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Embodied Artificial Intelligence: Enabling the Next Intelligence Revolution

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Abstract. There has been a long-standing debate about the extent to which the human mind controls the human body and vice-versa. Today this debate still powers a profound scientific desire to deepen our understanding of the nature of both humans' and animals' intelligent, adaptive behavior. In order to gain further insights into intelligence and explore how our brain and bodies develop through physical interactions with the world, Embodied Intelligence places the physical entity of the human body at the center of this subject. In the age of AI and Machine Learning, Embodied Intelligence research remains highly important as it can deliver valuable input which enhances the impact of conventional AI technology. Embodied Intelligence provides potential solutions for current AI technologies that are dependent on large amounts of data and reliable output whilst that output is reliant on uncertain, unstructured tasks and situations aligned closely to human users both as individuals and communities. In the following Chapter we discuss current trends and directions within this interdisciplinary community, and also the future challenges and opportunities.

1. Introduction

The concept and notion of computation and intelligence has historically seen significant evolution which continues to this day [17, 19]. It is shaped by our social awareness, needs and challenges, and also developments in both our understanding of intelligence, its origins, and technologies that show intelligent behaviors or interactions. At a time period in which we need solutions to global health, climate and societal challenges, there is a pressing need to advance the capabilities of intelligent embodied systems and to understanding how embodied systems can be used in understandable, fair and ethical ways [26].

The development of Artificial Intelligence (AI) technologies has been highly successful in developing general-purpose computing machines that can execute tasks with speed and scalability. AI is also increasingly being leveraged for widespread applications in the physical world, where it has significant potential. However, when compared to biological systems, AI based machines still struggle to complete unknown or previously unseen tasks, or to exploit their interactions with the environment. For example, AI based machines are still unable to autonomously recover from failures whereas animals can quickly and robustly find alternative solutions by exploiting their physicality. Most of the challenges of developing or fully utilizing the strengths of AI are related to the need to consider the algorithmic capabilities and also the physical 'embodiment' of the system. This has led to the emergence of the concept of "Embodied Intelligence" (EI) where the physical system, materials and design offers some physical intelligence of robustness [11, 5]. Pioneers in this field have investigated how embodied interactions are used in nature to develop ‘physical controllers’, cognitive processes and how machines can perform computation through ‘raw materials’[16].

The emergence of embodied intelligence has led to the development of smart materials or soft materials where passivity can be exploited to achieve highly complex interactions, or walking motion can be programmed physically removing the need for complex controllers. New fabrication methods such as multi-material 3D printing or micro fabrication have enabled significant acceleration of EI research through the development of unconventional structures, materials and systems[29]. These approaches also introduce new challenges as it becomes increasingly complex to model and understand interactions due to the scales, complexity or soft nature of the machines. Although there are many exciting capabilities offered by EI, to truly push the boundaries of conventional AI, we must understand how to design the EI of a body in conjunction with the algorithmic intelligence of the ‘brain’ [10] and how to understand and leverage the capabilities to better understand or interact with the surrounding environment.

The landscape of the EI community is hugely interdisciplinary and also ever growing. This leads to significant diversity in the technologies developed to exploit EI, and also the frameworks, perspectives and methodologies created to explain and develop and explain EI. In this Chapter we review some of the current trends in EI research, before commenting on future challenges and opportunities.

2. Current Trends

2.1. Bio-inspiration & Soft Robotics

Nature and biological systems show highly complex and nuanced interactions with the environment through imaginative and intelligent ways is made possible through their physical structure and embodied intelligence [4]. Analyzing biology allows us to develop artificial agents that have similar capabilities [20] and also to understand how EI arises in these beings through ’robo-physics’. There is increasing awareness and acceptance that plants offer and demonstrate many aspect of EI which can provide many insights into EI [21]. Furthermore, their ’brain-less’ structure still enables computation and intelligence, challenging views and perspective of standard concepts and ideas of intelligence.

Soft robotics is closely tied to bio-inspiration, with many animals exploiting soft body interactions[13]. However, soft robotics also allows for the development of technologies which are not purely bio-inspired. Exciting developments have been shown in manipulation, locomotion and also application orientated capabilities such as manipulation of food items. However, there are still unresolved changes in the scale-ability of sensing, actuation and control in comparison to biological systems [8].

2.2. Artificial Life & Bio-hybrid Systems

Developing artificial life, or ’living-creatures’ opposed to human-made materials, structures and fabrication would be a truly embodied approach to the design and creation of intelligence systems. This could enable a move towards systems that are Self-X, with capabilities in self-replication, self-healing or self-sensing for example[28]. Key developments with works such as the Xenobots [3], have shown how ’robots’ can be formed from living cells, with some ability for these ’bots’ to contribute to the creation of others. This is accompanied by an increase in the development of bio-hybrid systems, intersecting the key advances of biological and artificial systems. Although facing many technical hurdles, the integration of living muscle cells into robotic systems has been shown gao2021recent. In term of EI, this allows exploration of the balance and distribution of ’brain’ and ’body’ but also between different types of ’brain’ and ’body’, combining analog and digital computation.

2.3. Neuroscience & Cognition
The complexity of the behaviors and functions of human brains is incredible with billions of neurons, trillions of synapses operating with the human cerebral cortex, the outer layer of the brain that is associated with our highest mental capabilities [22]. To be able to design and develop artificial system with comparable capabilities we must better understand the behaviors and function of the brain. Analysis and exploration of human developmental behavior and cognition provides a means of understanding the importance and contribution of embodiment, emergence and continuous autonomous development [14]. Exploring the concept of embodiment through the lens of neuroscience leads provides the key concept that embodied intelligence provides the body with an means of dealing with open-ended and even unexpected interactions, as EI does not depend on specific inputs/outputs as in supervised learning which is the core of modern deep learning. Furthermore, EI has been show to have a role in 'shaping the way we think' [25], with congition and learning inherently tied to the body. This is a complex and multi-faceted research area, but is central to furthering our understanding of EI and human intelligence.

2.4. Understanding Intelligence & Philosophy
The term "higher level" intelligence is used to designate behavior that are purely sensory-motor, such as problem solving and reasoning, or even natural language, emotion, and consciousness. However, there is an intersection between the physical experience, its translation to memory and the long term implication in terms of this 'higher level' of intelligent behavior [18]. Links between physical interaction, sensory-motor control and memory are advancing through the creation of models that explain these responsive capabilities [9]. Likewise, the definition or requirements for consciousness is being explored within a number of disciplines, leading to diverse views and approaches.

2.5. Application & Deployment
As technologies that exhibit or exploit EI become more widespread and accessible, the ability to develop more application oriented systems becomes increasingly possible. One area that has seen growth is in manipulation. Soft Robotics Inc. demonstrated the ability to exploit jamming and variable stiffness to provide a universal gripper solution which relies on environmental interactions [2]. This has been followed by many soft or compliant solutions which exploit EI for robust and intelligence interactions.

Developments in haptic devices has provided technologies for embodied interactions between machines and humans, and also between humans[7]. In addition to the application enabled haptic devices they offer a platform to understand human embodied interactions, sensory-motor co-ordination, learning and more. This use of soft robotics as a tool to understand intelligence is also a growing field. This is seen in the use of soft wearable devices for wearers undergoing MRI studies[12]. Thus, the development of technologies that demonstrate and enabled embodied interactions has the potential to be used as tools to further our understanding of our response to embodied interactions.

3. Future Challenges & Opportunities
3.1. The Quest for a Unifying Concept
As engineers and scientists we seek a definitive, quantitative approach to representing and defining Embodied Intelligence in a tidy methodical manner. However, what does it mean to create a unifying theory or concept of EI? A number of approaches has been proposed including physical embodied intelligence [27], physical modeling of intrinsic and extrinsic interactions [15], energy levels, constraint driven actions [1] or behavioral lensing [24]. Whilst many of these show significant similarities, it highlights the range of approaches in terms of philosophical, level

of abstraction and also level of fidelity. In 2010, Friston presented his work entitled 'The free-energy principle: a unified brain theory?'[6] which presents perhaps the most universal approach, that accounts for action, perception and learning. This work identifies how optimization is a common theme throughout, where systems and perpetually seeking to optimize or minimize value (expected reward, expected utility) or its complement, surprise (prediction error, expected cost). This presents an exciting unified direction to approach the concept of embodied intelligence.

3.2. Design Creativity & Diversity
Biology and nature shows a vast range of creative and diverse solutions and forms. One observable limitation in robotics is the lack of diversity and innovation in structure and form in comparison to nature. However, there is not a clear solution for how, as a research field, we can develop a wider variety of forms. As already discussed, bio inspired and bio-hybrid robots is one approach; having a greater focus on plants could be beneficial as they show a hugely diverse form factor and have been less closely imitated in robotic form. There is also the need to have a more diverse set of human engineers to form these robots who have different backgrounds and experiences which provides them with different stimuli and experiences on which to form designs. Finally, there is the potential to explore learning based or large scale data-driven approaches to identify new design forms and structures.

3.3. Connection with Conventional AI
Conventional AI and machine learning has huge potential to be leveraged in conjunction with EI. To best interface these systems we must have an understanding on how to design or distribute intelligence, and how to incorporate or understand the role of EI. In addition, it is important to identify why tasks are a challenge for standalone AI, and would clearly benefit from EI. This will aid in demonstrating the role of EI alongside AI, and also for improve the standing of EI within the scientific and industrial community. Another consideration is the alignment of AI with human society. If we want AI systems to be more inline, accepted and understood by human society, we naturally must consider the intersection and interplay between embodiment and EI more carefully.

3.4. Researcher Education & Awareness
Embodied intelligence requires an interdisciplinary viewpoint with broadened views on the origins of intelligence. The requires researchers that are equipped with theoretical understanding and practical skills that straddle a number of disciplines ranging from materials science, biology to computer science [23]. To address this, we must develop methods for training the future generation of researchers to build and sustaining, active and growing EI discipline. There have been a number of mechanisms exploring this, for example summer schools and consortium for the training of early stage researchers. We must also consider the more fundamental aspects, for example what common language or theories tie together EI researchers to allow for interdisciplinary conversations, research and progress.

4. Discussion
In the last ten years there has been significant technological developments that have shown bio-hybrid robots, artificial bots and increasingly capable manipulators, swimming robots, growing robots and much more. Technology developments have also driven our capabilities to understand and characterize EI through development robotics, haptic devices and human-robot interactions. Going forwards we must further unite this research community to increase diversity, viewpoints and areas of expertise to address the key research questions in this area. We require both developments in application oriented solution but also further exploration of the fundamental

understanding and definitions of EI and physical cognition. The creation of a grand challenge for EI which drives both fundamental and applied EI research could provide one means driving this field forwards, whilst also finding and illustrating the role of EI alongside more conventional AI.

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