsic motivations and reusing these skills [35]. Project is about developing learning system having capability of intrinsic motivation to interact with environment and learn. Models for Object tracking, saccading, and reach development are of significant outcomes of this project. Project proposed bio-constrained models for both of these developments, saccade and reach. Models are inspired from the developmental stages of the infants. Models were integrated with the machine learning algorithms with capability of vision perception and abstraction [36], [37].
- Experience, another intrinsically motivated learning based project. Learning is based on the interaction and exploration of the surrounding and creating representation of the world. Computational models were implemented on humanoid robot, iCub, and achieved significant results [38]. Project focuses on high level representation of object and outcomes resulted with acting on those objects. Object Action Complexes (OAC) system was developed in this project [39]. OAC system recorders learning in high level representations and uses those to interact with novel situations in the environment. System is also capable of planning actions for given environmental state. Moreover, OAcs can also be generalised, that makes system to learn and act irrespective of environment.
- CHILD, a developmental learning approach in which learning takes place with the continual process. Learning paradigm is ANN supervised reinforced [40], combination of Q learning and temporal transition hierarchies, with no knowledge at the beginning. System creates knowledge units while acting on the environment continuously. Key aims of the project are; continual task independent learning based on the sensory information and learning new skills and reusing them. But the system has limitation for the states of particular sequence. Although system shows effective and fast learning in Maze problem [40], however its learning is environment dependent.
- GRASP project is an attempt to design cognitive grasp capability based on novel situations. Researchers aimed to develop a cognitive system which can act, grasping and manipulation, in the environment and learn. The acquired knowledge will be used to plan the strategy for grasping new objects. Learning grasping and affordance

of human will be the base of this model. Robot will decide optimum degree of freedom (DoF) for the task.

- MoDeL (Modeling Developmental Learning) is one of the recent projects related to developmental robotics. Purpose of this project is develop learning model for humanoid robot inspired from infants' developments, biological/physical and cognitive. Project is inspired from the autonomous learning in infants while playing with object in surrounding. Researchers in this project aimed to develop autonomous, intrinsic motivated play behaviour in artificial agents to learn physics of the environment.

5. Conclusion

Although AI is more than half century old but we don't have machines with human like general intelligence yet. There are two main reason for this; not enough developments in the field of neuroscience to understand human brain processing and inadequate technology to process information as fast as human brains do. Earlier researchers from AI focused on human brain and biology to mimic human brain like intelligence. In last decade, researcher also focused on developmental psychology for understanding human intelligence. Also embodied agents were used in the researches rather than just simulation. This is widely accepted in robotics community that AI system needs bo embodied and act in the environment to learn and build intelligence [31], [41].

Developmental psychology deals with the physical development of human body, language acquisition and cognition over lifespan. In humans learns and develop knowledge about surrounding over the life span. Human body, with different sensors, have limited capabilities and develops over time. Like human vision develops over earlier months of life [21]. Similarly poor muscles and muscle control limits infants to sit, stand and walk. This makes humans to perform and perceive with certain constraints and with the time, and learning, these constraints are removed and make human to develop knowledge hierarchical.

We believe that to develop a human like intelligence, an artificial intelligence should possess body, to act, cognitive capability, to learn, and constrained system, resembling humans, to learn and build hierarchical knowledge. Also large scale brain simulation will help to further understand the human brain and information processing within it.

We conclude that the field, Developmental robotics, provides a new directions for psychologist to explore the learning process in human beings and will assist robotists to build human like learning AI and robotics. The field will help psychologists to test their hypothesis about learning and cognitive development in humans, particularly infants and children, which otherwise will take long process of planning and experiments with subjects with matching criteria. For example to study about infant vision and object reaching will cost psychologists huge amount of time for planning, designing and conducting experiments. Similar Experiment can be easily performed on robot with just minute changes in the vision parameters in the robotic system.

In this context developmental robotics studies provides two main purposes, developing brain like intelligence in artificial agents inspired from developmental (psychology) theories and testing such theories on artificial agents to feedback. Thus field will help to explore high level learning in human brain. Whereas large scale brain simulations will help to understand the neural level understanding about learning and knowledge building.

In this paper, we aimed to focus origin of human brain like intelligence and its current development with two different research strategies. In continuation with this

paper series, our next work we will focus on particular example of learning in AI inspired by infants play.

References

[1] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki, and K. Fujimura, "The intelligent asimo: System overview and integration," in Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on, vol. 3. IEEE, 2002, pp. 2478–2483.

[2] G. Metta, G. Sandini, D. Vernon, L. Natale, and F. Nori, "The icub humanoid robot: an open platform for research in embodied cognition," in Proceedings of the 8th workshop on performance metrics for intelligent systems. ACM, 2008, pp. 50–56.

[3] S. Shamsuddin, L. I. Ismail, H. Yussof, N. I. Zahari, S. Bahari, H. Hashim, and A. Jaffar, "Humanoid robot nao: Review of control and motion exploration," in Control System, Computing and Engineering (ICCSCE), 2011 IEEE International Conference on. IEEE, 2011, pp. 511–516.

[4] M. Raibert, K. Blankespoor, G. Nelson, R. Playter, and T. Team, "Bigdog, the rough-terrain quadruped robot," in Proceedings of the 17th World Congress, vol. 17, no. 1. Proceedings Seoul, Korea, 2008, pp. 10822– 10825.

[5] G. M. Nelson, R. D. Quinn, R. J. Bachmann, W. Flannigan, R. E. Ritzmann, and J. T. Watson, "Design and simulation of a cockroach-like hexapod robot," in Robotics and Automation, 1997. Proceedings., 1997 IEEE International Conference on, vol. 2. IEEE, 1997, pp. 1106–1111.

[6] K. Capek, N. Playfair, P. Selver, and W. Landes, "Rossum's universal robots," Prague, CZ, 1920.

[7] E. Guizzon, "Geminoid f gets job as robot actress, blog in ieee spectrum," 2010.

[8] E. Ugur, "A developmental framework for learning affordances," Unpublished doctoral dissertation, The Graduate School of Natural and Applied Sciences, Middle East Technical University, Ankara, Turkey. Availa ble from http://www. cns. atr. jp/emre/papers/PhDThesis. pdf, 2010.

[9] W. Walter, "An imitation of life," Scientific American, vol. 182, pp. 42–45, 1950.

[10] R. A. Brooks, C. Breazeal, M. Marjanovic, B. Scassel-´ lati, and M. M. Williamson, "The cog project: Building a humanoid robot," in Computation for metaphors, analogy, and agents. Springer, 1999, pp. 52–87.

[11] A. D. Kuo, "A mechanical analysis of force distribution between redundant, multiple degree-of-freedom actuators in the human: Implications for the central nervous system," Human Movement Science, vol. 13, no. 5, pp. 635–663, 1994.

[12] S. Russell, P. Norvig, and A. Intelligence, "A modern approach," Artificial Intelligence. Prentice-Hall, Egnlewood Cliffs, vol. 25, 1995.

[13] U. Neisser, "The concept of intelligence," Intelligence, vol. 3, no. 3, pp. 217–227, 1979.

[14] N. Chomsky, "Language and mind (enl. ed.)," New York, p. 75, 1972.

[15] V. Honavar, "Artificial intelligence: An overview," 2006.

[16] I. Asimov, I, robot. Facwcett Crest, 1933.

[17] N. J. Nilsson, Artificial intelligence: a new synthesis. Elsevier, 1998.

[18] H. De Garis, C. Shuo, B. Goertzel, and L. Ruiting, "A world survey of artificial brain projects, part i: Largescale brain simulations," Neurocomputing, vol. 74, no. 1, pp. 3–29, 2010.

[19] R. A. Brooks, "Intelligence without representation," Artificial intelligence, vol. 47, no. 1, pp. 139–159, 1991.

[20] D. Marr, "Artificial intelligencea personal view," Artificial Intelligence, vol. 9, no. 1, pp. 37–48, 1977.

[21] E. B. Goldstein, The Blackwell Handbook of Sensation and Perception. John Wiley & Sons, 2008.

[22] Resource,"Online." [Online]. Available: http://web.simmons.edu/

[23] A. K. Jain, J. Mao, and K. M. Mohiuddin, "Artificial neural networks: A tutorial," IEEE computer, vol. 29, no. 3, pp. 31–44, 1996.

[24] I. Basheer and M. Hajmeer, "Artificial neural networks: fundamentals, computing, design, and application," Journal of microbiological methods, vol. 43, no. 1, pp. 3–31, 2000.

[25] B. V. Benjamin, P. Gao, E. McQuinn, S. Choudhary,

A. R. Chandrasekaran, J.-M. Bussat, R. Alvarez-Icaza, J. V. Arthur, P. A. Merolla, and K. Boahen, "Neurogrid: A mixed-analog-digital multichip system for largescale neural simulations," Proceedings of the IEEE, vol. 102, no. 5, pp. 699–716, 2014.

[26] J. Fleischer and G. M. Edelman, "Brain-based devices." IEEE Robot. Automat. Mag., vol. 16, no. 3, pp. 33–41, 2009.

[27] B. Goertzel, R. Lian, I. Arel, H. De Garis, and S. Chen, "A world survey of artificial brain projects, part ii: Biologically inspired cognitive architectures," Neurocomputing, vol. 74, no. 1, pp. 30–49, 2010.

[28] J. Piaget and M. Cook, The origins of intelligence in children. International Universities Press New York, 1952, vol. 8, no. 5.

[29] E. S. Spelke and K. D. Kinzler, "Core knowledge," Developmental science, vol. 10, no. 1, pp. 89–96, 2007.

[30] A. M. Turing, "Computing machinery and intelligence," Mind, vol. 59, no. 236, pp. 433–460, 1950.

[31] A. Cangelosi, M. Schlesinger, and L. B. Smith, Developmental robotics: From babies to robots. MIT Press, 2015.

[32] R. Baillargeon, "Representing the existence and the location of hidden objects: Object permanence in 6and 8-month-old infants," Cognition, vol. 23, no. 1, pp. 21–41, 1986.

[33] M. Schlesinger, "A lesson from robotics: Modeling infants as autonomous agents," Adaptive Behavior, vol. 11, no. 2, pp. 97–107, 2003.

[34] A. Cangelosi, T. Belpaeme, G. Sandini, G. Metta,

L. Fadiga, G. Sagerer, K. Rohlfing, B. Wrede, S. Nolfi, D. Parisi et al., "The italk project: Integration and transfer of action and language knowledge in robots," in Proceedings of Third ACM/IEEE International Conference on Human Robot Interaction (HRI 2008), vol. 12, 2008, p. 15.

[35] G. Baldassare, M. Mirolli, F. Mannella, D. Caligiore,

E. Visalberghi, F. Natale, V. Truppa, G. Sabbatini, E. Guglielmelli, F. Keller et al., "The im-clever project: Intrinsically motivated cumulative learning versatile robots," in 9th International Conference on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems, 2009, pp. 189–190.

[36] J. Law, P. Shaw, M. Lee, and M. Sheldon, "From saccades to grasping: A model of coordinated reaching through simulated development on a humanoid robot," IEEE Transactions on Autonomous Mental Development, vol. 6, no. 2, pp. 93–109, 2014.

[37] J. Coelho, J. Piater, and R. Grupen, "Developing haptic and visual perceptual categories for reaching and grasping with a humanoid robot," Robotics and Autonomous Systems, vol. 37, no. 2, pp. 195–218, 2001.

[38] Resource,"Online," 2016. [Online]. Available: http://www.xperience.org/

[39] N. Kruger, C. Geib, J. Piater, R. Petrick, M. Steedman,¨ F. Worg¨ otter, A. Ude, T. Asfour, D. Kraft, D. Omr¨ cenˇ et al., "Object–action complexes: Grounded abstractions of sensory–motor processes," Robotics and Autonomous Systems, vol. 59, no. 10, pp. 740–757, 2011.

[40] M. B. Ring, "Child: A first step towards continual learning," in Learning to learn. Springer, 1998, pp. 261–292.

[41] B. Rasolzadeh, M. Bjorkman,¨ K. Huebner, and D. Kragic, "An active vision system for detecting, fixating and manipulating objects in the real world," The International Journal of Robotics Research, vol. 29, no. 2-3, pp. 133–154, 2010.